A model for the planning and operation of heterogeneous irrigation schemes in semi-arid regions under rotational water supply

A MODEL FOR PLANNING AND OPERATION OF HETEROGENEOUS IRRIGATION SCHEMES IN SEMI-ARID REGIONS UNDER ROTATIONAL WATER SUPPLY

by

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SYNOPSIS

This research is aimed at developing the method for efficiently using the water in irrigation schemes in semi-arid regions. These irrigation schemes are often short of water to irrigate entire culturable command area (CCA) with maximum water requirement of different crops and are characterised with different weather patterns, soils and the possibility to grow several crops. The CCA of these schemes is also large with several users or units, each having different characteristics. The previous research in this field was mostly either on optimum allocation of the resources considering the irrigation scheme as a whole or on evaluating the performance of the irrigation scheme for certain irrigation schedules for different units in the scheme. However in such schemes optimum allocation of resources (land and water) to different crops and their distribution over different units is important (optimum allocation plan, OAP).

In the present study, the method and a computer model are developed to prepare OAPs for these irrigation schemes under rotational water supply, by incorporating the concepts of deficit irrigation and productivity and equity in the optimisation process. The previous research stressed the importance of equity observed in different ways but seldom adopted in optimum allocation of resources. Therefore this method includes the preparation of OAPs while observing equity in allocation of land and water resources and distribution of crop production and net benefits.

The developed model, Area and Water Allocation Model (AWAM), consists of four phases each one for generating irrigation strategies, preparing irrigation programme for each irrigation strategy, screening irrigation programmes and allocating resources optimally to different crops in different units. The AWAM estimates the irrigation water requirement, crop yield and net benefits by simulating the various process in the irrigation scheme, produces the OAPs at preseason planning with different scenarios of productivity and equity and management options, develops the steady OAP by considering the temporal variability in the weather and modifies the allocation plan optimally during the intraseasonal operation of the irrigation scheme. AWAM operates in seven different modes to achieve this. These are simulation, calibration, generation, optimisation, planning, operation and evaluation.

The AWAM was applied to Nazare Medium Irrigation Project (medium irrigation scheme) in semi-arid region of Maharashtra State, India to evaluate the existing practice of irrigation (fixed depth irrigation), full depth irrigation and deficit irrigation for obtaining the OAPs. The practice of deficit irrigation was found to be beneficial over the existing approach and full depth irrigation. The OAPs at preseason planning are obtained for several alternatives and compared. The OAPs were obtained for different equity criteria. The productivity and equity were found to be inversely related. The method is proposed to obtain the stable OAP with AWAM by considering several years' data.

The present research contributes towards efficient utilisation of water in the irrigation scheme by incorporating the deficit irrigation and productivity and equity in obtaining OAPs, developing the methods to obtain the steady OAP and modifying the allocation plan optimally during the intraseasonal operation of the irrigation scheme

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Symbol		Description
1,2	=	superscripts to indicate the part of soil layer with roots and without roots, respectively
A	=	Area to be allocated to each activity (ha)
a	=	index for AU
α	=	runoff coefficient
$ACamax_{ca}$	=	maximum limit on the area to be irrigated for c^{th} crop in a^{th} allocation unit (ha)
$ACamin_{ca}$	=	minimum limit on the area to be irrigated for c^{th} crop in a^{th} allocation unit (ha)
$ACmax_{c}$	=	maximum limit on the area to be irrigated for c^{th} crop (ha)
$ACmin_{c}$	=	minimum limit on the area to be irrigated for c^{th} crop (ha)
$ACsamax_{ca}$	=	maximum limit on the area to be irrigated for c^{th} crop in s^{th} soil group of a^{th} allocation unit (ha)
$ACsamin_{csa}$	=	minimum limit on the area to be irrigated for c^{th} crop in s^{th} soil group of a^{th} allocation unit (ha)
Adf_{i}	=	depth of application requirement for i^{th} irrigation (mm)
Ad_{i}	=	application depth for i^{th} irrigation (mm)
Ad_{i}^{u}	=	application depth (unadjusted) for i^{th} irrigation (mm)
$Aramax_{a}$	=	the maximum limit of area to be irrigated for a^{th} allocation unit (ha)
$Aramin_{a}$	=	the minimum limit of area to be irrigated for a^{th} allocation unit (ha)
$Arasmax_{sa}$	=	the maximum limit of area to be irrigated for s^{th} soil group of a^{th} allocation unit (ha)
$Arasmin_{sa}$	=	the minimum limit of area to be irrigated for s^{th} soil group of a^{th} allocation unit (ha)
β	=	set of deficit ratio
B	=	total benefits (unit/ha)
βi	=	the deficit ratio for i^{th} irrigation
βmax	=	the highest possible value of deficit ratio
βmin	=	the lowest possible value of deficit ratio and
C	=	index for the crop in S^{th} soil group of R^{th} region
C	=	total dependant cost (unit/ha)
Ca	=	area dependent cost (unit/ha)
$CCmax_{ikj}$	=	the maximum prescribed limit of carrying capacity of k^{th} canal at j^{th} level during i^{th} irrigation interval (m^3/s)

$CCmin_{ikj}$	=	the minimum prescribed limit of carrying capacity of k^{th} canal at j^{th} level during i^{th} irrigation interval (m^3/s)
ce	=	the exponent to represent the moisture extraction pattern.
cl_{ikj}	=	conveyance losses in m^3/s per m^3/s flow rate per 1000 m length of canal for k^{th} canal at j^{th} level for i^{th} irrigation.
$crop_{csa}$	=	c^{th} crop in s^{th} soil group of a^{th} allocation unit
$CROP_{CSR}$	=	C^{th} crop in S^{th} soil group of R^{th} region
cs	=	exponent representing the decay of soil evaporation rate since the wetting.
Cy	=	yield dependent cost (unit/ha)
d	=	decision variable,
Da_i	=	the depth of application at i^{th} irrigation
$\Delta\beta$	=	increament to vary deficit ratio
Dc	=	dry limit (days)
D_l	=	thickness of l^{th} soil layer (mm)
$\Delta\theta_t^Z$	=	change in soil water storage on t^{th} day (mm)
Δz	=	the thickness of the extraction layer (mm)
e	=	superscript to represent the values over the extraction layer
e	=	the subscript for the extraction layer
ε_{ikj}	=	supply factor for k^{th} canal at j^{th} level for i^{th} irrigation period
Ecc	=	Christianson Coefficient
Ecv	=	coefficient of variation
Egc	=	Gini coefficient
Ei1	=	inter-quartile ratio
Ei2	=	modified inter-quartile ratio
EI_i	=	Ending day of i^{th} irrigation
EI_{if}	=	ending day of if^{th} irrigation (days since the beginning of irrigation season)
el_i	=	evaporation losses from the reservoir during i^{th} irrigation period (ha-m)
εo_{ia}	=	supply factor for outlet of a^{th} allocation unit for i^{th} irrigation
ep_i	=	evaporation losses (depth) over the irrigation period (m)
$ESa_{l,t-1}^{l}$	=	soil evaporation from l^{th} soil layer on $(t-1)^{th}$ day (mm)
ESa_t	=	actual soil evaporation on t^{th} day (mm)
ES_t	=	potential soil evaporation on t^{th} day (mm)
e_t	=	extraction rate on t^{th} day (mm/mm)
ETa_S	=	actual crop ET of s^{th} stage (mm)
ETa_t	=	actual crop ET on t^{th} day (mm)

Eti	=	Theil's index
ETm	=	maximum crop ET of entire crop growth period (mm)
ETm1	=	maximum value of ETm (mm/d)
ETm2	=	minimum value of ETm (mm/d)
ETm_s	=	maximum crop ET of s^{th} stage (mm)
ETm_t	=	maximum crop evapotranspiration on t^{th} day (mm)
ETr_t	=	reference crop evapotranspiration on t^{th} day (mm)
$\phi(\theta)$	=	soil moisture diffusivity = $K(\theta)\frac{\delta\psi}{\delta\theta}$
FEIP	=	irrigation programmes for the unit
$f_n(x_i)$	=	maximum net benefits obtained from stage n onwards starting in state x_i in stage n.
ftn	=	fraction for minimum limit on area to be irrigated for irrigation scheme
ftx	=	fraction for maximum limit on area to be irrigated for irrigation scheme
ηa	=	application efficiency (fraction)
ηa_i	=	the application efficiency at i^{th} irrigation
hrd_{csa}	=	harvesting day of c^{th} crop grown in s^{th} soil group of a^{th} allocation unit
i	=	index for irrigation/observation number
I	=	number of irrigations
I1	=	the number of irrigations for which deficit ratio is predecided
ia	=	index of agreement
Ic	=	number of crop irrigations (excluding presowing irrigations, if any)
Ic'_{csa}	=	total number of irrigations for c^{th} crop in s^{th} soil group of a^{th} allocation unit (including presowing irrigation)
Ic'_{CSR}	=	total number of irrigations for C^{th} crop in S^{th} soil group of R^{th} region (including presowing irrigation)
Id_i	=	irrigation depth for i^{th} irrigation (mm)
$ID_{i,p}$	=	irrigation depth for i^{th} irrigation of p^{th} irrigation programme (mm)
IDi_i	=	the depth of irrigation at i^{th} irrigation
Idmax/IDmax	=	the maximum possible depth of irrigation
Idmin/IDmin	=	the minimum possible depth of irrigation
Id_i^u	=	unadjusted irrigation depth for i^{th} irrigation (mm)
if	=	number of first crop irrigation (irrigations since the beginning of irrigation season)

ifp	=	the difference in number of irrigations between presowing irrigation and first crop irrigation
II_i	=	the irrigation period of i^{th} irrigation interval (days)
il	=	number of last crop irrigation
Inf_i	=	the inflow of water into the reservoir
INF_t	=	inflow of water into the system during period t (mm)
IN_l	=	inflow into l^{th} soil layer (mm)
IP_i	=	irrigation period of i^{th} irrigation (days)
IP_p	=	p^{th} irrigation programme
j	=	index for canal level
J_a	=	the canal level at which j^{th} AU exists
k	=	index for canal at j^{th} level
k	=	index for canal number at any canal level
k'	=	index for canal number
$K(\theta)$	=	unsaturated hydraulic conductivity as a function of soil moisture, θ
K_{aj}	=	the canal number for j^{th} level of a^{th} allocation unit
Kcmax	=	highest value of crop factor in crop growth period
Kcmin	=	lowest value of crop factor in crop growth period
Kc_t	=	crop factor on t^{th} day
KN	=	3600*24/10000
Ky_s	=	yield response factor of s^{th} stage
l	=	index for soil layer
l	=	superscript to indicate that the values are over the soil layer
λa_a	=	actual allocation proportion for a^{th} allocation unit
λd_a	=	proportion for allocating the resources for a^{th} allocation unit (fraction) or desired allocation proportion for a^{th} allocation unit
Len_{kj}	=	length in m for k^{th} canal at j^{th} level for i^{th} irrigation. (lengths of canals at each level are those lengths which are active in carrying water to the AU or to canal for which efficiencies are computed)
lnp_{csa}	=	land preparation required for c^{th} crop grown in s^{th} soil group of a^{th} allocation unit(days)
L_t	=	total number effective soil layers on t^{th} day
L_T	=	total number soil layers in root zone
L_v	=	total number effective soil layers for soil evaporation
m	=	index for canal level
mae	=	mean absolute error
na	=	total number of allocation units
NB	=	net benefits (unit/ha)

$n\beta$	=	the number of deficit ratio
$n\beta 1$	=	the number of predecided deficit ratios
NB_p	=	net benefits for p^{th} irrigation programme (currency unit/ha)
ηC_{ikj}	=	conveyance efficiency of canal network from headworks to k^{th} canal at j^{th} level (fraction)
nca_{aj}	=	canal number at j^{th} level of a^{th} allocation unit
ηca_{ia}	=	conveyance efficiency of canal network for i^{th} irrigation for a^{th} allocation unit (fraction)
$Ncan_j$	=	total number of canals at j^{th} level
ηcc_{ija}	=	conveyance efficiency of canal network up to j^{th} level for a^{th} allocation unit (fraction)
ηc_{ikj}	=	conveyance efficiency of k^{th} canal at j^{th} level for i^{th} irrigation (fraction)
ncc_{kmj}	=	canal number at m^{th} level of k^{th} canal at j^{th} level
NCL	=	total number of canal levels
ηcl_{ikj}	=	conveyance efficiency of k^{th} canal at j^{th} level for i^{th} irrigation allocation unit per 1000 m length of canal
ηcl_a	=	number of canal levels for a^{th} allocation unit
nc_{sa}	=	total number of crops in s^{th} soil group of a^{th} allocation unit
NC_{SR}	=	number of crops in S^{th} soil group of R^{th} region
Nc_{Sr}	=	total number of crops in S^{th} soil group of R^{th} region
ηda_{ia}	=	distribution efficiency for i^{th} irrigation of a^{th} allocation unit.
nfp	=	the total number of feasible irrigation strategies
nis	=	the total number of irrigation strategies
noep	=	the total number of OEIPs
nos	=	number of crop seasons
NR	=	number of regions
NRS	=	total number of resources to be considered at scheme level and during irrigation season
NRS_a	=	total number of resources to be considered at AU level and during irrigation season
NRSI	=	total number of resources to be considered at scheme level and during intraseasonal period
NRSIa	=	total number of resources to be considered at AU level and during intraseasonal period
ns_a	=	total number of soil groups in a^{th} allocation unit.
nsp	=	total number of SIPs in **SIP**.

nsp_{csa}	=	total number of irrigation programmes of c^{th} crop in s^{th} soil group of a^{th} allocation unit
NS_R	=	number of soil groups in R^{th} region
NS_r	=	total number of soil groups in R^{th} region
nt	=	total number of activities.
NU	=	number of CSR units
$\Omega aTi\max_{ir}$	=	maximum level of availability or use of r^{th} resource at a^{th} AU during i^{th} intraseasonal period (total resource)
$\Omega aTi\min_{ir}$	=	minimum level of availability or use of r^{th} resource at a^{th} AU during i^{th} intraseasonal period (total resource)
$\Omega aT\max_{r}$	=	maximum level of availability or use of r^{th} resource at a^{th} AU during irrigation season (total resource)
$\Omega aT\min_{r}$	=	minimum level of availability or use of r^{th} resource at a^{th} AU during irrigation season (total resource)
OBJ	=	the value of objective function (currency unit)
$OCmax_{ikj}$	=	the maximum prescribed limit of carrying capacity of outlet of a^{th} allocation unit during i^{th} irrigation interval (m^3/s)
$OCmin_{ikj}$	=	the minimum prescribed limit of carrying capacity of outlet of a^{th} allocation unit during i^{th} irrigation interval (m^3/s)
$o\Omega_{csa}$	=	the use or need of r^{th} resource for c^{th} crop in s^{th} soil group in a^{th} allocation unit during per unit area during irrigation season (resource/hectare)
OEIP	-	optimal efficient irrigation programmes
Ωi_{icsa}	=	the use or need of r^{th} resource for c^{th} crop in s^{th} soil group in a^{th} allocation unit resource during i^{th} irrigation period per unit area (resource/hectare)
OIP	=	optimal irrigation programmes
ol_i	=	water to be diverted for other purposes (ha-m) during i^{th} irrigation period
olr_i	=	water to be diverted from the headworks for other purposes during i^{th} irrigation period
OTF_t	=	outflow of water from the system during period t (mm)
$\Omega Ti\max_{ir}$	=	maximum level of availability or use of r^{th} resource during i^{th} irrigation period (total resource)
$\Omega Ti\min_{ir}$	=	minimum level of availability or use of r^{th} resource during i^{th} irrigation period (total resource)
$\Omega T\max_{r}$	=	maximum level of availability or use of r^{th} resource during irrigation season (total resource)

$\Omega T\min_r$	=	minimum level of availability or use of r^{th} resource during irrigation season (total resource)
OYB_p	=	output from p^{th} irrigation programme (Kg/ha if output is crop yield and currency unit/ha if output is net returns)
p	=	index for irrigation programme for crop (c^{th} crop in s^{th} soil group of a^{th} allocation unit)
p1	=	p value corresponding to ETm1
p2	=	p value corresponding to ETm2
$Pamax_c$	=	maximum limit of crop production to be obtained from the AU, for c^{th} crop (Kg)
$Pamin_c$	=	minimum limit of crop production to be obtained from the AU, for c^{th} crop (Kg)
Pc	=	the market price of crop yield (unit/Kg)
P_{D_t}	=	deep percolation on t^{th} day (mm)
Pf	=	the market price of fodder yield (unit/Kg)
pld	=	planting day (days since the beginning of irrigation season)
pld_{csa}	=	planting date of c^{th} crop grown in s^{th} soil group of a^{th} allocation unit
$Pmax_c$	=	maximum limit of crop production to be obtained from the scheme, for c^{th} crop (Kg)
$Pmin_c$	=	minimum limit of crop production to be obtained from the scheme, for c^{th} crop (Kg)
pt	=	soil water depletion factor t^{th} day
θ	=	volumetric soil moisture content
$QCCO_{ikj}$	=	quantity of water to be carried by k^{th} canal at j^{th} level during i^{th} irrigation period for non irrigation purposes and estimated theft of water (ha-m).
$QCO_{ik'j'}$	=	quantity of water to be diverted from k'^{th} canal at j'^{th} level during i^{th} irrigation period for non irrigation purposes and estimated theft of water from this canal(ha-m)
θf_l and θw_l	=	volumetric soil water content in l^{th} layer (mm/mm) at field capacity and wilting point, respectively
θf^R	=	volumetric soil moisture content in the entire root zone at field capacity (mm/mm)
$\theta l,t$	=	volumetric soil water content in l^{th} layer and at the beginning of $(t-1)^{th}$ day (mm/mm)
$\theta_{l,t}$	=	the soil moisture of any layer on a particular day)
$QOHI_{ia}$	=	water to be diverted from the headworks for irrigating the crops not in plan during the i^{th} irrigation for a^{th} allocation unit

$QOHO_{ia}$	=	the water to be delivered from the headworks for other purposes
QOI_{ia}	=	quantity of water required for irrigating the crops not in the plan for the i^{th} irrigation at a^{th} allocation unit
θo_l	=	initial volumetric soil moisture content in the soil l^{th} layer (mm/mm)
QOO_{ia}	=	the amount of water required for other purposes during the i^{th} irrigation for a^{th} allocation unit
QOO_{ia}	=	quantity of water required for other purposes in a^{th} allocation unit for i^{th} irrigation (ha-m)
θw^{R}	=	volumetric soil moisture content in the entire root zone at wilting point (mm/mm)
$\theta \omega^{R}$	=	volumetric soil moisture content in the entire root zone at allowable level (mm/mm)
R	=	index for the region in irrigation scheme
r	=	index for the resource
R	=	superscript to indicate the values are over entire root zone.
$\overline{Ra}$	=	the average of allocation ratios of all AUs
Ra_a	=	allocation ratio of a^{th} allocation unit
$\overline{Ra^{qf}}$	=	the average of allocation ratios of all AUs in first division or quarter
Ra^{qfl}	=	the allocation ratio of the last AU of first division or quarter
$\overline{Ra^{ql}}$	=	the average of allocation ratios of all AUs in last division or quarter
Ra^{qlf}	=	the allocation ratio of the first AU of last division or quarter
Rc	=	regression coefficient
region	=	region of a^{th} allocation unit
$REGION_R$	=	R^{th} region
RFe_t	=	effective rainfall amount on t^{th} day (mm)
RF_t	=	total rainfall amount on t^{th} day (mm)
rme	=	relative mean error
rmse	=	root mean square
s	=	index for soil group in allocation unit/crop growth stage
S	=	index for soil group in the R^{th} region
$S(\theta)$	=	sink term (normally water uptake by plant)
SA	=	reservoir surface area (ha)
SID_p	=	seasonal irrigation depth for p^{th} irrigation programme (mm)
SID_p	=	seasonal irrigation depth of p^{th} irrigation programme (mm)
SI_i	=	starting day of i^{th} irrigation
SI_{if}	=	starting day of if^{th} irrigation (days since the beginning of irrigation season)
SIP	=	a set of selected irrigation programmes

Smax	=	maximum storage capacity of the reservoir (ha-m)
Sm_i	=	observed value of the simulated parameter for i^{th} observation
Smin	=	dead storage capacity of the reservoir or the minimum storage of water that should always be maintained in the reservoir (ha-m)
So	=	initial reservoir storage (at the beginning of irrigation season) (ha-m)
$soil_{sa}$	=	s^{th} soil group of a^{th} allocation unit
$SOIL_{SR}$	=	S^{th} soil group of R^{th} region
sp_i	=	seepage losses form the reservoir during i^{th} irrigation period (ha-m)
ST	=	reservoir storage (ha-m)
T	=	crop period (days)
t	=	days since planting/index for time period
TA	=	total irrigable area of irrigation scheme (ha)
$TAAS_{sa}$	=	total area that can be irrigated in s^{th} soil group of a^{th} allocation unit (ha)
Γa_{ca}	=	proportion of area to be irrigated under c^{th} crop in a^{th} allocation unit
Γan_{ca}	=	minimum limit on the fraction of total area of a^{th} allocation unit that can be irrigated for c^{th} crop
Γax_{ca}	=	maximum limit on the fraction of total area of a^{th} allocation unit that can be irrigated, for c^{th} crop
tm	=	the day at which crop attains Zm since sowing
TM_t	=	potential transpiration on t^{th} day (mm)
Γn_c	=	minimum limit on the fraction of total area of scheme that can be irrigated for c^{th} crop
tp	=	the time since wetting till $ES_t = ESa_t$ (days)
θp_t^R	=	volumetric soil moisture content in the entire root zone at depletion level (mm/mm) on t^{th} day
TR_t^e	=	transpiration from e^{th} extraction layer on t^{th} day (mm/day)
$TR_{l,t}^l$	=	transpiration through each soil layer (mm)
$TR_{l,t}^l$	=	adjusted transpiration of l^{th} soil
$TR_{l,t}^{lu}$	=	unadjusted transpiration of l^{th} soil
TR_t	=	actual transpiration on t^{th} day (mm)
θ_t^R	=	volumetric soil moisture content in the root zone depth (mm) on t^{th} day
Γsan_c	=	minimum limit on the fraction of total area of s^{th} soil group of a^{th} allocation unit that can be irrigated for c^{th} crop
Γsax_c	=	maximum limit on the fraction of total area of s^{th} soil group of a^{th} allocation unit that can be irrigated, for c^{th} crop

tw	=	time since the last wetting in days
Γwan_{ca}	=	minimum limit on the fraction of total water that is available for a^{th} allocation unit that can be irrigated for c^{th} crop
Γwax_{ca}	=	maximum limit on the fraction of total water that is available for a^{th} allocation unit, for c^{th} crop
Γwn_c	=	minimum limit on the fraction of total water that is available for irrigation in the scheme, for c^{th} crop
$\Gamma wsan_{ca}$	=	minimum limit on the fraction of total area of s^{th} soil group of a^{th} allocation unit that can be irrigated for c^{th} crop
$\Gamma wsax_{ca}$	=	maximum limit on the fraction of total area of s^{th} soil group of a^{th} allocation unit that can be irrigated, for c^{th} crop
Γwx_c	=	maximum limit on the fraction of total water that is available for irrigation in the scheme, for c^{th} crop
Γx_c	=	maximum limit on the fraction of total area of scheme that can be irrigated, for c^{th} crop
θ_t^Z	=	volumetric water content at the end of period t in soil root zone (mm/mm)
ω	=	allowable level factor
Wc	=	wet limit (days)
$WCamax_{ca}$	=	minimum limit on the water to be delivered for c^{th} crop in a^{th} allocation unit (ha)
$WCamin_{ca}$	=	maximum limit on water to be delivered for c^{th} crop in a^{th} allocation unit (ha)
$WCmax_c$	=	minimum limit on the water to be delivered for c^{th} crop (ha)
$WCmin_c$	=	maximum limit on the water to be delivered for c^{th} crop (ha)
$WCsamax_{csa}$	=	minimum limit on the water to be delivered for c^{th} crop in s^{th} soil group of a^{th} allocation unit (ha)
$WCsamin_{csa}$	=	maximum limit on the water to be delivered for c^{th} crop in s^{th} soil group of a^{th} allocation unit (ha)
$Wramax_a$	=	maximum limit of water to be allocated to a^{th} allocation unit (ha-m)
$Wramin_a$	=	minimum limit of water to be allocated to a^{th} allocation unit (ha-m)
$Wrasmax_{sa}$	=	the maximum limit of water to be allocated s^{th} soil group of to a^{th} allocation unit (ha-m)
$Wrasmin_a$	=	the minimum limit of water to be allocated s^{th} soil group of to a^{th} allocation unit (ha-m)
WUE_p	=	water use efficiency of p^{th} irrigation programme (Kg/ha-mm if output is crop yield and currency unit/ha-mm if output is net returns)
WUR_p	=	water use ratio for p^{th} irrigation programme (mm)

ξa_a	=	value of parameter by which equity is measured, computed for a^{th} allocation unit
ξd_a	=	the value of the parameter to which equity should be proportional, assigned to a^{th} allocation unit.
ψ	=	pressure head
Ya	=	actual crop yield (Kg/ha)
Ya_p	=	crop yield for p^{th} irrigation programme (Kg/ha)
Yfa	=	fodder yield (Kg/ha)
Ym	=	potential crop yield (Kg/ha)
Z	=	superscript to indicate that the values are over the soil root zone
z	=	depth of the midpoint of extraction layer from the soil surface mm)
z	=	vertical distance from soil surface
Zm	=	maximum depth of root zone during crop growth period (mm)
Zo	=	initial depth of root zone (depth of sowing, mm)
Z_t	=	depth of root zone on t^{th} day
ZT	=	depth of soil root zone (mm)

CHAPTER I

INTRODUCTION

Summary. This chapter introduces the topic of research and provides the justification of this research work. It also states the hypotheses and objectives of the study. Finally it outlines the method of approach used for conducting the study and the organisation of the report.

1.1 PREAMBLE

"On balance I propose, as our initial overall objective, that we should target now to increase crop production per unit of water by 20% by 2001"

In support of AGENDA 21 (UNCED, 1992) and Dublin Statement (ICWE, 1992), John Hennessy , President, International Commission on Irrigation and Drainage (ICID) set the goal stated above quantitatively before the water management community in his keynote address during Fifteenth Congress of ICID held in the Hague in 1993 (Hennessy, 1993:26). AGENDA 21 which was signed at "The Earth Summit" held in Rio de Janeiro in June 1992, provides a framework for sustainable development into the 21st century. The Dublin Statement, which followed from the International Conference on Water and the Environment (ICWE) held in Dublin in January 1992, emphasises effective management of land and water resources in the present decade and better than they have been in the past. Similarly, in his address to Regional Conference on Water Resources Management held in Iran in August 1995, Andras Szollosi-Nagy, Director, Division of Water Science, UNESCO, conveyed the importance of integrated water resources development, planning and management and affirmed (Szollosi-Nagy, 1995:1)

"...I firmly believe, water is going to be the issue of the 21st Century, the most valuable resource."

This speaks for the concern of the international community over the water shortages that we meet with today and should expect to face in future, and the need to act accordingly. The present research is aimed in this direction and particularly towards efficient use of water resources within an irrigation scheme to enhance its performance.

1.2 THE NEED FOR EFFICIENT UTILISATION OF WATER FOR IRRIGATION

The importance of water management in agriculture was realised long ago, but the situation has become more alarming in this decade. The following trends need to be considered when considering the future of irrigation.

- Competition from other users: Besides agriculture, industries and domestic water needs are the major water consumptive users and both these sectors are now receiving increasing attention in developing countries. The increased use of water for domestic purposes improves the health of the people and industries are the backbone of economies of many countries. The water needs for other users (though non consumptive) such as hydropower generation, navigation, fisheries and recreation are also growing.
- Growing global population: The world population is already more than 5 billion and 100 million people are being added every year. Developing countries are leading the way (Africa-2.5 to 3.5% per annum, Asia-1.5 to 2.0% per annum plus and Central/South America-1.5% per annum plus). This growing global population needs more water for these uses. Shiklomanov (1991) projected the water consumption for agriculture to 3250 km^3/year in 2000 from 2680 km^3/year in 1990 and for industries and domestic needs, to 1701 km^3/year from 1273 km^3/year (Ayibotele, 1992). This also shows the share of water for irrigation reducing from 68.9% presently to 62.6% in future. Irrigation being the major consumptive user of water, it has to release more water for other uses by ensuring effective use of water within each irrigation scheme (Burton, 1992).
- Declining rate of expansion of new irrigated areas in developing countries: This rate has been radically reduced from 5% per annum during the decade 1965-1974 to 1.5% in next decade, 1975-1984 (Carruthers, 1988). As Shanan (1992) pointed, this is due to

  (1) increasing difficulties and expenditure in developing new water from the finite water available, as traditionally the approach has been to harvest easily available and cheap water resources.

  (2) Investments in development are declining as economic constraints limit national budgets.

  (3) The growing understanding that the rates of return on investment in irrigation schemes are below the values that they could or should be and

  (4) Increasing awareness about environment and preservation of natural resources.

- Greater productivity of irrigated agriculture: Food is the necessity and according to FAO (1990), as Ayibotele (1992) cited, even though irrigated land formed only 15% of the global cultivable land, it contributed 36% of the total crop production in the mid 1980s.

All these facts impose pressure on irrigated agriculture to constantly use water more efficiently, and continuously improving management of the irrigation scheme is one such component. Otherwise there will be considerable increases in demand for irrigation water supplies (Hennessy, 1993) which might be impossible to meet.

1.3 PERSPECTIVE FROM DEVELOPING COUNTRIES

Today the need for water in developed countries is almost steady due to stable population and already developed related infrastructure. However water consumption in developing countries can be expected to increase rapidly due to various reasons (population growth, rapid urbanisation, industrialisation etc.). Moreover according to FAO (1990), 70% of the current world total land area under irrigation (240 million ha.) is in developing countries (major countries being China-45, India-43, Pakistan-16, Indonesia-8, Iran-6, Mexico-5 and Thailand-4 million ha.), and agriculture consumes more than 80% of water in developing countries. The most part of developing countries is characterised by arid and semiarid regions and thus already faced with water shortages. Therefore irrigation water management needs more attention especially in arid to semiarid areas of developing countries. One such typical case (India) is described in the following paragraphs.

It is estimated that India receives an average annual rainfall of 1190 mm, which looks substantial but is unevenly distributed over space and time. Most of the coastal and interior areas receive annual precipitation between 1000 to 2000 mm. The western part of the country such as parts of Punjab, Haryana, Rajasthan, UP, Maharashtra and Gujarat receives annual precipitation between 500-800 mm and some parts of Rajasthan and Gujarat even receive precipitation less than 400 mm (Sinha et al., 1985). Most of the precipitation falls during the months from July to September as monsoon rains, and very little rainfall is received in the remaining months as a consequence of which, the discharge in rivers is also maximum during these months. Though some rivers of north India receive water through the melting of snow from Himalayan region in summer months, discharge in rivers of central and southern India are very low during non-monsoon months.

The cultivation of crops is possible in India throughout a year, in three seasons. The kharif season starts in the month of July and lasts till mid October. Therefore the crops grown during this season do not need regular irrigation. But supplemental irrigation can be beneficial to avoid damage to the crop due to excessive stress during a long dry period. But the crops grown during rabi season (from the mid-October to February) and summer season (from the month of March to June) do not get much moisture from precipitation and are dependent on irrigation for their survival. During the summer season, crop water requirements are also high. Thus in India the periods of highest rainfall do not coincide with the periods of maximum water demand and therefore the pattern of rainfall and cropping seasons described above led to the use of reservoirs. The river discharge is diverted during the rainy season and stored in the reservoir to be used for protecting the crops grown in kharif season during the periods of water shortage due to long dry spells, and for irrigating the crops grown in rabi and summer seasons.

In India about 47% of the utilisable water resources are tapped and 83% of the total withdrawal is used for irrigating 30% of the total cultivable area (Sinha et al., 1985; Navalawala, 1993 and Reddy, 1993). Industrial and domestic water demands are also increasing every year exponentially, reducing the share of water for the purpose of irrigation. The pace of development of new irrigation schemes is very slow due to economical and environmental reasons. The cost of development of new water resources for irrigating one hectare of land is around Rs.40,000 - Rs.50,000 (Shanan, 1992)which is very high. Even if all the utilisable water resources are tapped, irrigated area may not be more than 50% of total cultivable area in India and 30% in the drought prone states like Maharashtra with the present practice of irrigation management. The need for increased food production is imposing pressure on the irrigated agriculture. The higher productivity of irrigated agriculture than unirrigated agriculture in India (two to three times more) (Sinha et al., 1985) also demonstrates the importance of irrigation. This indicates the need to increase area under irrigation and produce more with the available amount of water. In India generally the irrigation schemes are designed for an irrigation intensity of 30 to 40% (Shanan, 1992). Therefore even in wet years 100% of the command area can not be irrigated, indicating the scope for increasing area under irrigation within the irrigation scheme by improved water management.

Thus the most viable option left to increase the irrigated area and crop production is to improve the performance of existing irrigation schemes by adopting efficient irrigation practices, so that the productivity (output) of the available irrigation water in the reservoir of each irrigation scheme can be increased.

1.4 DIFFERENT WAYS FOR EFFICIENT UTILISATION OF IRRIGATION WATER

The productivity of available water in the irrigation scheme can be enhanced in many ways. These are classified in three main categories and are given below.

1. Improving hardware of the scheme: It includes

- Increasing reservoir storage by desedimentation, raising the dam height or developing the catchment area
- Structural changes in the water delivery system such as lining of canal network, installation of water regulatory and measurement structures
- Repairing and enhancing maintenance of existing water delivery system
- Development of onfarm structures
- Land levelling
- Automation

2. Adopting water saving irrigation methods: These methods are

- Pressurised irrigation methods such as sprinkler and drip
- Improvements in traditional irrigation methods such as skip furrow irrigation method
- Automated surface irrigation system such as surge flow irrigation

3. Improving software of the scheme: These include

- Adoption of appropriate water distribution method such as rotational water supply or on demand water supply
- Optimum allocation of resources (land and water) to different crops in the irrigation scheme
- Institutional reforms such as promoting the formation of water users organisation, training of farmers etc.
- Improving capital related activities such as availability of credits to water users, better marketing facility, incentives etc.
- Improving crop related management practices such as reducing runoff of irrigation water, rainfall harvesting etc.

All the three categories or different means in each category are not alternatives to each other, but could be adopted simultaneously. For example, lining the canal and forming water users organisation can go together, or adopting optimum allocation plan together with improved water distribution system would produce better results. According to Hennessy (1993), in the late 1970's 'hardware' related items dominated in the irrigation schemes; however it was realised that these dealt with only 30-40% of the system problems and the remainder demanded software solutions. Nowadays, therefore, the 'software' aspect is also receiving increasing attention. The present work deals with one such software related aspect i.e. optimum allocation of land and water resources in the irrigation scheme to make efficient utilisation of water available in the irrigation scheme.

1.5 OPTIMUM ALLOCATION OF LAND AND WATER RESOURCES

Several studies have been conducted on irrigation management through optimum allocation of land and water resources. These are reviewed in Chapter II. It is attempted here to describe the 'Optimum allocation of land and water resources' in irrigation water management from the aims and purposes of conducting those studies.

> Optimum allocation of land and water resources in irrigation water management includes assigning quantitatively land or water or land and water resources available in an irrigation scheme, temporally or spatially or both to selected crop(s), or by selecting crop(s) over an irrigation season which may constitute one or more than one crop seasons, such that the performance of the irrigation scheme, in terms of one or more performance parameters, is maximised under the influence of certain system restrictions.

Outwardly the optimum allocation may look just a simple optimisation problem. But in reality the process is difficult due to the varied characteristics of the irrigation scheme and the complex nature of the processes involved in allocation. Irrigation schemes in general and particularly in semiarid and arid regions, are characterised by varying climates, the existence of different types of soils, the possibility of growing multiple crops and the scarcity of water. The command area of an irrigation scheme can be large involving a complex network of water delivery system. Such schemes in this study are referred to as "heterogeneous irrigation schemes". The soil, plant and atmospheric subsystems are central to the allocation. As described in Chapter V, the processes involved in these subsystems are interdependent and complex.

In Chapter II, various models developed for the optimum allocation of land, water or both the resources (called irrigation water management models) are classified according to the types of resources that were optimised. The broad categories identified are allocation model and evaluation model. Allocation model includes land allocation models, water allocation models and land and water allocation models. These models vary greatly in capturing the details of a heterogeneous irrigation scheme and the soil, plant and atmospheric subsystems, depending on the situations for which the models had to be developed, the knowledge of the processes involved in subsystems at the time of model development, assumptions and computational facility.

1.6 THE NEED FOR THE STUDY

This classification of irrigation water management models for optimum allocation of land and water resources helped to establish a thorough understanding of the problems involved in the allocation of land and water resources, and a basis for ameliorating the use of water in irrigation schemes. This further identified the allocation model of type 'land and water allocation model' as the suitable tool for efficiently utilising irrigation water through optimum allocation of land and water resources because these models do not consider the allocation of any of the resources assumed or known, and they optimise the use of both resources in water limiting conditions, unlike other allocation models and evaluation models.

The three terms viz. allocation plan, pre-season planning of an irrigation scheme and intraseasonal operation of an irrigation scheme, which are frequently used in this study are described at this point for clarity in further discussion.

Allocation plan: This is the plan consisting of temporal and/or spatial allocation of land and water resources under different crops.

Pre-season planning of an irrigation scheme: This refers to the preparation of an allocation plan before the beginning of each irrigation season

Intraseasonal operation of an irrigation scheme: This refers to the execution of the allocation plan after the beginning of the irrigation season.

(Simply 'planning' and 'operation' are also used alternatively for pre-season planning and intraseasonal operation, respectively).

Land and water allocation models referred to in Chapter II are of single field type and thus do not produce the allocation plans that give spatial allocation of the resources. However in operation of a heterogeneous irrigation scheme, the spatial distribution of the resources is very important (like a multifield model) because several types of soils and climate may exist at different locations in the scheme, the capacity of the water delivery system may restrict the allocation at different locations, and water losses in the system may influence the allocation. The appropriate basis for the optimal allocation of both the resources needs to be established, taking spatial allocation into consideration.

When water is not limited, irrigation management involves the optimal allocation of land to different crops under consideration to maximise the net returns from the scheme with the irrigation depth which gives maximum yield (or net returns) per unit area, or the irrigation depth which is equivalent to satisfying maximum crop water requirement. These irrigation depths can be termed as the adequate irrigation depth and full irrigation depth, respectively. But when water is limited, the allocation process is not only limited to area but to available water also. When water is limited there is always a possibility of some area being left with no irrigation, if the adequate or the full irrigation depth is applied. When the crop is irrigated with the adequate or the full irrigation depth, the last few increments of water applied to the crop results only in a small yield increment, and if these last few increments of water are applied to some additional area, the total yields or net returns obtained from the scheme may be more (English and Nuss, 1982 and Trimmer, 1990), though the yield per unit area is reduced. Thus in water limiting condition, the additional problem is to decide upon the last few increments for each crop and the additional area that can be irrigated by those increments so that the net returns can be maximised. In this case the net return per unit of water applied is maximised, and when only one crop (and soil type) is involved, the area allocation is simple as the water can be allocated with the depth which gives maximum yield or net returns per unit of water applied. But in the typical irrigation scheme several crops can be grown and several types of soils and climatic regions are involved, so restricting consideration to the irrigation depth giving maximum yield or net return is not sufficient for two reasons. First, different crops grown on different types of soils in different climatic regions (which influences the availability of water to the crop and consumptive use of crop) are competing for limited water. Second, application of a certain depth of water to one crop influences the availability of water to another crop for irrigation and thus the net returns. Therefore it is also necessary to consider several other depths of irrigation water to be applied to each crop.

The above discussion shows that irrigating the crop applied with the depth less than adequate or full irrigation depth is also important in irrigation water management with limited water supply. The practice of deliberately applying less water than required to achieve full potential yield, or underirrigating the crop to reduce the yield per unit area, is known as deficit irrigation (English and Nuss, 1982; Hargreaves and Samani, 1984 and Trimmer, 1990) but at the same time water consumed by crop is also reduced. Thus the adoption of deficit irrigation is important in irrigation management with limited water. With this it is also necessary to know the means of obtaining deficit irrigation, the influence of deficit irrigation on output and the possibility of including deficit irrigation in a computer model for obtaining the allocation plan for heterogeneous irrigation schemes.

Another important aspect which needs to be included in a land and water allocation model is allocation of the resources to different users according to a certain required standard (see Chapter X) for example distribution of the water resources proportional to the culturable command area of each user (equity aspects), while optimising the allocation of these resources (productivity aspects). Productivity and equity are the performance parameters and in literature productivity and equity are considered as conflicting or supporting goals (see Chapter X). Therefore there is a need to establish the relationship between productivity and equity in the allocation process. The inclusion of equity aspects in allocation also emphasises the need for land and water allocation models with spatial allocation of the resources.

Based on above discussion the hypotheses are formulated, the verification of which could lead towards achieving the aim of the study.

1.7 HYPOTHESES AND OBJECTIVES

The efficient utilisation of water for irrigation through optimum allocation of land and water resources is an important element of the management of a heterogeneous irrigation scheme. The introduction of deficit irrigation in the allocation process is identified as a potentially useful tool to utilise the resources efficiently. Similarly the development of allocation plans considering productivity and equity together is conceived as important in the management of an irrigation scheme. The following hypotheses are formulated based on deficit irrigation and consideration of productivity and equity and will be verified in the present research work.

- 1. Prolonging the irrigation interval between two irrigations and/or applying water less than needed for full irrigation results in deficit irrigation. Deficit irrigation influences crop yield and water consumption. The detailed processes in the soil-plant-atmospheric system can be modelled accurately to include deficit irrigation in a computer program.
- 2. The reduction in water consumption by deficit irrigation brings additional area under irrigation, and the water saved through deficit irrigation, if applied to this additional area, gives higher incremental production or returns than by adopting adequate irrigation to satisfy maximum crop water requirements.

- 3. The concept of deficit irrigation can be included in a computer model for the allocation of the resources at pre-season planning and during intraseasonal operation of an irrigation scheme.
- 4. The resources can be allocated at planning and operation stages of a heterogeneous irrigation scheme to include the productivity and equity aspects (the fair allocation of resources to different users while optimising the output from the irrigation scheme). The deficit irrigation approach can be coupled with productivity and equity aspects and the entire scenario can be combined in a computer model.
- 5. Productivity is inversely related to equity in the process of allocation of resources.

The present research is aimed at verifying the above hypotheses and improve the planning and operation of the heterogeneous irrigation scheme for obtaining the improved performance from the irrigation scheme with the knowledge gained. The specific objectives of the study to achieve this goal are outlined below.

- 1. To develop the algorithm and computer model for obtaining the optimum allocation plan for land and water resources by incorporating the proposed methodology.
- 2. To study the applicability of the model by developing the case study for one of the irrigation schemes in semi-arid region of Maharashtra State, India and suggest land and water allocation plans for different conditions.
- 3. To perform the sensitivity analysis with various parameters and compare the results with the traditional approaches of scheduling irrigation.
- 4. To propose methodology for optimally reallocating the resources while the scheme is in operation.
- 5. To propose the method to obtain steady land and water allocation plan by considering the variation in inter annual weather pattern.

1.8 METHOD OF APPROACH

The literature survey of research conducted in the past revealed the gaps which exist in deciding the optimum spatial and temporal allocation of the land and water resources in heterogeneous irrigation scheme to achieve different performance goals. The hypotheses which could help to achieve this, were formulated. The model called 'Area and Water Allocation Model' (AWAM) which is of land and water allocation type was developed and coded into computer program. The model can allocate the resources spatially by considering the necessary details of complex soil-plant-atmospheric subsystems and the varied nature of a heterogeneous irrigation scheme. The hypotheses formulated in this study formed the base for the development of this model. The hypotheses were tested with the case study data from an irrigation scheme (Nazare Medium Irrigation Project) in India. The applicability of the model was also verified with the case study data according to the stated objectives.

1.9 ORGANISATION OF THE THESIS

The entire thesis consists of eleven chapters. Chapter I which is introduction provides the justification of the study, states the hypotheses and objectives of the study and outlines the method of approach. Chapters II and III are devoted to literature survey and providing the basis for the hypotheses. These chapters also show the direction for conducting the present study. Chapter II is related to various irrigation water management models and Chapter III is related to deficit irrigation.

The next three chapters i.e. Chapters IV, V and VI describe the formulation of the model in detail and relate to Hypotheses 1,3 and 4 and Objective 1. Chapter IV describes the model as a whole. Chapters V and VI give the detail formulation of the model by describing the various processes considered in the development. Chapter V also reviews the soil water flow and balance models briefly.

The remaining chapters describe the testing of hypotheses and validity of AWAM with the case study data. Chapter VII discusses the data collected for the study and calibration of the soil water balance submodel of AWAM. It also shows how the various processes in the soil-plant-atmospheric subsystems can be modelled accurately (part of Hypotheses 1). Chapters VIII and IX are devoted to testing part of Hypothesis 1, Hypothesis 2 and part of Hypothesis 3 and validity of AWAM according to Objectives 2 and 3. The Chapter X is on the performance parameters. The allocation plans obtained with the incorporation of productivity and equity are discussed in this chapter, and Hypotheses 4 and 5 are verified. This chapter also discusses how the proposed methodology can be used to reallocate the resources optimally while the scheme is in operation (part of Hypotheses 3 and 4 and Objective 4) and proposes the method to obtain a steady allocation plan with AWAM (Objective 5). The last chapter (Chapter XI) concludes the findings of the study.

CHAPTER II

IRRIGATION WATER MANAGEMENT MODELS

Summary. In this chapter, the various irrigation management models for the optimum allocation of land, water or both land and water resources are reviewed by classifying those according to the resources to be optimised. The two commonly used techniques for solving an optimisation problem, i.e. linear programming and dynamic programming, are also discussed. The review of the models led to investigation of the opportunities for development of irrigation water management models for more efficient utilisation of the resources in water limiting condition, and provides the basis of the model developed in this study.

2.1 INTRODUCTION

In irrigated agriculture land and water resources play a vital role towards increasing the productivity of irrigation schemes and are often scarce. Therefore, it is essential to use both the resources efficiently. Optimum utilisation of these resources by allocating them to different crops on different soils and at different locations and times in the scheme at the beginning of the irrigation season (this is also referred as the allocation plan) under various limitations is one of the several options for efficient utilisation of these resources. Several models have been developed to produce the allocation plans for the optimum use of these resources in the last three decades with differing objectives. In this study these models are referred to as irrigation water management models.

These models optimise the use of land, water or both land and water resources together by developing and adapting system analysis or other techniques. The setting of some formulations is on the scheme level and of some formulations is on the farm level. Some models allocate the resources by considering the area of the irrigation scheme or farm as a whole (single field models) however some models allocate the resources on different divisions of irrigation scheme or farm (multifield models). Some models maximised crop yield or monetary returns while others minimised the yield reduction or the water shortages over the irrigation season. Techniques used in the model also varied from optimisation to simulation or simulation-optimisation depending on the suitability of the technique to the formulation of the model. Optimisation techniques based on programming or simulation have the capability to represent physical, economical and institutional constraints encountered in the operation of the scheme whereas the optimisations based on calculus (differentiating the function and equating to zero) or mathematical equations derived from economic theory fail to represent these constraints. Therefore most of the models reported in the literature used programming or simulation techniques.

Several methods developed in the literature for water resources optimisation were earlier generally classified on the basis of techniques used in obtaining the solution. Yeh (1985) classified the reservoir management and operation models as linear programming (LP) models, dynamic programming (DP) models, non-linear programming (NLP) models and simulation models. Benedini (1988) discussed the various procedures for water resources optimisation and grouped those as LP, NLP, multi-objective (goal and compromise programming) and mini-max. While providing a short review of the mathematical models used in reservoir management and operations, Simonovic (1992) classified those into four categories: simulation, optimisation, multiobjective analysis and combination of these techniques. He further classified the models under optimisation technique as: LP, DP and NLP models. These classifications were reported with the intention to review the reservoir operation models only, where in the decision is to optimise the release of water from the reservoir with the consideration to hydroelectric power generation. The lumped demands of water for agriculture were considered in these models. Bernardo (1985) classified the different models developed in the optimisation of land and water resources in to three techniques: single or multistage mathematical programming, firm simulation and statistical decision theory.

In irrigation water management, the purpose of the models developed or to be developed is to allocate the land and water resources optimally. Therefore in this study which is aimed to optimise the allocation of land and water resources, the attempt is made to classify these models on the basis of optimising the resource to be allocated rather than the technique used to optimise the allocation of resources. Such type of classification is useful for understanding the varied situations for allocating the different resources and assessing the opportunities that exist for efficiently utilising these resources in the scheme. The classification is described in the next section and the various models developed under this classification and the optimisation techniques used to obtain the solutions in the model are discussed in the subsequent sections. The limitations of existing models demonstrate the need for a new model, as described in Section 2.6.

2.2 CLASSIFICATION OF IRRIGATION WATER MANAGEMENT MODELS

In irrigation water management, depending on the circumstances the need is to allocate the resources to optimise output from the scheme or for the proposed allocation, to know the output from the scheme. There may be several restrictions operating in the scheme besides limitation to land and water resources. In the literature, the models to fulfil both the needs are found. Thus irrigation water management models are chiefly classified in the following two types:

1. Allocation model : These models allocate the land, water or land and water resources optimally for maximising the productivity.
2. Evaluation model : These models evaluate the allocation plan to know the output generated from the irrigation scheme.

2.2.1 Allocation Models

These models develop the allocation plan for distributing land and water resources to different crops to be grown in the scheme for maximising the productivity. Depending on the resources to be optimised, these are classified into following three types:

1. Land allocation models: These models allocate optimally the available land area to different crops when water to be allocated to each crop is known.
2. Water allocation models: These models allocate the available water optimally to different crops when area to be irrigated under each crop is known.
3. Land and water allocation model: these models allocate both land and water resources optimally to different crops.

In this study, the allocation of land area to different crops and/or fields in the scheme is referred to as the 'area allocation plan'. The allocation of water to different crops and/or fields over the irrigation season or individual intraseasonal periods is termed the 'water allocation plan'. The allocation of both the resources to different crops and/or fields and over the irrigation season or intraseasonal periods is known as the 'area and water allocation plan' or simply the 'allocation plan'. When the allocation plan is 'proposed' rather than to be 'decided' or 'estimated', then it is referred to as 'allocation policy'.

2.2.2 Evaluation Models

These models do not allocate the resources optimally but with their allocation (area and water allocation policy) and input to the scheme known, they determine output from the scheme. With several allocation plans under consideration, the best can be selected among themselves from these models. However these models do not necessarily allocate the resources optimally but evaluate the chosen allocation policies.

In this chapter the various models developed and formulated in the literature are grouped under the two main categories of irrigation water management models and three sub categories of allocation models and are described in Sections 2.4 and 2.5.

2.3 TECHNIQUES

The two major techniques, linear programming and dynamic programming, are used in most of the allocation models to obtain a solution. These are described briefly before reviewing the different models.

The problem which needs the optimum of a function with 'n' variables can be expressed in the standard form as

$$\begin{array}{l} <\text{optimise}> \quad f(x_1, x_2, \ldots\ldots\ldots, x_n) \\ \text{subject to the conditions on the values of variables} \end{array} \tag{2.1}$$

There are various techniques to solve such type of problems. Linear programming and dynamic programming which are widely used in irrigation water management are among those techniques.

2.3.1 Linear Programming

Linear programming is the most widely used technique for solving the problems in irrigation water management. It consists of an objective function (function of decision variables) which is to be optimised (maximised or minimised) and certain conditions which should be satisfied or should not be violated. These conditions are also known as the constraints and are functions of the decision variables. All relations among the decision variables are linear, both in the objective function and in the functions forming the constraints.

A typical linear programming formulation is represented by equations (2.2) to (2.4).

$$<\text{optimise}> \quad Z = \mathbf{A}^T\mathbf{X} \tag{2.2}$$

subject to

$$\mathbf{BX} < \text{operator} > \mathbf{C} \qquad (2.3)$$

$$\mathbf{X} \geq 0 \qquad (2.4)$$

where,

Equation (2.1) is the objective function and equations (2.2) and (2.3) are the constraints (general and non negativity, respectively),

<optimise> = maximise or minimise

Z = value of the objective function, for example, total crop yield or gross net returns,

X = n dimensional vector of decision variables i.e. $[x_1, x_2, x_3, \ldots\ldots\ldots\ldots x_n]$. Each element of the vector, for example, x_n is the hectares of area to be irrigated by or allocated for irrigation to activity n (activity may be crop, soil, type of water resources, irrigation strategy or combination of these activities),

n = number of activities,

A = n dimensional vector of objective function coefficients or constants i.e. $[a_1, a_2, a_3, \ldots\ldots\ldots\ldots a_n]$. Each element of the vector, for example, a_n is the output (crop yields, net returns or total returns) per unit (hectare) of activity,

T = transpose operator (summation or subtraction),

B = m x n matrix of constraints coefficient i.e.

$$\begin{bmatrix} b_{11}, & b_{12}, & b_{13}, \ldots\ldots\ldots\ldots b_{1n} \\ b_{21}, & b_{22}, & b_{23}, \ldots\ldots\ldots\ldots b_{2n} \\ . & & \\ . & & \\ b_{m1}, & b_{m2}, & b_{m3}, \ldots\ldots\ldots\ldots b_{mn} \end{bmatrix}$$

Each element of the matrix represents the technological coefficient corresponding to each activity and constraint,

m = number of constraints,

<operator> = $<, \leq, =, \geq, >$ and

C = m dimensional vector of right hand side of constraints i.e. $[c_1, c_2, c_3, \ldots\ldots\ldots\ldots c_n]$

The solution of the formulation is the value of Z, selection of activities or decision variables and the value associated with each decision variable.

The formulation presented above is the deterministic linear programming (the constraints are imposed in a deterministic form). The other forms of linear programming are chance constrained linear programming (reflects the probability conditions on constraints) and stochastic linear programming (considers the uncertainty in the variables). These forms are described in detail by Kottegoda (1980); Loucks et al., (1981) and Yeh (1985). When some or all relations among the variables are non linear in constraints or in objective function or in both, the problem is solved by non linear programming technique (Yeh, 1985 and Benedini, 1988).

2.3.2 Dynamic Programming

In linear programming, the optimisation problem is solved as one problem with n variables and the values of n variables are found simultaneously. But in dynamic programming the entire problem is solved as a succession of problems, each associated with one of n variables (decision variables) or stages. If the optimisation problem is to distribute the available water over n irrigations for a crop to get maximum yield (or minimum yield reduction), then the decision variable is amount of water (or depth of irrigation water) to be delivered for each irrigation and each irrigation is a stage (this problem is used as an example for further discussion). If the problem is to allocate the available water to n crops so that the net returns are maximised, the amount of water to be allocated to each crop is the decision variable and each crop is a stage. In each of these stages, there are problems to be solved with only one variable (for example, depth of water to be delivered for n^{th} irrigation). The 'best value' of a particular decision variable (the one which optimises the function, for example the depth of irrigation which results in minimum yield reduction for the given stage) for that stage can be found. But at this stage it is not possible to know the consequences of this best value on the other n-1 variables (i.e. the effect of the particular depth which is decided as the best for n^{th} irrigation on the soil moisture in the root zone and on water availability for previous or next irrigations). Therefore it is necessary to find the best value for each of the several possible values of the parameters influencing the decision (parameter influencing the decision are soil moisture in the root zone and water availability for the irrigation). These parameters are the state variables and several possible values of the state variables for the particular stage are the states. Thus in this case soil moisture in the root zone and water available for irrigation are the state variables, and the values in the possible range of soil moisture and water available are the corresponding states. The possible range is discrete (discretisation depending on the accuracy required and the computational feasibility). Then the problem is solved sequentially with the recurrence relation based on the principle of optimality. Bellman (1957:83) put the principle in this way:

"*An optimal policy has the property that, whatever the initial state and initial decision are, the remaining decision must constitute an optimal policy with regard to the state resulting from the first decision*".

DP is extensively used in the optimisation problems associated with irrigation water management due to its relatively simple adoption to non linear features which characterise a number of problems in irrigation water management. In the agricultural irrigation system (described in Chapter 5), the number of variables influencing the decision (state variables) are so large that it becomes computationally impossible to consider all of them simultaneously. Therefore only those variables that influence the decision most are chosen as the state variables.

When the returns are independent and additive, a typical recursive equation of backward moving dynamic programming (Loucks et al., 1981) is described below (there is forward moving also but in irrigation water management backward moving is more popular).

Consider a system that can be in any one of m discrete states, x_1,..........x_m. If $R(x_i,x_j,d_n)$ are the net benefits during stage n when the system starts in state x_i and ends in state x_j when decision d_n is made. Then the recursive relation is represented by equation (2.5).

$$f_n(x_i) = \max_{d_n} \left[R\left(x_i, x_j, d_n\right) + f_{n+1}\left(x_j\right) \right] \tag{2.5}$$

where,

x	=	state variable,
d	=	decision variable,
R	=	return function,
n	=	stage,
i,j	=	states and
$f_n(x_i)$	=	maximum net benefits obtained from stage n onwards starting in state x_i in stage n.

The above formulation is deterministic dynamic programming as the subsequent state x_j is deterministic function of d_n and initial state x_i. In some cases the next state may depend on uncertain events such as rainfall, evapotranspiration, streamflow etc. The stochastic dynamic programming is used to consider the uncertainties. The formulation of stochastic dynamic programming is described in detail by Loucks et al., (1981) and Yeh (1985).

2.4 ALLOCATION MODELS

Various types of allocation models are described in this section .These are also summarised in Tables 2.1 to 2.8.

2.4.1 Land Allocation Models

Land allocation models distribute optimally the available land area among different crops when water is not limited, when water is limited but the objective is to maximise the net returns per unit area or when water is limited but crops are to be irrigated with certain pre-decided irrigation depth (unique for each crop) which may be optimum with non-irrigation considerations. Thus these models prepare an area allocation plan when water allocation policy is known. In all these cases, seasonal depth to be applied or its distribution over the season to each crop is known or pre-decided and based on those depths the areas to be irrigated under different crops are optimised. As the relationships among the variables are linear, the linear programming (See Section 2.3.1) which is based on the assumption of linearity i.e. the total amount of each input must be strictly proportional to the level of output (Wagner, 1975), is the most widely adopted technique in land allocation models. These models consider only one level of water application depth and its corresponding yield. The models determine simply the type of crops and hectarage under each crop and are therefore referred to as land allocation models.

Some of the models under this category consider the lumped seasonal irrigation depth while others consider the intraseasonal distribution of the seasonal irrigation depth. When all the water for irrigation is available before the start of the irrigation season or little inflow is expected (especially during the initial period of the irrigation season), the consideration of lumped seasonal irrigation depth is sufficient to solve the model. But when the irrigation water is expected throughout the irrigation season, the disaggregation of the seasonal irrigation depth into different intraseasonal periods needs to be incorporated in the model along with the intraseasonal water availability. Accordingly these models are classified into two groups which are discussed in the following sections:

1. Seasonal models
2. Intraseasonal models

2.4.1.1 Seasonal models

Some of the models under this category are reviewed in this section.

Lakshminarayana and Rajagopalan (1977) used the deterministic LP model to decide water release from two sources (canal and tube-well) to meet crop water requirements for optimum allocation of land to different crops to maximise the net returns subjected to a set of constraints for Bari Doab Basin in Punjab, India. Crop water requirements for each crop were calculated only for one level (probably the one giving maximum yield). Devaroroo et al., (1991) used LP to maximise total net returns from Pus Project, Maharashtra State, India when twenty different crops and crop varieties are irrigated. Kanade and Suryawanshi (1992) maximised the total net benefits for minor in Mula Command, Maharashtra State, India for twelve crops in one year by LP.

As the model considers only one depth of seasonal irrigation depth for each crop, it gives the optimum allocation for this depth only and not the overall optimum allocation which is important when water is limited. Similarly the information on only seasonal water allocation is not useful for the operation of irrigation scheme. All the models described above are of single field type.

2.4.1.2 Intraseasonal models

The models developed on this aspect for the allocation of area are reviewed below, leading to conclusions at the end of the section.

Windsor and Chow (1971) used a two level optimisation process. They decomposed a multicrop, multisoil farm irrigation system into a number of separable activities or subsystems (individual crop, soil, type of farm irrigation system and irrigation scheduling options in terms of irrigation cycle and irrigation application), each of which was optimised independently and then the entire system was optimised. Dynamic programming (stochastic) was selected for the first level of optimisation (subsystem) and LP for second level of optimisation (system). Maximisation of the expected profit was the objective of DP. The irrigation water was assumed as unlimited and the application was constrained by labour cost in applying irrigations. Irrigation cycle was the stage and state variables were soil moisture content and ET, whereas the amount of irrigation water so that soil moisture reaches to field capacity or no irrigation was the decision variable. Joint probability distribution of pan evaporation and rainfall was

Table 2.1 Summary of some land allocation models (seasonal models)

Sr. No.	Researchers and year	Solution technique and level of model	Variables, objective and constraints	Place of application and area	Crops	Water sources, uncertainty and others
1	Lakshminarayana and Rajagopalan (1977)	LP, single field model	DV=Ac, OF=maximisation of NB, Constraints: usual, main canal capacity, drainage system capacity, area to be irrigated under different crops	Bari Doab Basin, Punjab, India. Area: 1,800,000 acres	wheat, rice, maize, cotton, sugarcane and others	Two water sources viz. Canal and tube well are considered, deterministic approach
2	Devaroroo et al., (1991)	LP, single field model	DV=Ac, OF=maximisation of NB, Constraints: usual and food requirement	Pus Project, Maharashtra, India. Area: 373 ha.	sorghum, wheat, paddy, pearl millet, red gram, black gram, green gram, cotton, sugarcane, groundnut, safflower, linseed, chillies, potato	Canal water source, deterministic approach
3	Kanade and Suryawanshi (1992)	LP, single field model	DV=Ac, OF=maximisation of NB, Constraints: usual, fertiliser and area to be irrigated under different crops to meet food requirement	Minor in Mula Command, Maharashtra, India. Area: 13,680 ha.	sorghum, red gram, sugarcane, groundnut, sunflower, gram, safflower, wheat and sunflower	Water supply from reservoir, deterministic approach

(Note: The following abbreviations are also valid for other tables in this chapter.
Ac - area to be irrigated for c^{th} crop; NB - Net benefits; DV - Decision variables; OF - Objective function; StV - State variables;
SgV - Stage variables; Id_i - Depth of irrigation water to be delivered for i^{th} intraseasonal period; W_i - Storage in reservoir corresponding to i^{th} intraseasonal period; θ_i - moisture content in soil root zone corresponding to i^{th} intraseasonal period; θ_t - daily moisture content in soil root zone.
Usual constraints: limitations on water available over the season or intraseasonal period, reservoir balance (for intraseasonal models with water source from reservoir and land area available for irrigation.)

considered. One acre was considered as the optimisation unit and output was obtained in the form of maximum expected profit, total expected application of water, monthly expected labour requirement and optimum irrigation policy (in terms of depth per application). The outputs were obtained for all the combinations of crop, soil, type of irrigation system, irrigation cycle and irrigation application. LP was solved to maximise gross revenues minus total crop production cost obtained from various combinations, subject to the constraints of various resource inputs, to get optimum farm plans (in terms of area) among the multitude choices open to the farmers. The amount of water available for irrigation was not considered as the state variable in DP formulation as the water availability was assumed to be unlimited at subsystem level. Therefore the water allocation to each combination or subsystem was based on no stress or deficit, and any 'no irrigation' decisions which appeared in the solution were due to minimising the cost of water application (as the objective of DP was to maximise the expected profit). Thus effectively the model considered only one seasonal water level (intraseasonally distributed) corresponding to maximum profit. Thus the objective was to save on cost of application of water rather than saving water. They applied the model to hypothetical farm situation consisting of two soil types, or fields, each 150 acres in extent, and each capable of producing two crops (corn and soybeans).

Matanga and Marino (1977) developed an area allocation model to determine the optimal cropping pattern for three crops (corn, grain sorghum and pintobeans) for a 200 acre farm with weather parameters and market prices from Davis, California, USA. The objective was to maximise the economic returns from the cropped land area taking into consideration available water supply, irrigation labour cost, crop and water prices, and this was solved by using LP technique. They considered only one seasonal irrigation depth per crop and included water demands of all crops and water availability per irrigation. They obtained the solution with the seasonal irrigation depth that maximised the gross margin from crop yield and with a reduction of 5 inches in seasonal irrigation depth for each crop in water limiting condition. From this, they found the increase in total area with reduction in seasonal irrigation depth but the sensitivity analysis indicated that the corresponding changes in gross monetary returns depended on the market prices of the product.

Maji and Heady (1978) observed the monthly inflows into the reservoir as highly variable over the years for Mayurakshi irrigation project in India and that there existed the chance of crop failure due to unpredictable flood or drought condition. Therefore they formulated chance constrained LP to develop an optimal cropping and reservoir management policy. As the project area differed considerably in soils and other physical characteristics, it was disaggregated into six regions. The objective function was to maximise the total benefits from all the crop activities minus labour, water and fertiliser related costs. Restrictions were put on the acreage of certain crops and land use. Reservoir capacity, storage, inflow, canal capacity, intraseasonal irrigation requirements, nitrogen and hydroelectricity constraints were also included. Only one irrigation depth (equivalent to maximum crop water requirement) for each crop was considered. Inflow into the reservoir was considered as the random variable. The reservoir capacity, storage and inflow constraints which include inflow parameter could be violated 10% of the time at most (arbitrary chosen level). They considered Kharif rice, winter rice, mustard, potatoes and wheat crops. They found the cropping pattern obtained from the model indicated a change in existing cropping pattern and reservoir management policy for maximising the net returns. They also indicated that as the crop activities of the optimal cropping pattern suffered from drought or flood condition no more than 10% of the time, it was preferable for the majority of the tradition bound farmers with low risk bearing ability to have this cropping pattern rather than more ambitious pattern based on average reservoir inflows.

Gulati and Murty (1979) developed a model for optimum distribution of water in canal command areas to maximise the production (net returns) for a given cropping pattern (in terms of type of crops to be irrigated). The approach consisted of three submodels for estimating potential and actual ET, developing water production functions from available water use and yield data for different crops, and for distributing a given quantity of water among a given set of crops. The law of marginal value product (unit cost of irrigation water used and independent of fixed cost of production) presented by Heady and Dillon (1961) (which states that a given resource will be allocated optimally among different alternatives when the marginal value product of all those alternatives are equal) was utilised (with respect to yield and water) for the optimum allocation of a given amount of water among different crops, based upon water production functions of those crops, to maximise the net returns from all the crops. The model was applied for optimum allocation of a given quantity of water among five crops (wheat, barley, gram, berseem and sugar-cane). The area under each crop was computed from the total water allocation to the crop and the total water requirement assuming an irrigation efficiency of 60%. The water distribution pattern (with respect to time) was found by knowing the area and water requirement during different time periods. Authors found that high crop yields could be obtained when the water release pattern obtained from the model and the actual water release pattern for the same amount of total water available were compared. The method proposed by the authors is in fact based on the irrigation depth that makes the best use of water for the crop considered alone, and does not take into account its effect on the returns from other crops at the same time.

Morales et al., (1987) presented a linear optimisation model for planning the management of an irrigation scheme. The model maximises the net benefits when different crops are grown in the different seasons over a period of one year. The irrigation water requirement of each crop is considered on a monthly basis in the model. Irrigation water requirement and crop yield can be estimated either from statistical analysis of historical data of irrigation water requirement and crop yield, or from a seasonal water production function. The constraints included are related to monthly mass balance of the reservoir, capacity of the main canal, land requirement of crops, lower and upper bounds on the area of different crops and ground water withdrawals. The outputs of the model are the cropping pattern and a monthly schedule of reservoir releases and aquifer withdrawals. They applied the model to Irrigation District No. 38, in the State of Sonora, Mexico, by considering twelve crops grown over a period of one year. The results were obtained by running the model for initial and final reservoir storage volumes representing a full reservoir and for annual net inflows corresponding to 10, 20, 50, 80 and 90% exceedance probabilities.

Singh et al., (1987) formulated LP and goal programming models for optimum utilisation of irrigation water for wheat, early paddy, pulses, oilseed and potato grown in the winter season for Garufella catchment, Assam, India. The net returns were maximised subject to various constraints such as water availability, land availability, area constraint for each crop and protein and calorie requirements. They considered only one level of crop water requirements for each crop. They formulated a number of LP models based on different combination of constraints. Goal programming models dealt with the objectives of maximisation of net returns, nutritional value and production from different crops. They formulated number of models by varying the priority and weights given to each of the objectives and worked out the plan for land and water utilisation.

Afshar and Marino (1989) used the area allocation model to maximise the net benefits in a set of mathematical models presented to develop management guidelines for optimising a wastewater disposal and reuse plan for three cities in Sonama County, California, USA (Sonama, Petaluma and Santa Rosa). They considered the monthly water requirement to obtain the maximum crop yield. The area allocation to different crops (silage corn, pasture barley and wheat) was constrained by hectarage of land available for planting, maximum and minimum applicable water for a growing season, limited demand for production and other constraints (labour, machine hours available etc.). The allocation results were obtained for different levels of available land and water and these results were used in a further set of models.

Mayya and Prasad (1989) formulated a deterministic LP model to maximise the net returns of the crop and to determine the optimum cropping pattern subject to land, water and other resources (labour, animal power, fodder production and food requirement) constraints in water limiting condition and applied to one of the tank irrigation systems in Karnataka, India. They considered a week as an intraseasonal period, imposed the constraint on main canal capacity and included evaporation losses from the tank. In this formulation they considered the water requirement of the crop as one which gave optimal crop yield. In the analysis, rice, finger millets, maize, wheat, sorghum, oilseeds and pulses, produced in the region and surroundings were considered.

Prasad and Mayya (1989) modified the formulation of Mayya and Prasad (1989) to take into account insufficient inflow to the tanks in the initial period of the crop season, which caused delays in agricultural operations affecting grain yield due to unfavourable climatic condition in later stages. If the planting was not delayed, the area under irrigation would be less, due to insufficient water during early periods, than when planting was delayed. Therefore they proposed the deficit irrigation during the initial period of the crop season so that planting would not be delayed and area under irrigation would not also decrease. They reduced the maximum evapotranspiration (ET) requirement uniformly by 20% during initial periods. The reduced yield was considered in the formulation on the basis of the relationship between deficit in ET and corresponding yield reduction developed by Doorenbos and Kassam (1979). They found the grain yield per hectare was not reduced apparently by deficit irrigation, but practising deficit irrigation gave more overall net profit of the system by increasing area and total crop production.

Salokhe and Raheman (1989) used the LP technique to allocate land area to different crops for maximising the benefits in Bhargabi delta, Orissa State, India, with gross area of 1983 ha. They considered 19 crops and one level of water requirement for each crop equivalent to the maximum crop water requirement computed by pan evaporation method in each month. They considered the water available from two sources (canal and ground water) in each month and constraints related to land restrictions, labour and food requirement. They obtained the area allocation plan for different levels of water availability.

Paudyal and Gupta (1990) used an iterative multi-level optimisation technique to solve the complex problem of irrigation management in a large basin in Nepal (Tinao river basin with 75,000 ha area) i.e. determining the optimal cropping patterns in various subareas of the basin, the optimum design capacities of irrigation facilities including both the surface and ground water resources and optimal water allocation policies for the conjunctive use. The first level optimisation was LP to maximise net benefits for all subareas for an assumed value of the maximum surface water available for each subarea in each month, subject to the constraints of each subarea. This gave the optimal cropping pattern, net annual benefit and corresponding monthly water allocation for each of the subareas. The second level computed the new upper limit of the surface water supplies to all the subareas based on ground water balance, monthly streamflow continuity and other considerations and fed back to the first level to start the second iteration. The successive iterations continued until a convergence criteria was met. They considered the monthly crop water requirement as the one which gave maximum level of crop production. The division of the basin into subareas depending on soil, climate and terrain conditions considered the variation of costs and benefits, priorities of growing different crops and water availability due to different sources but not the influence of soil type on varying the irrigation requirements of the crops and their yield. The crops considered in the analysis were paddy, wheat, maize, pulses, oilseeds, sugarcane, potatoes and vegetables.

Afshar et al., (1991) developed the chance-constrained optimisation model to design the size of the reservoir and the canal, determine the extent of land development as well as the type of crops and area allocated to each crop, the reservoir target release and the monthly reservoir operation parameters. The optimisation criterion includes the total net annual benefits associated with the monetary returns from agricultural sales, and the construction and operational cost of the reservoir and the canal. This criterion is maximised under appropriate physical, hydrological and demand constraints. They considered the monthly water requirement of each crop (only one level). The corresponding crop yield is either obtained from empirically derived production functions (Stewart and Hagan, 1973) or from statistical analysis of crop yield records. A mixed linear integer programming technique was used to solve the model. The model was applied to an existing reservoir on the Zayandeh Road river in Iran. Wheat, clover, beans, vegetables, onion, potato, cantaloupe, sugar beets, rice, alfalfa, fruits and wood were included in the analysis.

Thandaveswara et al., (1992) developed a deterministic LP model for area allocation. The objective of the model was to maximise the net benefits from irrigating the crops in the command areas of the different irrigation schemes. The constraints of the model included total land limitation of each scheme, subregional land limitations, storage-continuity, beginning year storage constraints for each reservoir, range of possible downstream riparian release policy, essential crops constraints (upper and lower limits) and commercial crop limitation. They considered the irrigation depth applied to each crop during each intraseasonal period such that no or minimum stress occurred during its growth stage periods. They applied the model to the system which consists of the irrigation reservoirs in the upper reaches of the Cauvery river basin, India, by dividing the entire system into 19 subregions. They considered eighteen crops in the analysis. In all 137 crop activities (based on variety of a given crop, sowing date, duration and the subregion) were considered.

Shyam et al., (1994) developed an "optimum operation scheduling model for a canal system". The model distributes available main canal water amongst its branch and distributory canals, by allocating area under their commands to different crops, and the available running hours of main canal during the intraseasonal period to the running hours of the branch and distributory canals, by deterministic LP approach. They considered one level of irrigation water requirement corresponding to maximum crop evapotranspiration (ET). The constraints considered in the allocation process are available land area, irrigation water, running hours for different canals, available carrying capacity of the canal network, minimum allocation to different canals and the maximum and minimum crop area restrictions for different distributory commands. They applied the model to allocate the main canal water of Golawer Canal System, India among its branch and distributory canals for irrigating wheat, gram, lentil, sugarcane, Lahi and other minor crops. They also considered the area proportionate water allocation from the main canal to branch and distributory canals.

Onta et al., (1995) developed LP based optimisation model for allocating land area to different crops grown in different region for the run-of-river type irrigation scheme for different management strategies and simulation model to select the best management strategy according to required weightage to different performance measures (economic efficiency, equity and reliability) based on compromise programming. The equity was included through the area proportionate water diversion from the headworks to each region and the reliability through the system's ability to fulfil the required demand in any time period. The diversion requirement for particular crop grown in particular region was equivalent to maximum crop water requirement. The constraints included in the formulation are related to water and area availability, canal capacity, lower and upper limits on area to be irrigated under each crop and area proportionate water

Table 2.2 Summary of some land allocation models (intraseasonal models)

Sr. No.	Researchers and year	Solution technique and level of model	Variables, objective and constraints	Place of application and area	Crops	Water sources, uncertainty and others
1	Windsor and Chow (1971)	Two level optimisation (SDP-LP), multifield	DV=Id_i and θ_t is StV in DP and area to be irrigated under each activity is DV in LP, OF=maximisation of NB, Constraints: usual	Hypothetical farm situation consisting of two soil types or fields. Area: 120 ha.	corn and soybeans	water availability during individual intraseasonal period, joint probability of occurrence of random weather variables (pan evaporation and rainfall), water availability is not limiting in DP phase, each activity is the combination of crop, soil, type of irrigation system, irrigation cycle and irrigation application
2	Matanga and Marino (1977)	LP, single field	DV=Ac , OF=maximisation of NB, Constraints: usual, leaching, crop production, capacity of main canal, labour availability	Davis, California, USA Area: 80 ha.	corn, grain sorghum and pintobeans	water availability during individual intraseasonal period, deterministic approach
3	Maji and Heady (1978)	Chance constrained LP, multifield	Area to be irrigated under each activity is DV, OF=maximisation of NB, Constraints: usual, labour, fertiliser, canal capacity, total area under different crops and hydroelectric restrictions.	Mayurakshi Irrigation Project, India. Area: 212 ha.	rice, potato, mustard and wheat	Water availability is from storage reservoir. Reservoir capacity, storage and inflow constraints which include inflow parameter could be violated 10% of the time. Each activity is the area to be irrigated under different crops in different regions.
4	Gulati and Murty (1979)	differential equations, single field	DV=Ac, OF=maximisation of NB, Constraints: usual	Canal outlet in Bhakra Irrigation System, India.	wheat, barley, gram, berseem and sugarcane	deterministic approach
5	Morales et al., (1987)	LP, single field	DV=Ac , OF=maximisation of NB, Constraints: usual, main canal capacity and conveyance losses, water	Irrigation District No. 38, State of Sonora, Mexico. Area: 90,000 ha.	wheat, safflower, flax, alfalfa, vegetables, cotton, sorghum, corn,	Deterministic approach. Water source is from reservoir and aquifer.

			quality, lower and upper bounds on area for different crops		bean, soybean, sesame and other crops,	
6	Singh et al., (1987)	LP and goal programming, single field.	DV=Ac , OF=maximisation of NB, Constraints: usual (In goal programming protein and calorific related objectives and nutritional, NB and production related goal constraints are added).	Garufella catchment, Assam, India. Area: 8420 ha.	wheat, paddy, pulses, oilseed and potato	Intraseasonal water availability. Deterministic approach
7	Afshar and Marino (1989)	LP, single field model	DV=Ac, OF=maximisation of NB, Constraints: usual, labour and machine hours	Sonama County, California, USA. Area: 4960 to 12,160 ha.	silage, corn, pasture, barley and wheat	water supply from reservoir, deterministic approach
8	Mayya and Prasad (1989) and Prasad and Mayya (1989)	LP, single field model	DV=Ac, OF=maximisation of NB, Constraints: usual, canal capacity, labour, draft animal pair, capital input, fodder and nutritional requirements	Tank Irrigation System, Karnataka, India. Area: 113 ha.	rice, finger millets, maize, wheat, sorghum, oilseed and pulses	Storage reservoir scheme. Deterministic approach. Mayya and Prasad (1989) considered maximum crop water requirement while Prasad and Mayya (1989) reduced maximum water requirement uniformly by 20% during initial period.
9	Salokhe and Raheman (1989)	LP, single field model	DV=Ac, OF=maximisation of NB, Constraints: usual, food and labour requirements constraint	Bhargabi Delta, Orissa, India. Area: 1983 ha.	rice, sugarcane, jute, chilly, Ragi, sorghum, millet, potato, green gram, black gram, Kulthi, groundnut, sesame, mustard, wheat, onion and vegetable crops	Water source from canal and groundwater. Deterministic approach.
10	Paudyal and Gupta (1990)	Multilevel optimisation with LP in both the levels, multifield	DV=Ac, OF=maximisation of NB, Constraints: usual, canal capacity constraints and constraints related to streamflow	Tinao River Basin, Nepal. Area: 75,000 ha.	paddy, wheat, maize, pulses, oilseeds, sugarcane, potatoes and vegetables	Water availability during intraseasonal periods from streamflow and groundwater. Deterministic approach

		model				
11	Afshar et al., (1991)	Chance-constrained optimisation with mixed integer LP, single field model	DV=Ac, OF=maximisation of NB, Constraints: usual, canal capacity and leaching requirement constraints.	Reservoir on Zayandeh Road river, Iran	wheat, clover, beans, vegetables, onion, potato, cantaloupe, sugar beets, rice, alfalfa, fruits and wood	Streamflow as probabilistic variable in chance-constrained formulation.
12	Thandaveswara et al., (1992)	LP, single field model	DV=Ac, OF=maximisation of NB, Constraints: usual, crop area restrictions and downstream release constraints	Reservoirs in Cauvery river basin, India. Area: 438,1000 ha.	tobacco, maize, paddy, vegetables, soybean, groundnut, sorghum, sugarcane, coriander, mulberry, potato	deterministic approach
13	Shyam et al., (1994)	LP, multifield model	Area to be irrigated under each activity is DV, OF=maximisation of, Constraints: Usual, irrigation water running hours for different canals, carrying capacity of canal network, maximum and minimum crop area restrictions and water allocations.	Main canal of Golawer Canal System, India. Area: 10303 ha.	Wheat, gram, lentil, sugarcane, Lahi and other crops	each activity is th combination of crop and branch canals or distributories of main canal. Water availability during intraseasonal period is considered. The objective was also to allocate main canal water supplies to branch canals or distributories of main canal. The distribution of water from main canal to branch canals or distributories according to equity was also considered. Consideration of equity in water allocation
14	Onta et al., (1995)	LP, multifield model	area to be irrigated under each activity is DV, OF=maximisation of NB, Constraints: usual, bounds on crop area	Kankai Irrigation System, Nepal Area: 8134 ha.	Paddy, wheat, mustard, lentil and maize	each activity is area to be irrigated under each crop in each region, water availability during intraseasonal period, simulation over number of years. Consideration of equity in water allocation

delivery from headworks to each region. The authors discussed the applicability of the model with the case study of the Kankai Irrigation System in Nepal with five crops grown in the scheme (paddy, wheat, maize, lentil and mustard). The command area of the scheme is 8134 ha divided into three regions. They obtained the allocation plans for five different generated sequences of streamflow considering five different management strategies and different scenarios (different levels of streamflow availability and irrigation efficiency). The preferred management strategies were found for different weightage to each performance measures.

All the studies described above were intended towards optimal allocation of area under different crops in water limiting conditions. Excepting Matanga and Marino (1977) and Prasad and Mayya (1989), all the authors considered the depth of irrigation which gave maximum yield per unit area or full depth of irrigation. Therefore these studies gave the optimal allocation of area for full depth of irrigation maximising the returns per unit area, and not the overall returns from the scheme resulting from other depths of irrigation along with the full depth of irrigation. Prasad and Mayya (1989) considered the deficit irrigation by reducing the ET during initial irrigation periods by 20% (to avoid delay in planting) and obtained more net return from the project than when applying the irrigation with no reduction in yield. Matanga and Marino (1977) found the increase in total area under irrigation with reduction in seasonal irrigation depth. These studies indicate that the full depth of irrigation may not give the optimal allocation. But these authors also considered only one level of deficit. The consideration of other levels of deficit along with full depth of irrigation may give the different allocation, as in water limiting condition a certain level of deficit in irrigation depth of one crop influences the availability of water to other crops. The models developed by Windsor and Chow (1971); Paudyal and Gupta (1990); Shyam et al., (1994) and Onta et al., (1995) are of multifield type.

2.4.2 Water Allocation Models

These models allocate limited or unlimited water supply optimally to single or multiple crops. The area to be irrigated under each crop is known or computed from other rules as a function of initial reservoir storage, expected inflow into the reservoir and expected crop demands. Thus these models decide the water allocation plan when area allocation policy is known. The water allocation is done by distributing water shortage, if any, over different intraseasonal periods and crops such that minimum loss occurs. As the response of a crop to different amounts of water applied in different growth stages is different, the water allocation to a given crop becomes a sequential decision making process. This is because the decisions on the depth of water application per irrigation and timing of irrigation when water is limited, or timing of irrigation only when water is unlimited, have to be made recursively throughout the season, due to several feasible combinations of depth of water application and timing of irrigation, to search for the optimal combination. The dynamic programming (DP) which is well suited to sequential decision making process (described in Section 2.3.2) due to its ability to decompose the problem into stages (Yeh, 1985), is therefore, widely used in water allocation models.

As in the process of water allocation the decision to irrigate and how much to irrigate is required at different points in time or in space, some intraseasonal periods (generally a week, a decade of 10 days or irrigation period) and crops are considered as the stages of dynamic programming. The decision is generally how much to irrigate (and sometimes when to irrigate) at each irrigation in water limiting condition, and when to irrigate in no water limiting condition, to maximise crop yield or net return (single crop), or minimise relative yield reduction or maximise the net returns (multicrop). The variables influencing the decision are taken as state variables. Several variables in the water resource system influence the decision but the volume of water available in the reservoir for irrigation and the soil moisture available in the root zone influence the decision most, and therefore these are normally considered as the state variables by most of the authors who formulated water allocation models. When the uncertainty in different variables needs to be considered, the stochastic DP (SDP) is used.

Depending on the water allocation to a single crop or many crops over their growth stages, these models are classified into two groups as

1. Single crop models
2. Multicrop models

2.4.2.1 Single crop models

These models allocate the available water optimally over the irrigation season for a single crop grown on a known area. Many of the water allocation studies were conducted with single crop. These works are reviewed below.

Flinn and Musgrave (1967) demonstrated the use of dynamic programming to allocate a given quantity of irrigation water optimally over the irrigation season. Their model had only one state variable describing the state of the system at any stage i.e., the quantity of water available for allocation over the remainder of the season.

Hall and Butcher (1968) described the methodology making use of deterministic DP (DDP) to allocate the available water (which was insufficient to meet potential demands) intraseasonally to a single crop to maximise the net returns. A feature of their formulation of the DP model was the multiplicative relationship between the sequential steps rather than the usual additive form, and this was then converted into additive form by logarithmic transformation. The irrigation interval was the stage and moisture content at the end of irrigation period and total water available for irrigation were the state variables. The quantity of water to be applied during each irrigation period was the decision variable. This was an early attempt at the optimum allocation of water and therefore there were certain problems associated with the use of DP and also with the computation of certain variables (for example, actual ET was not considered as the function of soil moisture content). These were later discussed by Aron (1969). The study considered the stagewise contribution of yield by adding the yield coefficient corresponding to soil moisture conditions during each irrigation interval.

Burt and Stauber (1971) developed SDP (due to uncertain nature of precipitation) for temporal allocation of limited irrigation water within a growing season of a single crop. The objective was to maximise the benefits, and the state variables were "crop condition" (a partial sum of terms from the production function) and water in storage. They tested the model for corn grown in central Missouri, USA.

Dudley et al., (1971[a]) developed a two state variable SDP model to allocate a finite quantity of water over a growing season in the face of stochastically varying rainfall and water requirement of an already determined area of crop. The two state variables were soil water content and irrigation reservoir level per acre of irrigated crop, and the decision variable was the level to which the available soil water content was allowed to fall before irrigating. The objective was to maximise expected return. The irrigation depth applied per irrigation was assumed to be that needed to return the whole root zone to field capacity. The soil moisture-plant growth simulation model was used to estimate the crop growth parameters. In fact this model aids the decision maker in knowing when to irrigate rather than how much to irrigate at a specified time. However in a multicrop situation with rigid rotation schedule, the policy should be how much to irrigate at a specified time. In this model any deficit offered is due to prolonging of irrigation and not due to applying less water than required to fill the root zone to field capacity. They applied the model to corn assumed to be grown on homogenous, deep, well drained soil with a constant water holding capacity of 0.16 mm/mm, with climatological data from Inverell, New South Wales, Australia.

Palmer-Jones (1977) formulated the SDP to maximise the net returns when a single crop is grown. This differs from that given in Dudley et al., (1971) mainly in that Palmer-Jones included more than one soil moisture state variable to define the current state of the system, and considered irrigation applications which do not recharge the whole of the root zone to field capacity. He applied the model to tea grown in Malawi with two soil moisture state variables (uppermost layer of 30 cm, and remainder of the root zone). From his results he emphasised that the distribution of water within the root zone plays an important part in determining response to irrigation, meaning that two or more soil moisture state variables will be necessary in DP to find the optimum allocation policy. He further argued that consideration of these additional state variables will make DP more difficult to use in practice, and also stressed the need for more detailed representation of plant-water relationships. The consideration of several levels of irrigation depth to be applied in the root zone added one more state variable, but was useful in obtaining the optimal solution in water scarcity situation.

Schmidt and Plate (1980) presented a DDP model for optimal intraseasonal distribution of available water in the reservoir before the start of irrigation season and inflow into the reservoir during the irrigation season, over the area. The area was determined before the start of the irrigation season on the basis of available water in the reservoir before the start of irrigation season, expected inflow into the reservoir at a certain chosen probability, and the irrigation requirements estimated from the cumulative potential ET and project efficiency. They also considered the effect of sedimentation and evaporation in reducing the water availability in the reservoir. They divided the irrigation season into n stages (which need not all have the same length) and considered two stage variables: reservoir content and soil moisture available at the beginning of each stage. The quantity of irrigation water to be delivered for maximising the return was the decision variable. The yield response was included through multiplicative yield function and actual ET was computed by following the procedure proposed by Minhas et al., (1974). They applied the model to grain sorghum.

Bras and Cordova (1981) developed the SDP model for the optimal temporal allocation of irrigation water, taking into consideration the intraseasonal stochastic variation of crop water requirements and dynamics of the soil water depletion process. The objective function of the study was profit maximisation. They formulated an SDP model for unlimited and limited water supply. The stage was the interval between fixed irrigation decision points. For unlimited water supply, the soil moisture content at the beginning of each decision stage was the state variable. In limiting water supply, water supply per unit area was the additional state variable. The decision was the irrigation depth at each stage. The stochastic variation of crop water requirement was introduced by formulating the transitional probability matrix of soil moisture at each decision stage. They applied the model to corn grown in a uniformly deep clay loam soil with the data from experiments conducted at Colorado State University, Colorado, USA. For unlimited water supply only two options were considered at each decision stage: irrigate up to field capacity (FC) or not to irrigate at all. For limited water supply, five different policies were considered: irrigate up to FC, 3/4 FC, 1/2 FC, 1/4 FC and no irrigation.

Rhenals and Bras (1981) formulated a model based on SDP to maximise net benefits from a crop in homogeneous soil on known area (or known values of available water per unit area) and facing uncertain, correlated evapotranspiration demands. Their objective was also to know the effect of potential ET uncertainty on the measures of performance of irrigation scheduling (net benefits per unit area). The time horizon of the model was N weeks corresponding to the duration of the irrigation season and each stage corresponded to one week. The decision variable was the amount of the water to be applied at the root zone during week k (U_k, k = 1,....N) per unit area of given crop. The state variable (X_k) was a three dimensional vector representing the state of the system at the beginning of week k. The elements of X_k were absolute soil moisture content at the root zone (S_k), estimated potential evapotranspiration during the previous week (PET_{k-1}) and total effective amount of water available during weeks k,k+1,....N (r_k). PET_k was chosen as the only stochastic disturbance of the model. The serial correlation between any two consecutive weekly PET's was included in a formulation through a first order Markov model. The objective function of the model was to maximise the expected net benefits. The recurrence equation of SDP formulation was coupled with support models for potential and actual ET, average soil moisture, percolation and crop yield. Weekly irrigation decisions were made after observing current soil moisture and available irrigation water as well as potential ET in the past week. The model was applied to corn with the help of data used by Blank (1975) for a typical farm located in the Lower South Plate, Colorado, USA. The model is different from earlier models for it considers potential ET as a state and stochastic variable in defining the optimum irrigation application. However for the particular case, they found the differences between deterministic and stochastic approaches small and not large enough to justify the use of the stochastic models.

Tsakiris (1982) made an attempt to optimise the intraseasonal distribution of irrigation water for the single crop when the available irrigation water for the entire season was limited, by using the multiplicative form of yield response function with modification of stagewise sensitivity index to suit the irrigation interval. He found the relative water consumption (the ratio of actual and potential water consumption) which should be maintained during each irrigation cycle in order to maximise the crop yield under a given average relative water consumption throughout the irrigation season, by using the method of Lagrange multipliers. This may give the different relative water consumption during different irrigation cycles (variable relative water consumption). He applied the method to grain sorghum and found 12.7% increase in the crop yield if water allocation during the growing season followed as per variable relative water consumption during each irrigation interval instead of uniform relative water consumption during each irrigation interval.

Tsakiris and Kiountouzis (1982) described a procedure to derive the optimal irrigation policy (depth and timing) which will minimise the total cost per unit time during each stage in the growing season of a single crop. The total costs consist of both the cost of applying water, and the economic loss due to any decrease in yield caused by delayed irrigation. The analysis is based on an inventory control model and by deriving equations for calculating crop yield reduction and economic losses. First the water depletion by the plant is derived. Then, the economic loss due to the decrease in yield caused by delaying irrigation and the cost of water application are considered. They illustrated the use of this method for sugar beet irrigated with a semi-permanent sprinkler irrigation system.

Swaney et al., (1983) developed the methodology to allocate the water to the crop to maximise the net profit based on taking the decision on any day during the crop season about irrigating 'today' or delaying irrigation for one or more days. The methodology involves determining the irrigation strategy (irrigation trigger level i.e. when to irrigate in terms of % of available soil moisture and amount per application) that maximises the expected net profit over historical data. Thus during the irrigation season, the final yield, net profit, water use and energy use are estimated for the case in which irrigation is applied 'today' and the recommended strategy is followed for rest of the season, and for the case in which irrigation is delayed for some days and then the recommended irrigation strategy is followed. The process is repeated for several years of weather data. The current season weather data is used to simulate crop growth till 'today' and historical weather data after 'today'. Average profit is computed for both the cases and the decision to irrigate is taken. They applied this methodology for soybean growing in sandy soil and found the increase in net profit of 5% by allocating water in this way. The net profit is affected by decisions of either irrigating today or delaying irrigation due to saving in energy cost and labour cost but availability of water is not considered while taking the decision. Therefore as such the method is not demonstrated for water scarcity case.

Rees and Hamlin (1983) developed the procedure to allocate water for irrigation in times of shortage. The area to be irrigated is based on certain rules e.g. as a function of reservoir storage at the beginning of the irrigation season. The irrigation scheduling rules included are

- to bring soil moisture to field capacity at the end of each week
- to allow soil moisture to fall to the fraction p (soil water depletion factor) before any water was applied to return the soil to field capacity
- to return the soil moisture to certain millimetres less than capacity (for minimising the losses if rain fell soon after an irrigation release) and
- minimise the cost of irrigation by deterministic forward DP with soil moisture as state variable and time as stage.

Initially the scheme is operated according to the scheduling rule for the forecast set of data to obtain the optimum allocation schedule and then scheme is operated according to optimum schedule by using real data for one time period. The states of the system are updated, forecasts are produced for remaining season and the optimum allocation schedule is obtained for remaining season. The procedure is repeated for the stages of entire crop growth season and a set of optimum allocation schedule is obtained. This method was applied to Vals drainage basin, a south bank tributary of the Vaal river in South Africa. A wet season crop of cotton and dry season crop of peas were considered.

Tsakiris and Kiountouzis (1984) presented DDP model to optimise the intraseasonal distribution of irrigation water (for maximisation of crop yield) to a single crop under the constraints of limited water availability and predetermined irrigation timing. The system underlying the model was characterised by two discrete state variables: the available soil water in the root zone and the net quantity of water to be transformed to the root zone of the crop. The state was the timing of the irrigation. A multiplicative yield function was employed to estimate the crop yield as influenced by soil moisture. They computed relative water consumption in the yield model by using a soil water availability function proposed by Slabbers (1980) and equations given by Tsakiris and Kiountouzis (1982). They described the model with a numerical example for the condition prevailing in Greece for sorghum under rotational delivery of irrigation water in sandy clay loam with an irrigation interval of 15 days.

Houghtalen and Loftis (1988) presented "aggregate state dynamic programming" (ASDP) to optimally operate irrigation water delivery systems. They suggested the use of this technique to multiple reservoir systems to avoid dimensionality problems and to incorporate the random nature of water supply and consumptive crop demands. They described the disadvantages of "separation approach" (DP algorithm to distribute seasonal irrigation water over time and LP to distribute water within the system on intraseasonal basis using the releases found from the DP results) proposed by Loftis and Stillwater (1986) for the solution of such systems, and described the ASDP approach which simultaneously optimises temporal and spatial allocation of irrigation water. They demonstrated the technique for the "ditch company" near Fort Collins, Colorado, USA supplied with water by four reservoirs. The crop considered was corn over 16,200 hectares. ET computed by Penman equation was the random variable, however rainfall and inflows were deterministic variables. They minimised the expected sum of squared shortages (demand minus supply). A stage was one week, current system storage was the state and target system storage was the decision variable. They found that ASDP showed a significant improvement over the separation approach.

Rao et al., (1988[a]) formulated DDP model for temporal allocation of limited water to a single crop. They discussed the disadvantages of an allocation model determining the optimal water allocation at specified period which may be either the crop growth stage or a smaller period (week or decade). According to them the water allocation made according to crop growth stage limited its practical applicability and if water allocation was made on the basis of a smaller interval, the adjustment of the growth stagewise sensitivity factor to the period under consideration was not realistic. Therefore they solved the problem at two levels: growth stage and weeks. At the first level the dated water production function was maximised by DP to obtain the optimal allocation for growth stages. At the second level, the water allocated to each growth stage was reallocated to satisfy weekly water deficits within the stage in a sequential order, beginning with the first week of the growth stage. They applied the procedure described above to cotton using the soil and rainfall data of an irrigation project in India, by considering the average potential ET and rainfall at 75% exceedance probability, and obtained the weekly irrigation schedules. However they did not compare the results with the usual DP formulation. Though the method is supported agronomically, the weekly irrigation interval is not followed in many irrigation projects. The consideration of a higher irrigation interval is expected to offer certain difficulties such as all the water allocated to particular growth stage (based on limited water supply) may be allocated to the first few irrigations of that growth period, and the remaining irrigations may not be

Table 2.3 Summary of some water allocation models (single crop model)

Sr. No.	Researchers and year	Solution technique and level of model	Variables, objective and constraints	Place of application and area	Crops	Water sources, uncertainty and others
1	Flinn and Musgrave (1967)	DP, single field model	SgV-Irrigation events StV-W_i, DV-Id_i OF-Maximisation of NB, Constraints: usual	-	-	deterministic approach
2	Hall and Butcher (1968)	DP, single field model	SgV-Irrigation event StV-θ_i and W_i, DV-Id_i OF-maximisation of NB, Constraints: usual	-	-	deterministic approach
3	Burt and Stauber (1971)	DP, single field model	SgV-Irrigation event StV-Crop condition and W_i, DV-Id_i OF-maximisation of NB, Constraints: usual	Missouri, USA	corn	stochastic approach. RV-precipitation
4	Dudley et al., (1971[a])	DP, single field model	SgV-Irrigation event StV-θ_i and W_i DV-level to which available soil water content was allowed to fall before irrigating OF-maximisation of NB, Constraints: usual	Inverell, New South Wales, Australia	corn	stochastic approach. RV-precipitation and water requirement. Irrigation application is to fill the soil root zone to FC.
5	Palmer-Jones (1977)	DP, single field model	SgV-Irrigation event StV-θ_i of each soil layer and W_i DV-Id_i OF-maximisation of NB, Constraints: usual	Malawi	tea	stochastic approach. RV-rainfall and evaporation (for computing water requirement)
6	Schmidt and Plate (1980)	DP,	SgV-Irrigation event	-	grain sorghum	deterministic approach

		single field model	StV- θ_i and W_i, DV-Id_i OF-maximisation of NB, Constraints: usual			
7	Bras and Cordova (1981)	DP, single field model	SgV-Irrigation event StV- θ_i and W_i, DV-Id_i OF-maximisation of NB, Constraints: usual	Colorado State University, Colorado, USA	corn	stochastic approach. RV-crop water requirement
8	Rhenals and Bras (1981)	DP, single field model	SgV-a week StV- θ_i, Wi and potential evapotranspiration during previous week. DV-Id_i OF-maximisation of NB, Constraints: usual	Lower South Plate, Colorado, USA	corn	stochastic approach. RV-evapotranspiration
9	Tsakiris (1982)	DP, single field model	Constraints: usual			
10	Tsakiris and Kiountouzis (1982)	Mathematical equations, single field model	DV-irrigation depth and timing OF-minimisation of total costs (cost of applying water and economic loss due to any decrease in yield caused by delayed irrigation) , Constraints: usual	semi-permanent irrigation scheme	sugar beet	deterministic approach
11	Swaney et al., (1983)	Mathematical equations, single field model	DV-irrigate today or delay irrigation for some days OF-maximisation of NB, Constraints: usual	Gainesville, Florida, USA Area: 55 ha.	Soybean	stochastic approach (simulation with weather data over available length)
12	Rees and Hamlin (1983)	DP, single field model	SgV-irrigation event StV- θ_i DV-Id_i OF-minimise the cost, Constraints: usual	Vals Drainage Basin, Vaal river, South Africa Area: 69,000 ha.	cotton (wet season) and peas (dry season)	stochastic (forecasting over number of years)
13	Tsakiris and Kiountouzis (1984)	DP, single field	SgV-irrigation event StV- θ_i and W_i	Greece	sorghum	deterministic approach

		model	DV-Id_i OF-maximisation of crop production, Constraints: usual			
14	Houghtalen and Loftis (1988)	DP, single field model	SgV-a week StV-W_i (current system storage) DV-target system storage OF-minimisation of sum of squared shortages (supply minus demand) , Constraints: usual	ditch company near Fort Collins, Colorado, USA. Area: 16,200 ha.	corn	stochastic approach. RV-evapotranspiration (in case study example, however they suggested inflow also cab be included as RV without encountering the dimensionality problem in their formulation)
15	Rao et al., (1988[a])	DP, (at two levels) single field model	SgV-crop growth stage at one level and a week as irrigation event at second level StV- θ_i and W_i DV-Id_i OF-maximisation of crop production, Constraints: usual	India	cotton	deterministic approach. At first level DP was formulated with crop growth stage as stage and at second level a week as stage variable as authors considered either assuming crop growth or irrigation event not matching to crop growth stage inappropriate

supplied with any water subjecting the crop to long stress towards the end of growth period. This may give less yield than when water is spread uniformly over all irrigation intervals of the growth period. Similarly optimality obtained in the first stage may be lost in the second stage due to readjustment of the water allocations.

The models discussed in this section, use the DP technique to obtain the solution, allocate the available water optimally over different intraseasonal periods in the irrigation season, consider only one crop and are of single field type. The area to be irrigated under the crop is also predecided. But this situation is quite uncommon in heterogeneous irrigation schemes. However this simplicity enabled many studies (Burt and Stauber, 1971; Dudley et al., 1971[a]; Palmer-Jones, 1977; Bras and Cordova, 1981; Rhenals and Bras, 1981 and Houghtalen and Loftis, 1988) to consider the stochastic nature of one or more random variables.

2.4.2.2 Multicrop model

The optimum allocation of water to multicrop situation involves formulating the DP model either with two stage variables or decomposing the problem at two levels. The studies related to multicrop water allocation are reviewed below.

Trava et al., (1977) developed the model for optimal onfarm allocation of irrigation water with the objective to minimise labour cost, based on zero-one linear integer programming formulation. The model compares the sum of the volumes needed to irrigate the fields on any day with the total water availability per day. The field must be irrigated if it is within the range specified by the scheduling program. If it is not desirable to irrigate a field in a given week, the field is excluded from the optimisation scheme. They tested the model with the data collected at the Northern Colorado Research Demonstration Centre, Colorado, USA, by considering 16 to 33 fields grown with corn , beans and sugar beets.

Loftis and Houghtalen (1987) presented an SDP algorithm for allocation of irrigation water over time by "ditch companies". In their algorithm the stage corresponded to time steps of one week each, and the decisions were the volume of irrigation water to be delivered during each time step. A single state variable, total reservoir storage, was used to describe the system. Inflows and rainfall were treated as deterministic, and reference ET as stochastic, with the objective of isolating the effect of treating crop consumptive use as random variable. The model used minimisation of sum of squared shortages (the difference between demand and available water, demand being equivalent to maximum crop water requirement) as the DP objective, because the authors rejected soil moisture based and yield model based approaches as impractical for representing the varied physical condition and varied agricultural enterprises served by a ditch company. This conclusion was derived from the limitation of the works by Rhenals and Bras (1981), Martin et al., (1983) and Martin (1984) in accurate estimates of soil moisture. Solution of the algorithm provided operating policies for the entire season. Though the minimisation of sum of squared shortages added to the simplicity in formulation for obtaining the operating policies, the operation policies obtained need not be optimal economically as the formulation did not consider the crop and soil parameters of the system (which influence yield) in any other way. They applied the model to a water supply and storage company in Colorado State, USA. The irrigated area was 16,200 ha. For simplicity a single crop, corn, was used.

Abderrahman et al., (1989) developed a model (An Irrigation Management Information System, IMIS) to distribute the water at the farm level in an irrigation scheme containing several farms in arid region. The irrigation interval was computed from the water extraction rate by roots from different soil depths and the lowest interval was adopted. The effect of relative decrease in crop ET on reduction in yield was calculated by the yield response function (Doorenbos and Kassam, 1986), and water shortages were distributed among selected crops according to the value of yield response factor (K_y) of each crop during each growth stage. The model was similar to a DP model wherein the water is allocated optimally over a certain given area. In this model water shortages were spread over the area. They tested the model on an irrigation scheme containing many farms cultivated with different types of crops (alfalfa, sorghum, wheat, barley and date palm) in the Eastern Province, Saudi Arabia.

Hiessl and Plate (1990) developed the model based on simulation optimisation technique for distribution of water among various crops grown in different fields in an irrigation scheme. The simulation mode is used to represent the system and basic control structures mathematically. In this simulation phase a "controller" is defined which provides different irrigation strategies or a set of rules based on available "soft" information or heuristic. Then for each crop in the scheme at a particular instance of time or irrigation an average "need for irrigation" (numerically represented in between 0 to 1, where 0 means an irrigation is definitely not necessary and 1 means that an irrigation is absolutely necessary) is computed as an average over all these rules in the rule set. If the need for irrigation exceeds a certain value, the crop is said to have definitely need for irrigation. If the amount of water in the reservoir exceeds the irrigation demand of all crops at the particular instance, only the crops with definite need for irrigation are provided with water, which is distributed to these crops proportionally according to their potential water demands. An optimisation model is used to find an optimal control strategy for the scheme. This is found by obtaining the average annual system yield for different cropping patterns and is computed by using compromise programming (Zeleny, 1982 and Goicoechea et al., 1982). They applied this model to an irrigation scheme in Saudi Arabia.

Rao et al., (1990) addressed the problem of a limited water supply for irrigation of several crops grown in the same season by considering seasonal and intraseasonal competition of water between crops by DP approach. The area under each crop was assumed to be known and the problem was limited to the optimum allocation of water if the total volume of water available was known at the beginning of the season. The allocation problem was decomposed to two levels, seasonal and intraseasonal. Seasonal allocation consisted of two models, a single crop irrigation scheduling model, and a multicrop irrigation scheduling model. The single crop scheduling model allocated the given amount of water optimally to all growth stages by DP by maximising the stagewise water production function given by Doorenbos and Kassam (1979), and then the weekly allocation of water within each crop growth stage was computed. This was done for several feasible levels of water available. The seasonal water production function was developed with the data generated. This was repeated for all crops. If the competition among the various crops over the season was found (by comparing total water available with the multiplication of area under each crop and water required to get maximum yield), the allocation problem was again solved by DP with the objective of maximising the net benefits from all the crops with the help of a seasonal water production function (with crop as stage variable). If there was competition for water within the season for a certain week, the intraseasonal reallocation using an intraseasonal model was done by determining the water yield response function for each crop for the growth stage under consideration, using the single crop model for all crops by DP. The weekly irrigation programmes for all crops for the entire season were modified by running the single crop model for each crop. The process was repeated successively for each week to the end of the season. Economic coefficients and crop growth stage effects were included in the formulation. As all the water availability was considered at the start of the irrigation season, the competition for water during different intraseasonal periods may be due to the constraint on carrying capacity of the canal. They demonstrated the model for allocation of water to two crops (sorghum and cotton) on a 31 ha farm in India.

Vedula and Mujumdar (1992) developed a model for optimal operating policy of a reservoir for irrigation under a multiple crop scenario using SDP. They considered reservoir inflow as random variable. Intraseasonal periods smaller than the crop growth stage duration formed the decision interval or the stage of the model. Reservoir storage, inflow into the reservoir and the soil moisture in the irrigated area were treated as state variables. The decision was the release of water from the reservoir to minimise the cumulative yield reduction from all the crops as represented by the additive crop production function given by Doorenbos and Kassam (1979). The irrigation policy was to apply irrigation to a crop in a certain intraseasonal irrigation period only when the available soil moisture in the root zone was below allowable depletion level, and the amount of irrigation, if sufficient water was available, was based on raising the soil moisture content to field capacity. If the water was not sufficient during any of the intraseasonal periods, the water was allocated optimally to different crops during that period by minimising the cumulative yield reduction during that period by single state (the water available during that period) DDP. Though they have computed the yield response of different crops to different water availability during intraseasonal periods by incorporating soil water balance and yield response models, the essence of considering these facts was lost by averaging the soil moisture content of all the crops at the end of the intraseasonal period. According to the authors, this could have been avoided by defining the soil moisture state variable for each crop in the SDP formulation but at the cost of computational complexities which could have rendered their model unworkable. They have demonstrated the application of the model through a case study of Malaprabha reservoir in Krishna Basin, Karnataka State, India for cotton, maize, sorghum, pulses, wheat and safflower.

Akhand et al., (1995) developed a model for water allocation to different fields in the command area of canal and in different intraseasonal period. The area to be irrigated in each field is predecided and only one crop can be grown in a particular field. Authors formulated the model in the framework of LP, unlike previous studies which predominantly used DP for water allocation. The objective function consists of maximising the sum of net benefits from all the fields irrigated with different water sources. The net benefits from each field irrigated with each water source is calculated as the sum of contribution from individual intraseasonal or irrigation periods, which is a function of crop yield contribution during the corresponding period. The crop response function given by Doorenbos and Kassam (1979) was used to compute crop yield, by assuming actual ET during any period as the product of irrigation depth to be delivered to a field and the irrigation efficiency during that period. The irrigation efficiency is increased from initial crop growth stage to the crop maturity by linear interpolation to

Table 2.4 Summary of some water allocation models (multicrop models)

Sr. No.	Researchers and year	Solution technique and level of model	Variables, objective and constraints	Place of application	Crops	Water sources, uncertainty and others
1	Trava et al., (1977)	zero-one linear integer programming multifield model	DV-to irrigate field on particular day OF-minimisation of labour cost, Constraints: usual	Northern Colorado Research Demonstration Centre, Colorado, USA	corn, beans and sugar beets	water availability during individual time periods deterministic approach
2	Loftis and Houghtalen (1987)	DP single field model	SgV-a week StV-W_i DV-volume of water to be delivered from reservoir during each time step OF-minimisation of difference between water available and maximum crop water requirement, Constraints: usual	Colorado, USA. Area: 17,000 ha.	corn	water supply from storage reservoir stochastic approach, RV-reference crop evapotranspiration
3	Abderrahman et al (1989)	simulation similar to DP multifield model	DV-Id_i OF-minimisation of yield reduction, Constraints: usual	Eastern Province, Saudi Arabia	alfalfa, sorghum, wheat, barley and date palm	deterministic approach
4	Hiessl and Plate (1990)	simulation-optimisation (with compromise programming) multifield model	DV-whether to irrigate certain crop at particular instant of time and Id_i (if to be irrigated) Objective is the minimisation of difference between supply and demand, Constraints: usual	Saudi Arabia	-	water supply from irrigation reservoir implicit stochastic optimisation
5	Rao et al., (1990)	Two level DP	SgV-crop growth stage	Major irrigation	sorghum and	deterministic approach

		(seasonal and intraseasonal) and single crop and multiple crop models single field model	(seasonal level) and week (intraseasonal level) for single crop model and crop for multiple crop model StV-θ_i and W_i DV-Id_i OF-maximisation of crop production (single crop model) and maximisation of NB (multiple crop model) SgV-crop, Constraints: usual	project in southern India. Area: 30 ha.	cotton	water availability at the beginning of irrigation season
6	Vedula and Mujumdar (1992)	Two level DP (over season and over irrigation period) single field model	over season: SgV-irrigation event StV-θ_i (average for all crops) ,W_i and inflow into the reservoir DV-Id_i for each crop OF-minimisation of cumulative yield reduction from all crops within season: SgV-crop StV-W_i DV-irrigation depth for each crop OF-minimisation of cumulative yield reduction from all crops, Constraints: usual	Malaprabha reservoir in Krishna Basin, Karnataka State, India. Area: 202,708 ha.	cotton, maize, sorghum, pulses, wheat and safflower	water supply from storage reservoir stochastic approach for over season model, RV-reservoir inflow
7	Akhand et al., (1995)	LP, multifield model	DV-Id_i, OF- maximisation of NB, Constraints: usual, canal carrying capacity, minimum irrigation depth and minimum water delivery to each crop.	Maricopa Agricultural Centre, Arizona, USA. Area: 330 ha.	Barley, cotton, grapes and wheat	water availability during intraseasonal period, deterministic approach.

take care of root zone depth variation. Thus the amount of water to be applied to each field is the decision variable in objective function. The constraints included in the formulation are related to the water availability, canal carrying capacity, minimum depth of irrigation and minimum water delivery to each crop. They evaluated a model using the data obtained from the Maricopa Agricultural Centre demonstration farm for the 1988-89 cropping season. The considered the total area of 330 ha divided in 14 fields and served by a single water delivery canal. The crops grown are barley, cotton, grapes and wheat. They obtained the water allocation plan for different water availability. The use of LP technique enabled the authors to consider system constraints properly. However the uncertainty component can not be considered in this formulation as appropriately as in DP formulations. The approximation of actual ET to water stored in the root zone and ignoring the soil water balance phenomenon may add to the errors.

It can be concluded from this review that water allocation models essentially allocate the water optimally over the irrigation season to a crop or crops grown over the known area under the water limiting condition. Excepting the models developed by Trava et al., (1977) and Akhand et al., (1995), all the models are based on DP technique to obtain the solution and are of single field type. However if the greater complexities involved in the physical systems need to be considered for better approximation, the DP approach used in these models has limitations constrained by the computational requirements and therefore needs certain approximations. Windsor and Chow (1971:369) noted

"*the approach using dynamic programming if applied to a multicrop, multisoil farm irrigation system becomes unmanageable due to the large number of state variables involved*".

Palmer-Jones (1977:1), while confirming the need of consideration of the distribution of water within the root zone for tea in Malawi in determining the response to irrigation, quoted

"*...two or more soil moisture state variables will be necessary in dynamic programming (DP) method of finding the optimum allocation policy, and this makes DP even more difficult to use in practice than has been previously indicated.*"

and Benedini (1988:347)

"*complexities caused mainly by the high number of variables restricted its use to very simple system*".

But stochastic features which characterise a large number of water resources systems can be translated appropriately into DP formulation (Yeh, 1985) as evident from most of the models based on DP described in this study which considered the uncertainty in one or more parameters.

2.4.3 Land and Water Allocation Models

Models described in land allocation models and water allocation models determine the land area under different crops for a known water allocation policy, and the water to be delivered to different crops under a known distribution of land area under different crops, respectively. In water limiting condition the models of both the categories do not give optimal allocation of land and water as an allocation policy for one of the resources is predecided (and may not be optimum). Only if the predecided allocation policy for one of the resources is optimal, allocation policy obtained for another resource from the model can be optimal. However the optimal allocation policies for land area and water can not be obtained separately when water is limited and deficit irrigation is considered for maximisation of the returns.

The stagewise yield response function developed by Jensen (1968) and Stewart et al., (1974) and the yield response factors of different growth periods of different crops (Doorenbos and Kassam, 1979), indicate that the rate of change of yield with respect to water applied is different in different growth stages for the same crop, and also different in same growth period for the different crops. Therefore, in the case where water allocation policy is predecided and area allocation policy is determined from an area allocation model, the change in water allocation policy during certain growth stage for certain crop affects the water availability during other growth stages for the same crop or for different crops during the same growth stage. Similarly the returns obtained due to change in availability of water during an other growth stage or for another crop may be different than returns obtained from an earlier water allocation policy. The change in water allocation policy can also alter the area under different crops, and this may give different returns than from the area obtained from the initial water allocation policy. Similarly, in the case of area allocation policy predecided and water allocation policy determined from the allocation models, the change in area allocation policy may change the water allocation policy obtained from the initial area allocation policy and thus the net returns may also be different as observed in the results of Dudley and Burt (1973).

Many studies have been conducted for optimum allocation of both the resources using various techniques including LP, DP, combination of LP and DP and non-linear programming (NLP). For land area and water allocation, the allocation of water is a sequential decision making process, involving the non-linearity in the relation between yield and water applied, and therefore the LP technique which is based on the axioms of linearity and one stage decision making process may not suit these non-linear relations and sequential decision process. However the continuous non-linear function can be discretised into several activities (transforming the non-linearities) and similarly the sequencing of the activities can be combined into the another activity and incorporated in to the LP formulation. This can be done by obtaining several irrigation programmes by changing the combination of irrigation amount and timing of irrigation and corresponding influence on yield. But the number of combinations and thus activities may be too many to make the LP formulation feasible. However at farm level, this technique has been used for area and water allocation (see Section 2.4.3.3).

The function of yield response to water applied is non-linear, and therefore NLP can effectively handle the formulation and give optimal allocation of both the resources. However this technique involves a lot of complexities in handling the sequencing of deficit, or applying different amounts of irrigation water in different growth stages, and its influence on yield, and may not give an optimal solution. Incorporation of sequencing of deficit in a multicrop scenario requires the development of too many relationships, and thus difficulties in the formulation, making the optimisation process too slow and requiring a lot of computer time and storage. The chance of losing the optimality also increases due to the errors involved in the development of the relationships required in the formulation. The NLP technique has been used to allocate land area and water to different crops mostly without considering the effect of ET deficit in different growth stages on yield.

Dynamic programming does not offer any difficulties in allocating water, with due consideration to deficit and its distribution over the season, to different crops grown over a certain area when the different processes in the root zone are simplified. But while deciding the optimum allocation of land area also, at least nc+1 more state variables in addition to the state variables required to describe the water resource system are to be incorporated into the formulation, where nc is the number of crops involved (one for total area to be irrigated and nc for the area to be irrigated under each crop). Already in most DP formulations used for only water allocation, important state variables such as total water available for irrigation and soil moisture in the root zone are considered, and addition of each state variable increases the computational problems exponentially, and the optimal path becomes untraceable. However with certain simplifications, the attempts have been made to allocate water and land resources.

Some authors also tried to take the advantage of simplicity of LP in land area allocation and of DP in water allocation by combining both the techniques in deciding land area and water allocation.

The area and water allocation models are classified into four groups depending on whether optimisation is done for single crop or multicrop and on seasonal or intraseasonal basis as

1. Single crop-seasonal models
2. Single crop-intraseasonal models
3. Multicrop-seasonal models
4. Multicrop-intraseasonal models

The models developed under these groups are described below.

2.4.3.1 Single crop-seasonal model

Hall and Buras (1961) were probably the first to use the technique of sequentially allocating the water by the approach of dynamic programming. They formulated a DP model which decided the optimum area to be irrigated and the optimal allocation of irrigation water when water supply was limited in a single crop situation. The allocation was based on knowing the statistically expected value of the net economic benefit as a function of the quantity of the water applied annually (and thus the effect of intraseasonal distribution was not considered) for each subunit of the farm; each subunit was sufficiently small to be treated as homogeneous, with a stated economic benefit function representing the best available practice for any given subunit and quantity of water used. Each subunit was treated as a stage and the quantity of water available as the state variable. The decision variable was the quantity of water to be applied to a subunit to get maximum net returns. The core of the formulation was in knowing the benefit function for each subunit. The formulation was suitable for a single crop. With a number of crops involved there may be several alternatives for the same unit of land, and the authors suggested consideration of land to be allocated to each crop as a separate problem. Dividing the land into homogeneous subunits and considering each as the stage is only feasible at farm level and can not be used for the analysis of a large irrigation system.

Such consideration of only one crop and optimising the use of water resources without intraseasonal distribution of seasonal depth of irrigation water does not have practical value. Perhaps for this reason not many further studies were reported in the literature till Barrett and Skogerboe (1980) described the methodology to decide optimum depth of water application and optimal land area by equating marginal revenues and marginal costs to get maximum net returns. Returns were the function of yield (which is in turn the function of irrigation depth) and costs were the function of yield dependent costs per unit area, constant costs per unit area, and area dependent costs per unit area. The authors incorporated some cases with the data from Grand Junction, Colorado, USA for maize.

Martin et al., (1989[b]) developed a method to determine optimal irrigation strategies for a single season using crop production functions which incorporate physically based coefficients. The relationship of yield to evapotranspiration is used to develop the yield-irrigation function. The physical parameters used in the production function can be determined from field measurements or various types of computer simulation. Using this approach, the optimal irrigated area and depth of water to apply can be related to prices, costs and physical parameters. According to the authors, this produces a more general solution than commonly used production functions that depend on limited experimental results. The optimal irrigation depth and irrigated area can be determined for either land or water limiting conditions. They applied the method for corn and sorghum with the data from various locations in USA.

English (1990) developed the concepts developed in heuristic discussion into a set of rigorous mathematical expressions for determination of optimum water use under deficit irrigation. According to the author those expressions also could be used to estimate the range of water use within which deficit irrigation would be more profitable than full irrigation. His approach involved the determination of five levels of irrigation viz. W_m, the level of irrigation that would maximise the yield, W_l, optimum level of irrigation when land is limiting (the deficit at which the returns to land are maximised), W_w, optimum level of irrigation when water is limiting (deficit at which the returns to water are maximised), W_{ew} and W_{el}, the deficit levels at which the net income would just equal the net income at full irrigation, either when land is limited or when water is limited. He derived a set of equations to estimate the values of the aforementioned variables which can be combined with any yield and cost function to derive the five relevant levels of water use. With the help of these the analyst can gain a useful perspective on the risks and returns associated with the deficit irrigation. He also stated that within the range between W_m and either W_{el} or W_{ew}, deficit irrigation would be

Table 2.5 The summary of some land and water allocation models (single crop-seasonal models)

Sr. No.	Researchers and year	Solution technique and level of model	Variables, objective and constraints	Place of application and area	Crops	Water sources, uncertainty and others
1	Hall and Buras (1961)	DP multifield model	SgV-field StV-seasonal quantity of water available DV-seasonal quantity of water to be applied to each field OF-maximisation of NB, Constraints: usual	-	-	deterministic approach
2	Barrett and Skogerboe (1980)	analytical method single field model	DV-optimal seasonal depth of irrigation water and area to be irrigated Objective-maximisation of crop yield or net benefits, Constraints: usual	Grand Junction, Colorado, USA	maize	deterministic approach
3	Martin et al., (1989b)	analytical method single field model	DV-optimal seasonal depth of irrigation water and area to be irrigated Objective-maximisation of net benefits, Constraints: usual	various locations in USA. Area: 53 ha.	corn and sorghum	deterministic approach
4	English (1990)	analytical method single field model	DV-optimal seasonal depth of irrigation water and area to be irrigated Objective-maximisation of crop yield or net benefits, Constraints: usual	Columbia Basin	wheat	deterministic approach

more profitable than full irrigation. Thus his approach can be used to know the levels of water to be applied at which deficit irrigation is profitable. He demonstrated the method with a case study from Columbia Basin for wheat.

This review has shown that single crop-seasonal models have contributed to analytical methodology but are too simplified to have general application. The model developed by Hall and Buras (1961) is of multifield type due to consideration of each field as the stage variable.

2.4.3.2 Single crop-intraseasonal model

This type of model allocates the area and water over the entire season optimally to one crop.

Dudley et al., (1971[b]) determined the best acreage to plant and the corresponding water allocation policy for a single crop by DP. The procedure includes initially selecting arbitrarily the acreage to be planned for irrigation with a single crop and then calculating the water supply available per acre by knowing the reservoir content and losses. The simulation-DP model (Dudley et al., 1971[a]) is run over the entire crop season to obtain the water allocation policy. The gross margin (gross revenue less variable costs) is computed. The process is repeated for all years of data and the sum of the gross margins is computed. The procedure is repeated for other acreages also. The acreage interval to be chosen depends on the accuracy required for the results. The acreage that maximises the sum of the gross margins is chosen as the optimal acreage to plant. The entire procedure can be repeated for different initial reservoir volumes. With modification in DP, the procedure can be applied when the inflows are received during the crop season. The authors applied the procedure to corn grown in a hypothetical system with climatological data from Inverell and streamflow data from the reservoir on the Gwydir river at Copeton, New South Wales, Australia.

Dudley and Burt (1973) developed an integrated intraseasonal and interseasonal SDP model, to determine an optimal decision rule with respect to optimal acreage to plant for potential irrigation at the beginning of the season, and intertemporal water application rates for a single crop. Area available for irrigation, % available soil moisture, a measure of crop growth and available water in the reservoir were considered as the state variables. The soil moisture to be maintained in the soil zone was the decision variable. There were certain drawbacks. The area to be irrigated were discretised at an interval of 10,000 acres. The irrigation depth was the one required to raise the soil moisture to field capacity and not to other levels (for consideration of deficit), and deficit in the amount of irrigation water to be applied was due to moisture stress observed at the end of the irrigation period. Therefore this model did not allocate the resources optimally in water limiting condition. The model was applied to the same empirical problem as described in Dudley et al., (1971[b]).

Schmidt and Plate (1983) developed the model to determine the size of the irrigated area and the operation schedule of a reservoir delivering the irrigation water. The optimum water releases are calculated by DP for the known flows (historical or generated). Then the optimum releases are correlated with parameters known at the time at which releases have to be decided (the storage content at the beginning of the period for which release has to be decided, and the mean inflows during the period) by multiple regression analysis. The procedure is repeated for different sizes of irrigated area. With the developed model simulation runs were done over the life time of the scheme. The net water yield (sum of the products of the relative yield and the size of irrigated area of every year over the life time of the scheme) are obtained for all the values of the design area and the optimum design area and operation schedule are selected by comparing net water yields. They applied the model for a basin located in the Arabian Peninsula. The authors described the limitations of the model as: the model is only suitable for monocrop situation and the processes at farm levels are only considered in a very approximate fashion.

Dudley (1988) developed the model for optimising irrigation decisions for surface water reservoirs when land is plentiful relative to available water. The model allocates land and water optimally to a single irrigated crop and land to a single dryland crop. The irrigation events are the decision points. At the first decision point, choice is made between irrigated crop and dryland crop. Later in the season irrigated area can be either maintained or reduced by abandoning some of it to rainfed status for the rest of that season. The approach involved the simulation models and stochastic DP. The irrigation event is the stage, and the irrigated area and the reservoir content at each stage are the state variables. First the simulation model simulates reservoir operation for each combination of stage and state for the entire length of data available. SDP decides the optimal maximum irrigated area for each stage-state combination. Second the simulation model sequentially simulates the net revenue from each of the years considered, and then computes mean and standard deviation for each discretised area considered.

Table 2.6 Summary of some land and water allocation models (single crop-intraseasonal models)

Sr. No.	Researchers and year	Solution technique and level of model	Variables, objective and constraints	Place of application and area	Crops	Water sources, uncertainty and others
1	Dudley et al., (1971[b])	DP single field model	SgV-Irrigation event StV-θ_i and W_i DV-level to which available soil water content was allowed to fall before irrigating OF-maximisation of NB model to be run for different acreage, Constraints: usual	Inverell (climatological data) and reservoir on Gwydir river at Copeton (streamflow data), New South Wales, Australia. Area: 240,000 ha.	corn	water supply from storage reservoir stochastic approach. RV-precipitation and water requirement. Irrigation application is to fill the soil root zone to FC.
2	Dudley and Burt (1973)	DP single field model	SgV-irrigation event StV-θ_i, W_i, area to be irrigated and measure of crop growth, Constraints: usual	similar to Dudley et al., (1971[b]) given above. Area: 240,000 ha.	corn	water supply from storage reservoir stochastic approach. RV-evapotranspiration loss from soil per acres, streamflow into the reservoir and rainfall in the crop growing area
3	Schmidt and Plate (1983)	DP single field model	SgV-irrigation event StV-W_i and mean inflows during irrigation period DV-releases from reservoir OF-maximisation of crop production, Constraints: usual. Model to be run for different acreage	Arabian Peninsula. Area: 870,000 ha.	-	water supply from storage reservoir implicit stochastic optimisation
4	Dudley (1988)	simulation and DP single field model	SgV-irrigation event StV-W_i and irrigated area DV-irrigated area and water to be released at each stage OF-maximisation of NB, Constraints: usual	data from Hearn and Constable (1984). Area: 48,000 ha.	cotton	water supply from storage reservoir stochastic approach with state variables as RVs and simulation over number of years with weather data

He applied the model with cotton as the irrigated crop and wheat as the dryland crop. Maximum irrigable area is 48,000 ha. He used 84 years of weather data and a complex soil water plant growth simulation model for cotton (Hearn and Constable, 1984). The model did not consider any state variable which represents the status of irrigated crop and soil water in its root zone (like earlier DP models). The author described the current complex nature of the crop growth model as the reason for not considering the soil water status as another state variable. Instead during the simulation, he considered the irrigations are applied whenever soil moisture deficit reaches 50 %. The discretisation of the area for a large irrigation scheme gives suboptimal solution due to limitation to the number of states (the author considered only six states for the irrigation scheme with 48,000 ha).

The other attempt found in literature to integrate optimal allocation of area and intertemporal distribution of water by SDP is by Dudley et al., (1972) for determining the best size of irrigation area for a reservoir. Studies under this category were not reported by other authors. Most of the authors who adopted DP technique assumed area to be irrigated as known and optimised the water allocation as consideration of area allocation would have led to the addition of another state variable. The main difficulty associated with the models under this category was, while adding area to be irrigated as state variable in the formulation, another important state variable of soil moisture status was not properly considered. All the models developed in this category are of single field type.

2.4.3.3 Multicrop-seasonal model

If the yield or returns by applying different seasonal irrigation depths are known, LP technique can be used for allocation of area to different crops, and optimal seasonal distribution of water, by incorporating yields or returns obtained at different seasonal irrigation depths into the formulation. NLP technique is also suited well to allocation of area and water to different crops without considering intraseasonal distribution of water, and therefore models under this category used LP or NLP technique to get the solution.

Kumar and Khepar (1980) compared the alternative levels of water use and the fixed yield approach when there was a constraint on water, in a multicrop farm located in a command area irrigated by Kotkapura distributory, Punjab, India, in terms of optimal cropping pattern and total net returns. The different crops considered are wheat, gram, mustard and berseem in winter season, cotton and paddy in monsoon season and sugarcane as an annual crop. Fixed yield model was the LP model with the objective of maximising annual net returns subject to constraints on water availability and other inputs. The yields included in the objective function were the maximum yields, and water requirement in the constraints corresponded to maximum yield. The models with alternative use of water use was an extension of the theoretical analysis by Pomareda (1977). This model took into account stepwise production functions for the crops. The method was described by the authors. Inclusion of a water production function added the yield response to variable supply of water. They applied the model with three different levels of water availability and found more benefits with the use of alternative levels of water. They concluded that the model with the variable water demand levels was superior to the fixed yield approach for optimal utilisation of land and water resources. They also concluded from the sensitivity analysis that it was desirable to bring more area under cultivation.

Rao et al., (1986) formulated an LP model to maximise the net returns under water limiting condition by considering the effect of different seasonal water and Nitrogen levels (management levels) on the yields which were obtained by conducting experiments. The net returns obtainable under each management level were used as the coefficients, and the areas under each crop under each management level were treated as variables. They applied this model for crop planning under Araniar irrigation project, Andhra Pradesh, India for allocating area under groundnut, finger millet and rice. They studied the results at four different water availability in the reservoir. The formulation considered the effect of applying different seasonal water levels on the crop planning, but the different seasonal water levels were obtained by varying the irrigation frequency (based on cumulative evaporation). Therefore in an irrigation scheme where the fixed irrigation interval approach is followed, it may be difficult to apply the solution of the model.

Martin et al., (1989[a]) developed a simulation-optimisation model using NLP technique to develop operating rules for deficit irrigation management of a limited water supply. They used a previously developed model described by Martin (1984) and Martin et al., (1984) to simulate corn, sorghum and soybean yields for a 52 ha field. The yield function in the model did not involve crop growth stagewise response of yield to irrigation water applied. Irrigations were scheduled in the model when the soil water depletion exceeded an allowable deficit similar to the method given by Jensen et al., (1971). Dryland and five irrigation levels were simulated. One irrigation level was the one which gave maximum yield and other four irrigation levels represented applications equal to approximately 20,40,60 and 80 % of the water required for maximum yield. For the deficit irrigation levels, the irrigation season was shortened by delayed start-up and

Table 2.7 Summary of some land and water allocation models (multicrop-seasonal models)

Sr. No.	Researchers and year	Solution technique and level of model	Variables, objective and constraints	Place of application and area	Crops	Water sources, uncertainty and others
1	Kumar and Khepar (1980)	LP incorporating stepwise water production function using separable programming technique single field model	DV-Ac and seasonal water to be allocated for each crop OF-maximisation of NB, Constraints: usual and on availability of other inputs	Kotkapura distributory, Punjab, India. Area: 173 ha.	wheat, gram, mustard, berseem cotton ,paddy and sugarcane	deterministic approach
2	Rao et al., (1986)	LP single field model	DV-Ac and seasonal water to be allocated for each crop OF-maximisation of NB Constraints: usual and minimum area to be irrigated under each crop	Araniar Irrigation Project, Andhra Pradesh, India. Area: 2230 ha.	groundnut, finger millet and rice	deterministic approach water supply from reservoir
3	Martin et al., (1989a)	simulation-optimisation (NLP) single field model	DV-Ac and seasonal water to be allocated for each crop OF-maximisation of NB Constraints: usual and minimum and maximum area to be irrigated under each crop	Southwest Nebraska, USA. Area: 52 ha.	corn, sorghum and soybean	simulation over available weather time series

early shutoff which caused water stress early and late in the season. Crop yields were related to the irrigation depth by a quadratic equation. A non-linear constrained optimisation programme was used to determine the optimum area and depth of water for each irrigated crop, and area and type of dryland crop, with the objective to select the cropping pattern and irrigation depth for a season that maximised the net returns for a given water supply (the non- linearity in the model was due to the quadratic equation used to express grain yield as a function of irrigation depth). The constraints were based on minimum and maximum irrigated area for each crop, the volume of irrigation water available for the season, the total area that can be irrigated and the maximum irrigation depth for each crop. The irrigation system considered was central pivot, in south-west Nebraska, USA. Two crops (corn and soybeans) were considered.

Though these models considered yield response to a variable supply of water, the optimum intraseasonal distribution of water was not studied as a stagewise yield response function could not be considered in the formulation. The models allocate the resources at scheme or farm level.

2.4.3.4 Multicrop - intraseasonal model

Models under this group give the optimal allocation of both area and water with intraseasonal allocation of water to different crops. The DP and NLP techniques can not serve this purpose due to difficulties in adopting areas as other state variables in DP and difficulties in inclusion of intraseasonal distribution of water in NLP. Therefore models developed under this category use LP technique by generating a number of irrigation programmes either by simulation model or DP model.

While discussing the studies on "Optimal Irrigation Programmes" by Stewart et al., (1974), Blank (1975[b]) suggested the LP formulation which considered the objective function of maximisation of net returns from various crops irrigated with different levels of water. He also considered the water availability and water requirement of different crops irrigated with various levels of seasonal irrigation depth in different periods of the season. The formulation suggested can give the optimal allocation of area and water if different water levels, their intraseasonal distribution and corresponding yields are included in the formulation properly. The feasible combination of different water levels and their intraseasonal distribution may be numerous, and their incorporation may end up with too many activities in the formulation.

Matanga and Marino (1979) realised the need of considering the various levels of seasonal irrigation depth for each crop, to obtain the optimal allocation of area and water in a situation where deficient water supply exists. Therefore they modified the area allocation model of Matanga and Marino (1977), to make allowance for more than one seasonal irrigation depth for each crop, and applied it to the ET data obtained from the experimental plots situated at University of California, USA for corn, grain sorghum and pintobean to determine the cropping pattern on a 200 acre land area. Sensitivity analysis was also performed to study the effect of changes in crop prices on the optimal solution.

As the area allocation model of Matanga and Marino (1977) required the water demand per irrigation, the optimal depth of irrigation water to be applied for each irrigation during the irrigation season was obtained for various seasonal irrigation depths. This necessitated the need for generation of irrigation programmes. They used Stewart's model (Stewart et al., 1974) for generation of irrigation programmes where in cumulative maximum ET, and ET under non irrigated condition, and linear yield functions were used. Stewart's model distributes the seasonal irrigation depth such that minimum deficit occurs during critical plant growth stages, and gives the irrigation programme specified in terms of date and depth of irrigation. As Stewart's model is based on minimising the ET deficit during the periods of critical growth stages for the given seasonal irrigation depth and the yields are estimated from the linear yield function for the seasonal irrigation depth, it does not consider the effect of ET deficit occurring during the growth stage on crop yield. The authors of Stewart's model (Stewart et al., 1974:191) also wrote:

"The biggest problem involved is to avoid bringing about specific growth stage effects on Y (yield) i.e. to avoid ET deficits that, because of their timing with respect to growth stage succession and their intensities relative to ET deficit intensities in prior growth stages, cause Y reductions greater than expected from seasonal ET deficit alone".

This is comparable to the water allocation model presented by Matanga and Marino (1979) which considered the different 'optimal' seasonal irrigation depths (thus different seasonal deficit), but not its optimal sequencing as for as its effect on yield was concerned. The Stewart's model in generating irrigation programmes is not suitable for command areas with multiple crops grown on various types of soils with a rigid irrigation schedule (unlike in flexible sprinkler irrigation), as the model assumes the timing of irrigation as whereas when timing of irrigation is fixed or dependent on other factors, the amount of deficit along with its sequencing at predecided irrigation timings should be optimal. As the irrigation programmes generated by Matanga and Marino

(1979) did not consider the sequencing of the deficit, their model also does not lead to optimum area and water allocation on a command area basis when water resources are finite.

Reuss (1980) presented the use of the LP technique for optimising cropping mixes by maximising the net benefits within fixed water supply constraints. He considered different levels of monthly water requirement. One level was for "no stress" irrigations and remaining levels were for "stress" irrigations. No stress level of irrigation was equivalent to maximum crop water requirement computed by Penman (1948) or Jensen-Haise (1963) method over the particular month for average weather conditions. The stress levels of irrigation consisted of reducing the water requirement in certain months and the crop yield by a certain amount based on farm budget information. Though the author emphasised the use of information concerning the relationship of irrigation to stress and stress to yield, he did not incorporate this due to lack of such information. He applied the technique to the area of 200 ha in Sargodha region of Punjab, Pakistan. He covered six crops with 2 to 3 levels of no stress irrigation for each crop. Though the approach is to allocate land and water resources optimally, it has certain drawbacks such as consideration of monthly water requirement rather than water requirement of the irrigation period, arbitrary selection of different levels of water application and failure to consider some physical constraints such as canal capacity. The formulation of the technique used also limits its use to farm level or small irrigation schemes.

Yaron and Dinar (1982) presented a system approach to intrafarm water allocation and irrigation scheduling for major crops. Instead of considering all the feasible "irrigation activities" (water to be delivered per hectare for each irrigation and corresponding crop yield) in the LP formulation and making the model with unmanageable matrix, they solved the LP with a few initial irrigation activities (subsystem I), generated alternative irrigation activities by DP based on the shadow prices of water obtained from LP (subsystem II), and incorporated new irrigation activities into the original LP formulation (subsystem I). This iterative process continued till the optimal solution was obtained. Thus the overall system contained two interrelated subsystems.

Subsystem-I was an LP model intended to maximise the farm's income subjected to constraints with the given technology. The peak season was divided into several operational units and water supply and other restrictions were expressed. Initial irrigation activities for major crops during the peak season were incorporated as the initial set. The results of the LP model were the hectarage under each activity, the shadow prices of water for each subperiod and the farm income. Subsystem-II was a DP model intended to generate new irrigation scheduling activities with shadow prices of water given by the LP solution. The objective of DP was to maximise cumulative net returns. The DP model considered an activity unit as one hectare. Soil moisture level and quantity of irrigation water available per hectare were state variables. The planning horizon was divided into a number of subperiods and each subperiod was the stage. The DP model calculated the optimum total quantity of water to be allocated to one activity unit throughout the season, with the help of shadow prices of water obtained from LP. The new activity generated by DP was incorporated into the LP model and was solved again to get hectarage, farm income and shadow prices which again were input to DP to generate yet another new activity. LP-DP loop continued until the optimal solution was achieved. In the DP phase, each alternative irrigation activity is generated by considering only one crop, so in a multicrop-multisoil situation either the convergence to optimality will be difficult, or independent generation of an activity for each crop by DP may not lead to the optimal solution. The procedure is based on the fixed water availability in different irrigation periods and not carryover of remaining water from one irrigation period to another (the case required for the irrigation scheme with a storage reservoir). They applied this system approach to the typical farm in south region of Israel for cotton (though the irrigated fruit crops and unirrigated wheat were grown in the farm, the fixed predetermined water was allowed to fruit crops and irrigation activities were varied only for cotton crop) by formulating three irrigation activities initially. They found the optimum solution at the fifth iteration i.e. with seven irrigation activities. The total farm income increased by 11% over the solution obtained by the initial irrigation activities.

Bernardo et al., (1988) developed a two stage model to determine the optimal intraseasonal allocation of irrigation water and the distribution of area to different crops under conditions of limited water availability. The first stage was the crop simulation model and the second stage was the economic optimisation model. A crop simulation model (SPAW-IRIG based on models developed by Saxton et al., 1974 and Sudar et al., 1981) calculated daily soil plant moisture to estimate the water requirement for a given irrigation schedule. It then estimated yield from an accumulated weighted water stress index which was derived from the daily calculations and the relationship between yield and water stress. The yield and water requirement (intraseasonal) were calculated for several combinations of different irrigation schedules based on time (fixed time, specified dates, soil moisture %, accumulated actual ET since the previous irrigation, and accumulated potential ET since the previous irrigation) and depth (fixed depth per irrigation, soil moisture %, % of accumulated actual ET and % of accumulated potential ET) of irrigation. For each combination of time and depth options employed, several sets of irrigation schedule were generated by varying the irrigation schedule parameters that trigger the time of irrigation and dictate the quantity of water applied. The economic optimisation model allocated a specified land acreage and water supply among the schedules generated based upon a criterion of economic efficiency among several crops. The optimisation model was solved by LP with the objective function of maximisation of net returns, and the restrictions were imposed on subperiod and total water availability, labour use, use of non-irrigation inputs, quantity of each crop produced and individual and total crop acreage. The model gave the output of area under different crops to be irrigated by different irrigation schedules for given water availability and area. The model was applied to a surface irrigated farm (210 ha) on sandy loam soil in Columbia River Basin, Washington State, USA. Four crops viz. Grain corn, dry beans, spring wheat and alfalfa were included in the analysis.

In an irrigation scheme with irrigations at a fixed time interval, any fixed time interval criteria can be used, along with any criteria for determining the depth of irrigation. The procedure includes the generation of irrigation strategies for any one combination (fixed time and depth criteria), for incremental levels of the parameters that dictate the quantity of water to be applied. This does not generate all possible irrigation strategies for a particular combination as the combination of the parameters at every irrigation is not considered. The procedure does not consider restricting the number of schedules which may be a limiting factor in a large heterogeneous irrigation scheme. The water availability is computed and compared with irrigation demand for each individual irrigation period. This is the situation applicable to a run-of-river irrigation scheme or at farm level optimisation. As there is no intraperiod adjustment of water, the procedure is not suitable for a storage reservoir irrigation scheme.

Mannocchi and Mecarelli (1994) proposed the three phase optimisation model for maximising the net benefits for deficit irrigation. In the first phase, for a particular soil-crop unit and irrigation intervention point (when the required % of available soil moisture is depleted), they estimated crop yield (and net benefits) per unit area for different amounts of net applied seasonal irrigation water (IW). IW varies from 0 to maximum IW, with a step of 10 mm. While scheduling the irrigation, waterings are primarily applied during the growth stage with the highest value of yield response factor, and successively following the order of decreasing value of yield response factor in the other periods. In the second phase, they maximised the total annual net benefits for the various cropping pattern and total irrigated area subject to some constraints. In the third phase, they determined the cropping patterns which gives maximum benefits over a period of certain year. They applied the model to a 100 ha farm in the district of

Table 2.8 Summary of some land and water allocation models (multicrop-intraseasonal models)

Sr. No.	Researchers and year	Solution technique and level of model	Variables, objective and constraints	Place of application and area	Crops	Water sources, uncertainty and others
1	Matanga and Marino (1979)	LP single field model	DV-Ac and Id_i for each crop OF-maximisation of NB, Constraints: usual & related to food prod., water distrib. capacity & labourer	University of California, Davis, USA Area of 80 ha.	corn, grain sorghum and pinto bean	water supply during intraseasonal periods deterministic approach
2	Reuss (1980)	LP single field model	DV-Ac and Id_i for each crop OF-maximisation of NB, Constraints: usual and related to labourer	Sargodha region of Punjab, Pakistan Area of 200 ha	cotton, sugarcane, rice, wheat and fodder	water supply during intraseasonal periods deterministic approach
3	Yaron and Dinar (1982)	DP-LP single field model	DP: SgV-irrigation event StV-θ_i and W_i DV-Id_i OF-maximisation of NB for one hectare LP: DV-Ac and Id_i for each crop OF-maximisation of NB, Constraints: usual	south region of Israel Farm of 310 ha.	cotton, wheat and fruits (irrigation activities were varied only for cotton crop)	deterministic approach
4	Bernardo et al., (1988)	LP single field model	DV-Ac and Id_i for each crop OF-maximisation of NB, Constraints: usual and related to labourer, crop acreage and other inputs	Columbia River Basin, Washington State, USA Farm of 210 ha	grain corn, dry beans, spring wheat and alfalfa	water supply during intraseasonal periods deterministic approach
5	Mannocchi and Mecarelli (1994)	simulation-optimisation (LP) single field model	DV-Ac and Id_i for each crop OF-maximisation of NB Constraints: usual and related to crop acreage (max. limit)	Upper Tiber Valley, Central Italy farm of 100 ha.	wheat, sunflower and maize	water availability at the beginning of irrigation season deterministic approach

the Upper Tiber Valley, Central Italy with three crops (wheat, sunflower and maize) irrigated by a semi-permanent sprinkler system. They determined the estimates of yield (net benefits) when soil moisture was depleted by 50%. They maximised the total net benefits for different water availability and different cropping patterns which were annually constant for twenty five years, and compared them with annually varying cropping patterns.

This model computes the crop yield for different levels of seasonal irrigation depth such that every time watering is made, full irrigation is applied. The different levels of partial irrigation also need to be included for evaluating all possibilities of irrigating the crops. The model is typically suitable to the irrigation system which operates on demand due to the irrigation scheduling based on depletion of a certain level of soil moisture. The model does not have the flexibility of varying the total irrigated area, though the area under different crops can be varied. Under deficit irrigation it might be profitable to divert some water from one crop-soil unit to the additional new area.

2.4.3.5 Conclusions on land and water allocation models

The land and water allocation models described in this Section 2.4.3 were formulated for allocation of both the resources optimally. But the models under the first two categories (single crop-seasonal models and single crop-intraseasonal models) are not appropriate for the irrigation scheme where several crops are grown, and the models under third category (multicrop-seasonal models)does not give intraseasonal distribution of water which is important in allocation plan. The land and water allocation models described in fourth category allocates water to different crops over the intraseasonal periods of irrigation season. However the setting of most of the models discussed is either for on-farm level (Yaron and Dinar, 1982; Bernardo et al., 1988 and Mannocchi and Mecarelli, 1994) or for on-demand system (Matanga and Marino, 1979; Bernardo et al., 1988 and Mannocchi and Mecarelli, 1994). The model developed by Reuss (1980) is quite primitive in this class as it does not consider the influence of irrigation on changes in soil water status and crop growth parameters. All these models allocate the resources at farm level or scheme level (single field type). However the models of multifield type are useful for the operation of the irrigation scheme.

2.5 EVALUATION MODELS

Several models are reported in the literature which do not optimise the allocation of any of the resources, but with certain decision rules (area and water allocation plans or policies) and system inputs, they generate an output of the system in the form of irrigation schedules and total crop production or net returns. These models are based mostly on the simulation technique and therefore can approximate the behaviour of the system representing all the characteristics of the system (Yeh, 1985). The response of the system can be obtained from the various decision rules or plans. However the decision rules involved are generally too many to make these models act as an optimisation model. Thus for a certain area and water allocation policy, the net returns or output from the system can be obtained, or certain allocation plans can be evaluated to find the appropriate one, but the policy itself may not be optimised. These models are thus useful in evaluating the known allocation policy or allocation plans obtained from the allocation model.

Numerous models are developed in this category. These vary from very simple (for example to obtain the irrigation depth per irrigation when water allocation policy is to give full irrigation) to complex (for example to adjust allocation policies depending on certain conditions and to give the scheme output in various forms). Some of these models are described in this section and summarised in Table 2.9.

Kundu et al., (1982) reported the CORNGRO model (Childs et al., 1977) modified by Kundu (1981) which took into account the crop variety, soil and climate conditions for determining the optimum soil moisture depletion and replenishment levels and timing and amount of irrigation during different crop growth stages. He demonstrated its applicability using the data at Grand Junction, Colorado and Davis, California, USA.

The Unit Command Area (UCA) model (Keller, 1987[b]) developed at Utah State University, Utah, USA consists of two integrated sub-models. One is for on-field maintenance of the water balance, and the other for water allocation and distribution. The on-field submodel predicts consumptive use, crop growth and yield in response to irrigation events and weather conditions for all fields in the unit command area. The distribution and allocation sub-model allocates water from the UCA turnout to individual fields, according to the aggregate field demand and rules governing the share system. The model also attempts to integrate technical and socio-economic aspects in management decisions.

Raes et al., (1988[b]) reported that Raes et al., (1988[a]) developed IRSIS - IRrigation Scheduling Information System to solve the problems concerning irrigation scheduling at field level, with the objective to formulate irrigation strategies which plan the future irrigation at the right period and with the proper depth. The core of IRSIS was a water balance model BUDGET (Van Aelst et al., 1986) which simulated on a daily basis the water content in the root zone. In the model the number of timing and depth criteria could be selected to determine the irrigation amount. In the case of limited irrigation water supply, an optimal distribution of the available water was calculated on the basis of minimising the yield depression. A yield response function was used in the model by following the methodology of Doorenbos and Kassam (1979).

Jian (1990) developed the programme "Irrigation Scheduling of Farm Water Delivery" (ISFWD) for determining the irrigation schedules for the farm. The programme is based on a fixed supply to each farm within the rotational block, while the supply duration and supply interval are varying to the changed field requirements over the growing season. ISFWD considers both constant irrigation intervals and varying irrigation intervals over the growing season. The example was worked out for five crops: tomato, groundnut, peas, cotton and maize. The reason cited for not preferring constant interval and constant depth is the increased water losses due to constant depth when soil can not hold the prescribed constant depth, and the reason for not preferring constant interval and different depth is the system may not be easily understood by the farmers. Therefore the model tries to overcome both the difficulties by varying the supply duration and supply interval. However when the supply interval is varied the scheduling may not be suitable for rotational water supply with multicrop and heterogeneous soil. Constant irrigation depth and varying supply time is almost equivalent to different irrigation depth for the farmers, if he is not to alter his area to be irrigated every time.

Rajput and Michael (1989) developed the model for scheduling canal deliveries to meet the actual water requirements of the crop in the command area, with the help of soil water balance in the root zone and accounting for the losses of water in the conveyance. The authors commented on developing a set of operation schedules in case the total annual water requirement according to the schedule developed by the model exceeds the estimated water supply. Shayya et al., (1990) developed "Micro-Scheduler", a general irrigation scheduling package for microcomputers which is suitable for on-farm irrigation scheduling and regional analysis. It schedules irrigation based on real time or historical weather data using a simple soil water balance model, for any number of fields and crops and soils.

The CROPWAT simulation model developed by FAO (1991) could give irrigation scheduling for different scheduling options and prepare scheme water supply. However it is not an optimisation model though it can be approximated to an optimisation model by running several times, each time choosing different options. However this model can be operated for one crop situation only.

Burton (1992) developed a simulation model, CAMSIS, (Computer Aided Management and Simulation of Irrigation Systems) for allocating irrigation water within an irrigation scheme to different crops planned to be grown on a known hectarage in different tertiary units. The water requirements are calculated for each tertiary unit from all crops grown in the unit during each irrigation period. If the water available during a particular irrigation period exceeds the water requirement (demands), then all demands are met, otherwise available water is allocated according to one of the following six options (water allocation policies).

1. Proportional to each crop's irrigation water requirement
2. Proportional to gross irrigable area
3. Priority allocation to most valuable crops
4. Priority allocation to crops in most sensitive growth stages
5. Restrict allocation to most water use efficient areas and
6. Water allocation made according to instructions received from the operator.

As the model compares water demand and available water during each irrigation period and then allocates water, it is suitable for the run-of-the-river type of irrigation scheme and not for a storage reservoir scheme. The author described the utility of the model with "Mogambo Irrigation Project", Somalia. The total command area of 2052 ha was selected with 891 ha of rice, 756 ha of maize and 405 ha of cotton. The results were obtained in terms of ten performance indicators (area harvested, total production, total value of production, production value per unit area, average scheme yield, total water requirement, total water supply, total water losses and water use efficiency in terms of Kg/m^3 and water use efficiency in terms of \$/m^3). The author analysed the results in detail for each water allocation policy and found the complexity of identifying a rational water allocation policy in times of water shortages.
He opined (p.335)

"Due to complexity of the inter-relationships that exists in space and time in an irrigation scheme it is not considered possible to have developed this analysis without the use of simulation package such as CAMSIS".

The CAMSIS package can be used to evaluate different cropping patterns, and to know corresponding irrigation schedules based on a certain water allocation policy at the planning stage when water supplies are short. The model can also be used to know "best options" for the water allocation for the remaining irrigation season in real time operation. The model can evaluate different crops, varied soil types and different sizes of land holdings together. However the model is not optimisation model. He also reviewed extensively several other 'evaluation' models.

Clarke et al., (1992) developed an expert system, IRRIGATOR, to schedule supplemental irrigation to fruit and vegetable crops in Ontario in a subhumid region of Canada. Equations and heuristics are both used to reproduce the expert's method for predicting irrigation dates and determining the amount of irrigation water to apply. They found from the test results that the expert system consistently matched the recommendation made by the experts. Kemachandra and Murty (1992) developed a simulation model named as Water Allocation and Distribution Program (WADPRO) for the purpose of estimating water deliveries at tertiary and secondary canal levels of a large irrigation scheme, based upon a water balance approach for low land paddy and simulation of the soil moisture profile for other crops. They included the expected rainfall in the computation of irrigation water requirement. They applied the model to Mae Klong Project of Thailand consisting of two crops (paddy and sugarcane). The scheme operates on a continuous flow system. The weekly irrigation schedules were predicted for paddy, and a soil moisture depletion approach was adopted for sugar-cane to know the irrigation schedules.

Steiner and Walter (1992) described the simulation model, Irrigation and Land Management (ILM), developed over five years by Keller (1987[a]); Steiner (1991) and Steiner and Keller (1992). The model simulates the demand and response of a multiple-field multicrop irrigation system in a variety of environments. The total demand and total supply are compared daily and the water supply is distributed according to the water distribution rules (i.e. queue, equity etc.), the soil moisture parameters of each field are updated, yield calculations are done and the control is passed over to next day. They described the utility of ILM for Bear River System, Utah State, USA with corn, sugar beets and spring barley. They also discussed the limitations of ILM.

Lenselink and Jurriens (1993) summarised some packages used for irrigation system management. These packages simulate the response of the irrigation scheme to different water allocation policies and compute irrigation water requirement, crop yield, benefits etc. Some models have the facility to allocate the water by certain water distribution policies in times of shortages. These models include spreadsheets developed by Baily (1985) and Bullock and Burton (1988) (MAINSYST), INCA (Irrigation Network Control and Analysis, developed at Hydraulics Research Ltd., Wallingford, UK), UCA by Keller (1987[b]), SIWARE (SImulation and Water management in the Arab Republic of Egypt) developed at the Institute for Land and Water Management Research at

Wageningen, Netherlands in co-operation with the Drainage Research Institute in Egypt (El-Din El-Quosy et al., 1989), OMIS (Operation and Management of Irrigation System) developed by Delft Hydraulics Laboratory (Varhaeghe and Van der Krogt, 1990), CIMIS (Computerised Irrigation Management Information System) by Sagardoy (1991), WASAM (Water Allocation, Scheduling and Monitoring, developed at Euroconsult), CAMSIS by Burton (1992), ILM by Keller (1987[a]), Steiner (1991) and Steiner and Keller (1992), WADPRO by Kemachandra and Murty (1992), and MIS (Management Information System) for minor irrigation systems in Maharashtra, India by USAID (Sheng and Holden, 1992).

Hales (1994) developed the model, IRMOS (IRrigation Management and Optimisation System) which is a essentially modification of CAMSIS (Burton, 1992), for planning, operation and assessing the performance of the irrigation scheme. IRMOS allocates water to different crops grown in several tertiary and quaternary units. The procedure for allocation is similar to that used by Burton (1992) by modifying allocation options as

1. Allocation of fixed discharge
2. Allocation proportional to gross area
3. Allocation proportional to cropped area
4. Allocate in order of crop value
5. Allocate in order of soil moisture deficit
6. Allocate in proportion to irrigation demand
7. Allocate to minimise crop yield loss
8. Allocate to optimise crop production

Options (1) to (7) are applicable only to run-of-the-river schemes however the last option can also be applied to a storage reservoir scheme. In this option the total net benefits over the planning period (as a function of net benefits per unit area of crop irrigated, estimated yield obtained from the additive crop production function, and area allocated to the crop) is maximised by LP. The decision variable is relative ET ratio during each irrigation period for each unit (in each unit only one crop can be grown) that would satisfy the condition of maximisation of net benefits for the entire scheme over the planning period and related constraints. The use the of model is described for Rio Cobre Irrigation Scheme, Jamaica.

Singh et al., (1995) described the model called AISSUM (Automatic Irrigation Scheduling System of the University of Montreal), which is used for irrigation scheduling (to determine the frequency and dosage of irrigation application). AISSUM is based on water balance approach to irrigation scheduling. The timing of irrigation is

Table 2.9 Summary of some evaluation models.

Sr. No.	Researchers and year	Name of the model	Place of application and area	Crops	Water sources, uncertainty and others
1	Keller (1987[a])	UCA	several locations	several crops	deterministic approach
2	Shayya et al., (1990)	Micro-scheduler	Several farms in Michigan State, USA	several crops	water availability in intraseasonal period, rainfall as probabilistic variable
3	FAO (1991)	CROPWAT	several locations	several crops	deterministic approach
4	Burton (1992)	CAMSIS	Mogambo Irrigation Project, Somalia. Area: 2052 ha.	Rice, maize and cotton	water availability in intraseasonal period, deterministic approach
5	Kemachandra and Murty (1992)	WADPRO	Mae Klong Project, Thailand. Area: 450 ha.	paddy and sugarcane	water availability in intraseasonal period, rainfall as probabilistic variable
6	Steiner and Walter (1992)	ILM	Bear River System, Utah State, USA. Area: 202 ha.	Corn, sugar beets and spring barley	water availability in intraseasonal period, deterministic approach
7	Hales (1994)	IRMOS	Rio Cobre Irrigation Scheme, Jamaica Area: 12,000 ha.	sugarcane, pasture, vegetables and mixed crops	water availability in intraseasonal period and from reservoir, deterministic approach
8	Singh et al., (1995)	AISSUM	Trinidad and Quebec, Canada	okra and raspberry	water availability in intraseasonal period, deterministic approach

decided by critical soil moisture or allowable depletion approach and the amount of irrigation is computed based on full or deficit irrigation. They applied the model for an okra crop in Trinidad and raspberry in Quebec, Canada.

The irrigation games which familiarise and motivates managers and potential managers in the effective utilisation of water resources in general and in irrigation operation in particular (Dempster et al., 1989) can be classified under the allocation models of evaluation models. The irrigation games are mainly devised as training tool for the irrigation managers and staff to improve the performance of the scheme through operation of various activities and are not supposed to simulate the systems accurately. Some such games (SUKKUR BARRAGE GAME, MAHAKALI and NILE) are developed by Dempster et al., (1989) and Stoner et al., (1989). Lenselink and Jurriens (1993) also summarised some irrigation games (IRRIGAME by USU, 1992 and IRRIGATION REHAB by Steenhuis et al., 1989).

This type of model can evaluate different area and water allocation rules by incorporating the complexities in the irrigation schemes, but they are not able to decide the optimum operating rules. In such models, the area to be irrigated under different crops in each unit (say tertiary unit or farm) is known and allocation is done separately for each period. Therefore it is possible to represent the scheme properly for conveyance losses and capacity of canal network, which is difficult in allocation models.

2.6 CATEGORISING AND ILLUSTRATING THE NEED OF THE MODEL TO BE DEVELOPED

Several irrigation water management models have been developed under different categories for optimum allocation of land and water resources. However in a water limiting condition the models developed are not adequate to cater for all the requirements of an irrigation scheme, and a need exists to develop the model to produce the allocation plan. This is illustrated below with categorisation of the model to be developed in this study.

1. The main purpose of the study is to develop the allocation plan for the heterogeneous irrigation scheme in a water limiting condition. Therefore the setting of the model should be of 'allocation type' rather than of 'evaluation type'. As described earlier the previous models under 'land allocation' and 'water allocation' categories do not give the optimum allocation plans. In a water limiting condition, area allocation policy can not be established independently of water allocation policy, as a few increments of water

applied to a crop, if applied to additional land, may give more production, or if diverted to an other crop, may generate more benefits. Similarly water allocation policy can not be obtained separately, as alteration in area under different crops by transferring a few units of water from one crop to another may give different results. Therefore the model type under category 'land and water allocation' which allocates land and water by considering their availability together is suitable for this study.

2. Several crops are grown in the irrigation scheme with varying soil types and climatic characteristics. The intraseasonal distribution of water over the irrigation season is imperative to make the allocation plan effective in the actual operation of the irrigation scheme. Therefore it is conceptualised that the model for this study be of multicrop-intraseasonal type.

3. The heterogeneous irrigation scheme (HIS) is the scheme with spatial variation in soil and climate over the scheme. Several crops are generally grown in HIS on different soils and climatic conditions. In a large irrigation scheme, it is not sufficient to know the allocation of the resources to different crops grown on different soils and climatic zones, but the allocation of the resources should be disintegrated at the smaller level unit for operational ease. This may not be the case for farm level optimisation. The allocation of the resources at a smaller level unit can not be considered separately as the characteristics of each smaller level unit may be different (the carrying capacity of the canal network delivering water to the smaller level unit, conveyance losses and distribution losses besides soil and climatic variations) and the allocation to one smaller level unit may influence the allocation to another unit. Therefore the optimisation procedure for allocating the resources should include smaller level units. The review of the land and water allocation models (and for that matter all allocation models) indicated that mostly the allocation is done at top level (scheme level or farm level) i.e. they are of single field type and not multifield type. It is necessary to integrate the different crops, soils, climatic conditions, characteristics of different smaller units and canal networks for water delivery for optimum allocation of land and water resources, to make the allocation plan operative. The allocation models developed and reviewed in this chapter did not synthesis these components, though evaluation models did. The requirement of an allocation plan in water limiting condition and its use in operation of the scheme, therefore, shows the need for the development of the model in this study.

4. It is seen that the allocation models excepting those developed by Shyam et al., (1994) and Onta et al., (1995) only consider the issue of one performance parameter i.e. productivity. The other important performance parameter i.e. equity (see Chapter X) is

unnoticed. The models developed by Shyam et al., (1994) and Onta et al., (1995) are of land allocation type and equity consideration in the models is at distributory canal (branch of main canal) level and at headwork, respectively, but it also overlooks many dimensions of equity. Therefore there is a need to develop the procedure and model to integrate the productivity and equity parameters in the allocation process.

5. It is necessary to know the allocation plan which is stable or steady over the years to minimise the associated risks, and this need is recognised in many studies. The models which employed the technique of SDP considered the uncertainty in water availability or water demand or both. These models mostly fall in the category of water allocation model. The many land allocation models and land and water allocation models which depend on the LP technique to get a solution did not attempt to obtain stable allocation plans mainly due to difficulties associated with LP in representing the uncertainty in climatic and inflow parameters. However the models developed by Maji and Heady (1978) and Afshar et al., (1991) used chance-constrained LP to treat streamflow as probabilistic variable and by Martin et al., (1989) and Onta et al., (1995) obtained the steady allocation plan by analysing the allocation plans over the number of years for which data was available. The model to be developed as outlined in (3) and (4) also needs to be able to produce the steady allocation plans.

6. The development of a steady allocation plan should generally be sufficient for minimising the risks, when adopted in real time operation. However the risk minimisation is only brought about at the cost of losing certain optimality (or productivity). If the model is flexible to reschedule optimally the allocation plans in real time operation, or the allocation plan itself is produced with the optimum alternatives against the changing situations due to uncertainty in the parameters, a trade off can be achieved between minimisation in risk and loss of optimality. This is possible in water allocation models using the technique of SDP (the decision table obtained by SDP contains the information on future allocation of water by knowing the current status of the system). But the requirements for the development of the model as discussed in (1) to (3) limit the setting of the model to the land and water allocation type. The models developed in this category did not include the optimum allocation of the resources when the scheme is in actual operation. Thus there is need to include the method which accounts for this aspect in the development of the model for optimum allocation of land and water resources.

The above discussion opens the need for the development of irrigation water management models which are able to integrate the efficient utilisation of the resources in the scheme and the performance of the scheme for producing the steady optimum allocation plan, and adaptable to real time operation of the irrigation scheme. Therefore in this study the model is developed in this direction.

2.7 CONCLUSIONS

The following conclusions are drawn from the review of different irrigation water management models.

1. The classification of different irrigation management models developed for the allocation of the resources based on the resources to be optimised is useful in understanding the issues concerned with planning and operation of the irrigation scheme.

2. It is observed from the various studies reviewed that the need for allocation of both the resources optimally in a water limiting condition has been recognised, and many researches were carried out. However the difficulty observed in general was to consider the complexities involved in a heterogeneous irrigation scheme. These complexities are in representing soil-water-atmospheric subsystems and physical characteristics of the scheme. However in this study it is considered that it is possible to represent these complexities and develop a computer model for optimisation of both the resources in water limiting condition. This formed the basis of Hypotheses 1,2 and 3 and achieving Objectives 1,2 and 3.

3. In spite of the development of various irrigation water management models for planning and operation of irrigation schemes, opportunities still exist for improving the performance of an irrigation scheme by combining performance parameters while obtaining the allocation plans. In the present study it is considered that it is possible to obtain allocation plans by incorporating the different performance parameters. This formed the basis for Hypotheses 4 and 5 and achieving Objectives 4 and 5. Thus the development of the model in the present study is justified.

CHAPTER III

DEFICIT IRRIGATION WATER MANAGEMENT

Summary. In this chapter certain terms related to deficit irrigation and used in this study are described with the help of the general form of the water production function. The results of the studies conducted by several researchers on deficit irrigation are discussed. The findings led to the need and basis for the formulations of Hypotheses 1 and 2 and to study the deficit irrigation in relation to various parameters.

3.1 INTRODUCTION

In many parts of the world water resources are limited and less than required for various purposes. Agriculture has been the prime consumer of water. Still according to FAO (1977) estimates, irrigated agriculture represented only 13% of global arable land (Jensen, 1983). The fact that new development of water resources is taking place at a very slow pace due to economic and environmental reasons, while several competitors are emerging for nearly the same magnitude of water, is reducing the share of water for agricultural purposes (also see Chapter I). But the importance of irrigation for agriculture is already apparent from the fact that global irrigable land which was 13% of global arable land produced 34% of the total value of world agricultural production (Jensen, 1983). The similar results are also reported by FAO (1990) and Ayibotele (1992). The need of the day is, therefore, to utilise the available water as efficiently as possible to cater for the needs of the growing population. The inadequacy of available water supplies to irrigate the entire arable land presents two alternatives to irrigation planner.

(1) Irrigate a limited area so that maximum yields or net returns per hectare irrigated are obtained and

(2) Irrigate more land than what can be irrigated with option (1).

The first choice definitely gives maximum output per unit of land irrigated and the second could be followed to give maximum output per unit of water utilised. But it was unknown which of two would give maximum net returns from the farm or project. Thus the scarcity of water to irrigate the entire land resulted in attention to the option of underirrigation. This led to the management of water supplies as there was not only one rule for underirrigation but many alternatives (depending on how much more area should be brought under irrigation so that maximum food production or net returns can be obtained), and it was impossible to know precisely which level of water use would maximise profits. Realisation of advantages of underirrigation, therefore, prompted many researchers to use the functions representing the effect of underirrigation on crop yield, which ultimately is the most useful aid of irrigation water management i.e. water production functions (Hexam and Heady, 1978) and to work on the management of scarce water to produce maximum yield. This led to the start of a new branch of water management with limited water or deficit irrigation water management. English and Nuss (1982); Martin et al., (1984); Hargreaves and Samani (1984); English (1990); English et al., (1990); Martin et al., (1989)[b] and Trimmer (1990) worked conceptually while others (Hall and Butcher, 1968; Dudley et al., 1971[a]; Dudley and Burt, 1973; Palmer-Jones, 1977; Matanga and Marino, 1979; Kumar and Khepar, 1980; Tsakiris and Kiountouzis, 1984; Rao et al., 1986; Bernardo et al., 1988; Prasad and Mayya, 1989; Rao et al., 1990; Vedula and Mujumdar, 1992; Mannocchi and Mecarelli, 1994; and Akhand et al; 1995) presented the results of applications of deficit irrigation water management.

In this chapter the terminology related to deficit irrigation used in this study is described, with the help of the general form of the water production function. It is assumed that only land or water or both land and water can be limited resources. The other factors such as other inputs (seeds, fertiliser, insecticides, pesticides, power etc.), equipments, labourers and animals are considered to be available at optimum level and do not limit the crop production. The basis and formulation of Hypotheses 1 and 2 are discussed with some results of previous research on deficit irrigation.

3.2 GENERAL FORM OF THE WATER PRODUCTION FUNCTION

Actual ET is the parameter which is the most directly related to crop yield (Stewart and Hagan, 1973). The sources of water from which ET is derived at farm level are moisture from soil root zone, effective rainfall and irrigation water applied (IWA). These three together constitute total water applied (TWA). It is necessary to know the influence of ET and each one of these three sources of water on crop yield individually and jointly. This was discussed in detail by Stewart and Hagan (1973) for corn grown in Davis, California, USA. In this section, these are described in relation to the development of present model and how they are included in the model. Figure 3.1 also shows these relationships. Figure 3.1 is drawn with the help of results of the studies described below and from the similar figures reported by Stewart and Hagan (1973) and Stegman (1983)

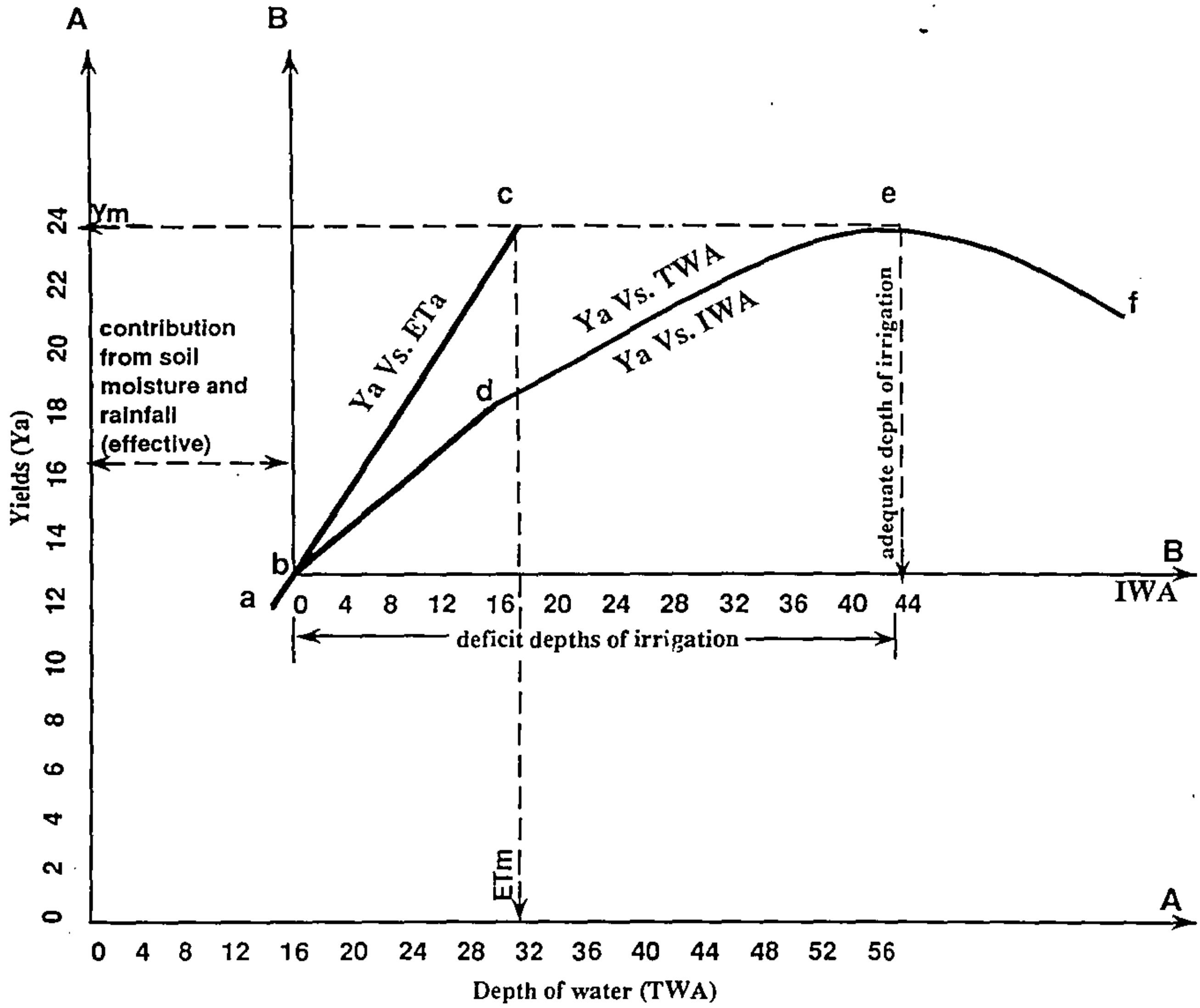


Fig. 3.1 Yield(Ya) versus ET/TWA/IWA (seasonal)

for the purpose of describing the terminology related to the adequate and deficit irrigations used in this study.

Actual evapotranspiration is a measure of water actually used by the soil and plant subsystems. (In this chapter 'evapotranspiration' is also used alternatively for actual evapotranspiration). These subsystems are described in Chapter V. Evapotranspiration involves transpiration by the plant of stored soil moisture and evaporation of moisture from the soil surface (Vaux Jr. and Pruitt, 1983). The evapotranspiration requirements are satisfied by available soil water in the root zone, the effective part of rainfall and the artificial application of water i.e. irrigation. The relationship between evapotranspiration (ETa) and crop yield (Ya) can be approximated as linear as pointed out by several researchers (Jensen, 1968; Stewart and Hagan, 1973 and Stegman, 1982). Vaux Jr. and Pruitt (1983:73), from the studies by Cuenca et al., (1978), Pruitt et al., (1980) and Stewart's water production function, concluded that

"*when the ET (evapotranspiration) deficit sequencing is optimal, the relationship between yield reduction and seasonal ET deficit is well represented by straight line*".

The curve abc in Figure 3.1 shows the Ya-ETa relationship. There is an upper bound to evapotranspiration which is the maximum evapotranspiration or ETm, and the corresponding yield at ETm is Ym.

The relationship between irrigation water applied (IWA) and yield is also important in this study as the model under consideration is aimed at deciding the quantity of irrigation water to be applied to different crops to obtain maximum total production or net returns (benefits). Unlike the Ya-ETa relationship, this function (Ya-IWA) is found to be nonlinear for many crops, as reported from the studies at various places (Stewart and Hagan, 1973; Hargreaves, 1975; Musick, et al., 1976; Barrett and Skogerboe, 1978 and Stegman, 1983). Citing the works of Musick and Dusek (1971) for grain sorghum, Shalhevet et al., (1981) for many crops and Singh and Mann (1979) for wheat, Vaux Jr. and Pruitt (1983) found the relationship between yield and applied irrigation water varied in form from a linear relationship under a low range of irrigation amounts to a convex relationship as Ym was approached. The curve bdef in Figure 3.1 shows the relationship between irrigation water applied and yield. The intercept on x-axis at point b indicates the water contributed from soil root zone and effective rainfall.

The relationship between total water applied (TWA) to the crop and crop yield is represented by curve abdef in Figure 3.1 (TWA includes water available from soil moisture present in the root zone at the time of planting, effective part of rainfall and irrigation water applied. Stewart and Hagan, 1973 called this as 'field water supply')

In this thesis, the allocation of land and water resources to the crops grown in different irrigation seasons is considered in the model and the allocation of resources during winter and summer seasons is considered in the case study. Some moisture is available in the root zone of the crops which are grown in the winter season following rainy season or which are grown in rainy season. Some extra water is expected in the root zone later in the season as a contribution from the rainfall (effective rainfall). Therefore in the winter season, even if no irrigation water is applied, crops get water to meet some of their evapotranspiration requirements and produce some yield (depending on the amount of water available from initial soil moisture and effective rainfall in relation to maximum evapotranspiration). According to Stewart and Hagan (1973) all available soil water in the root zone at the time of planting is converted to ETa and conversion of effective rainfall to ETa is also 100% (as rainfall contributing to soil moisture in the effective root zone is considered as the effective rainfall). Therefore the curves Y-ETa and Y-TWA are same if no irrigation water is applied. These are indicated by curve ab.

Water is added to the crop root zone in the form of irrigation, if contributions from initial soil moisture and effective rainfall are not sufficient to get the desired crop yield. All the irrigation water added to the root zone is converted to ETa (except for the water which is retained in the effective root zone at the time of harvesting) but all the water diverted from the source of water can not be added to the effective root zone. Therefore more water needs to be delivered from the source to provide the required amount of irrigation water to the root zone due to various losses (conveyance and distribution losses and field losses) associated with the process of adding water in the root zone. These losses are represented by irrigation efficiencies and are a function of various parameters including the amount of irrigation water to be applied itself. Thus the yield corresponding to a certain amount of TWA is less than the yield corresponding to the same amount of evapotranspiration. Therefore Ya-ETa and Ya-TWA curves start deviating from each other once TWA also contains the contribution from the irrigation water. According to Stewart and Hagan (1973), the two curves would be the same if irrigation efficiency were 100%. For the crops grown in the summer season little or no moisture is present in the root zone at the time of planting and no rainfall is expected to be received during the season. Therefore TWA is practically the same as the irrigation water applied. In this case the frame B starts form point a. The Ya-TWA and Ya-IWA curves are same and deviate from the Ya-ETa curve from the beginning.

As the present study deals with the management of the available water for irrigation, the behaviour of the Ya versus irrigation water applied (IWA) curve compared to Ya versus ETa curve (which estimates the yield obtained from that part of irrigation water applied which is converted to the ET) is important and is described in the following paragraph. This was also explained in detail by Stewart and Hagan (1973).

If the water losses were the same amount irrespective of the amount of irrigation water applied, the two curves (Ya-ETa and Ya-IWA) would be parallel to each other. But as the amount of irrigation water applied increases, the losses also increase. This is because more irrigations are required for more IWA and there are losses associated with each irrigation, or if two different irrigation amounts are applied in same number of irrigations, the deep percolation losses are more for the irrigations corresponding to more IWA. Citing Shearer (1978); Norum et al., (1979) and Peri et al., (1979), English (1990) found that deep percolation losses increased with applied irrigation water. Therefore the two curves depart further as Ym approaches. If the losses proportionally increase with IWA or irrigation efficiency is constant irrespective of IWA, Ya-IWA is also the straight line (like Ya-ETa curve) making an angle to the Ya-ETa line (according to Stewart and Hagan, 1973, this angle depends on the numerical constant value of irrigation efficiency). In practice however the losses do not increase proportionally to IWA, or irrigation efficiency is not constant with respect to IWA, but it (irrigation efficiency) decreases as ETm is approached. This is because when a small amount of water is applied it is almost used by the crops. This is evident from the fact that for small amount of IWA, there are fewer irrigations with a low depth of water application per irrigation and deep percolation losses may be minimal or even zero (there will be conveyance losses). When IWA approaches towards Ym, the deep percolation losses increase disproportional more. Another reason is that with small IWA, most of the soil moisture is extracted from the root zone before maturity however with large IWA, there are chances that some available water will remain in the root zone at the time of harvesting (which is not used by the crop for ETa). Therefore the Ya-IWA curve is nonlinear and more divergent from the Ya-ETa curve as it approaches Ym. The Ya-IWA curve is linear up to approximately 50% of the IWA which gives Ym (Doorenbos and Kassam, 1979; Hargreaves and Samani, 1984 and English, 1990) and later it becomes nonlinear with the slope of the curve decreasing. English (1990:400) described this

"In a word, the irrigation system will become less efficient as water use approaches full irrigation".

The linear part of the curve is indicated by segment bd and nonlinear part is represented by the segment de.

The Ya-IWA curve drops down when more water is applied than is required to achieve Ym (indicated by the segment ef). The reasons are reduced aeration in the root zone (water logging), leaching of nutrients, lodging and diseases associated with wet soils (Stegman et al., 1983). These are also described by English (1990).

It is seen from the above discussion that the water to be diverted from the source to obtain a particular quantity of crop yield depends on the water available in the root zone in the beginning of the crop season, the effective rainfall received during the crop season and the water lost while transporting it from the source to the root zone (represented by efficiency). In the present study the simulation model developed (Chapter V) is designed to consider all these aspects while estimating the crop yield in response to the delivery of a certain amount of water. In previously developed model, the efficiency was the neglected factor (except in some evaluation models). Mostly it was considered as a certain constant value irrespective of crop, soil, irrigation depth, number of irrigations and irrigation method. However the above discussion indicates that the efficiency is not only the important factor which decides the Ya-IWA relationship but also it is variable with the irrigation depth and the number of irrigations for particular crop, soil and irrigation method. In the present study, the appropriate consideration is given to the efficiency in accordance with Hypothesis 1 that the detailed processes can be modelled accurately in a computer program.

The concept used in the simulation model of this study is that the water diverted from the source after all the losses in its transportation, along with the effective part of rainfall, is stored in the root zone, where in there may be some water already available. The water available in the root zone is available for the process of evapotranspiration, on which crop yield depends.

In the present study, the water applied in excess of obtaining Ym is assumed not to be beneficial and therefore only the segment bde of IWA-Ya curve is important. In fact the model does not attempt to estimate the crop yield when water is applied in excess or whenever crop yield is to be estimated in response to excess water application, the adverse effects of excess water on crop production are not considered.

3.3 NET RETURNS AS A FUNCTION OF IRRIGATION WATER APPLIED

The irrigation depth which produces maximum yield does not necessarily give maximum net returns (NB) and thus the nature of the IWA-Ya and IWA-NB curves might be different. Though the main component of the net returns per unit area is the yield obtained, other factors also play a role such as price of the produce, and the costs associated with various operations which are affected by the variation in application of irrigation water. Hargreaves and Samani (1984) presented the detailed analysis of the economic consideration of the irrigation water when it is applied in different amounts. The Figure 3.2 (A) and Figure 3.2 (B) are reproduced from their analysis to show how net benefits and yields vary with applied water in different situations. In Figure 3.2 (A), maximum net benefits are obtained at nearly maximum yield. This is the situation for wheat under low rainfall and low water cost condition. In the case of alfalfa under the condition of high rainfall and high water cost (Figure 3.2 (B)), the maximum benefits occur for the amount of irrigation water applied in amount less than what is required to get Ym. Both the crops were irrigated by a sprinkler irrigation system.

According to English and Nuss (1982) and English et al., (1990), there are savings associated with low application of water such as in the cost of water, the cost of application of water through energy and labour saving, and less investment on the irrigation system itself (especially if the irrigation system is a pressurised irrigation system) and other associated costs (harvesting, transportation, storage, interest on operating capital and taxes). With low IWA there is a decrease in gross returns but at the same time the total cost also decreases. This fact and the nature of the Ya-IWA curve near Ym may result in less marginal increase in total cost than the marginal increase in total profit for the last few increments. Hence for certain situations the net benefits may be maximum when the yields are less than maximum in sprinkler irrigation system.

Under water limiting conditions English and Nuss (1982), Hargreaves and Samani (1984) and English et al., (1990) found higher net returns at an IWA which is less than the IWA giving Ym, mainly due to consideration of sprinkler irrigation systems in which many costs vary with the amount of water application (from investment of system to water application cost). But in a surface irrigation system, there may not be substantial saving in labour cost due to less application of water. Energy cost does not influence the economics in a gravity irrigation system. Therefore the costs which could reduce the total cost with less application of water are harvesting, transportation and storage and water costs. Some times the reduction in these costs may not be enough to compensate for the reduction in yield compared to irrigation to produce maximum yield. Therefore in a surface irrigation system the IWA which gives maximum yield might

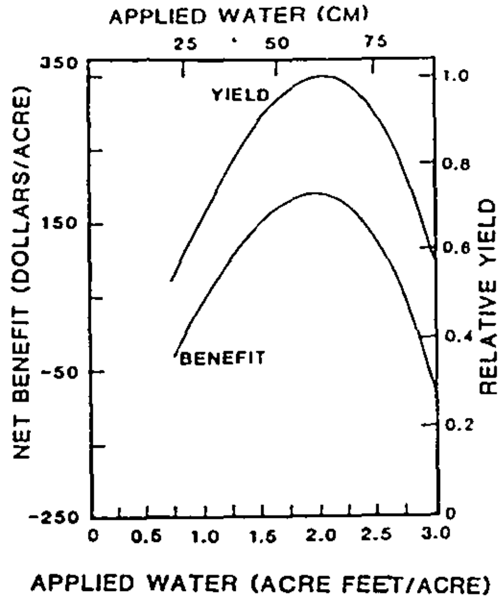


FIG. 1.—Comparison of Yields and Net Benefits at One Price Level for Wheat with 4 In. (102 mm) Effective Rain

Figure 3.2 (A) Comparison of yield and net benefits for wheat (Source: Hargreaves and Samani, 1984)

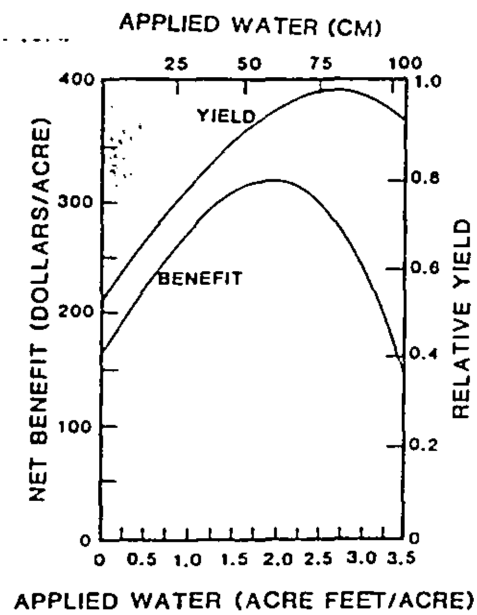


FIG. 2.—Comparison of Yields and Net Benefits at One Price Level for Alfalfa Hay with 26 In. (660 mm) Effective Rain

Figure 3.2 (A) Comparison of yield and net benefits for alfalfa (Source: Hargreaves and Samani, 1984) give maximum net returns also. There is not much research published on this aspect, but Hargreaves and Samani (1984:350) rightly pointed that

"irrigating for maximum yield is more likely to produce maximum benefit when
1)land is limited and water is abundant
2)crop value and yields are high
3)rainfall makes little contribution to the crop water supply
4)the irrigation costs are low".

In short there are several factors associated with the nature of NB-IWA function.

In the present study, the costs are divided in to area, yield and water application dependent costs (Chapter V) to consider the contribution of individual elements of cost in computing total cost. Therefore it is possible to estimate the net returns appropriately in response to application of different amounts of water.

3.4 DEFINITIONS

The discussion presented in Sections 3.2 and 3.3 is limited to the irrigation water supplied over the entire irrigation season. Its distribution to different irrigations over the irrigation season is assumed to be optimal. This section describes the terms related to individual irrigation and their relations.

1. Irrigation interval (I) : It is the interval between two successive turns of irrigations.
2. Water deliver interval (WDI) : It is the interval between two successive applications of water.

Thus the water delivery interval is equal to the irrigation interval or the sum of successive irrigation intervals when an intermediate irrigation is skipped. When the irrigation interval is constant throughout the irrigation season, the water delivery interval is a multiple of the irrigation interval.

3. The depth of application : In this study the depth of application is used in relation to the amount of water stored in the soil root zone. The amount of water to be stored in the soil root zone to bring the soil water in the root zone to field capacity is known as depth of application requirement and the depth of water actually stored in the root zone is known as the depth of application.

4. The depth of irrigation : The depth of irrigation is used in relation the amount of water to be delivered to the farm so that the required depth of application is stored in the

root zone. If the method of water application is surface, the irrigation depth can be applied within certain limits depending on soils, field channel capacity, crop and its growth stage. Thus the depth of application and the depth of irrigation are related by equation (3.1)

$$ID_i = \min\left[\max\left\{\left(Da_i / \eta_{a_i}\right), ID\min\right\}, ID\max\right] \qquad (3.1)$$

where

IDi_i	=	the depth of irrigation at i^{th} irrigation
Da_i	=	the depth of application at i^{th} irrigation
IDmax	=	the maximum possible depth of irrigation
IDmin	=	the minimum possible depth of irrigation
ηa_i	=	the application efficiency at i^{th} irrigation

If these depths are specified over the irrigation season, then these are termed as the seasonal depth of application, seasonal depth of application requirement and seasonal depth of irrigation.

Depending on whether the irrigations are supplied to fill the root zone completely or partially, two irrigation (or application) depths are specified. These are

1. Full depth of irrigation (or application) : The full depth of irrigation (or application) is the one which brings the soil moisture in the root zone to field capacity.

The irrigation practice of applying full depth of irrigation (or application) for all the irrigations over the entire irrigation season is termed as the '**full irrigation**'. It is also referred as "full depth irrigation" in this study.

2. Partial depth of irrigation (or application) : The depth of irrigation (or application) which does not bring the soil moisture to the field capacity is known as the partial depth of irrigation (or application)

The irrigation practice of applying partial depth of irrigation (or application) for at least one irrigation during the irrigation season is known as the '**partial irrigation**'

Full and partial irrigations may or may not produce maximum crop yield depending on the water delivery interval. If the water delivery interval is small, partial irrigation may produce maximum crop yield and if the water delivery interval is large full irrigation also may not produce maximum crop yield. The similar thing is true about irrigation interval as irrigation interval governs the water delivery interval.

The practice of applying water in the amounts (partial or full irrigation) and at the intervals such that no stress is caused to the crop, and maximum crop yields are obtained, is known as '**adequate irrigation**'. The seasonal depth of irrigation corresponding to adequate irrigation is known as the seasonal depth of adequate irrigation.

The practice of applying water in the amounts and at the intervals such that crop is subjected to stress during certain days in the crop growth period, resulting in reduction in crop yields, is known as '**deficit irrigation**'. The seasonal depth of irrigation corresponding to the deficit irrigation is known as the seasonal depth of deficit irrigation. English and Nuss (1982) and Trimmer (1990) defined the deficit irrigation as the practice of applying deficit depth of irrigation or underwatering.

As the water can be applied in the combinations of several depths and intervals, adequate and deficit irrigation can occur in various ways. In deficit irrigation, there can be several variations due to the different levels and ways of causing stress and thus reduction in crop yield. Therefore it is important to know the levels of adequate irrigation and deficit irrigation (seasonal depths) which are optimum (in case of deficit irrigation optimality may be for different levels of crop yield reduction or alternatively the seasonal depth should be optimum meaning that the irrigation depths and water delivery intervals for this particular seasonal irrigation depth should cause minimum reduction in crop yields).

In the Figure 3.1 the irrigation water applied corresponding to point e is the seasonal depth of adequate irrigation. In adequate irrigation the soil root zone is supplied with water in an amount and time such that plant is never short of water to meet its ETm and thus not subjected to any stress. Therefore the yields are not reduced (Hall and Butcher, 1968; English and Nuss, 1982 and Trimmer, 1990)

In Figure 3.1 the irrigation water applied at all points on the curve bde (except at point e) are the seasonal depths of deficit irrigation. When water is applied in an amount less than required for adequate irrigation, the moisture in the soil root zone drops below the allowable depletion level and the crops are subjected to the stress. The result of stress is a reduction of crop yields (Hall and Butcher, 1968; English and Nuss, 1982 and Trimmer, 1990)

Optimal depth of irrigation (seasonal): It is the seasonal depth of irrigation at which the net returns per unit area are maximum when water is not short in supply (Martin et al., 1989[b]).

Optimal depth of irrigation may be full depth of irrigation or deficit depth of irrigation.

The different depths of irrigation are described below in the context of unlimited water supply and limited water supply.

3.4.1 Unlimited Water Supply

The general trend when water is not scarce and does not have a high cost compared to the crop value should be to adequate depth of irrigation, so as to obtain maximum yield per unit area and also from the farm or project (Martin et al., 1989[b]), but when the objective is based on the economic criteria this is not applicable. Citing theoretical economic analysis as presented by James and Lee (1971), Hargreaves and Samani (1984:349) wrote

"if the price of irrigation water exceeds zero, irrigation water application should be reduced below the point of maximum yield inorder to increase profit".

According to English (1990), if land is limiting, the optimum irrigation strategy would be to apply that amount of water which would maximise the net income derived from each unit of land i.e. to apply optimum depth of irrigation.

3.4.2 Limited Water Supply

Under the finite supplies of water many researchers found applying less water than what is required for maximum yield is beneficial. These are summarised below (see Section 3.6).

English and Nuss (1982) found the water saved through deficit irrigation of the field could be used to put additional land into production, as according to them the increased area would compensate for the reduced yield per acre and increase total crop production. Hargreaves and Samani (1984) found total benefits increased if the available water was spread over an increasing land area when water supply was limited. Martin et al., (1989)[b] stated that when water supply was inadequate to irrigate the entire area with the net returns maximising depth (optimal depth of irrigation), either the irrigated area or the depth applied, or both, must be decreased. Citing English and Orlab (1984), English (1990:402) explicitly pointed out

"*when the amount of land under irrigation is constrained by a limited water supply, the economic returns to water will be maximised by reducing the depth of water applied and increasing the area of land under irrigation until, the marginal profit per hectare multiplied by the number of hectares irrigated just equals the total profit per hectare*".

Trimmer (1990) pointed that with limited water, the water saved through 'partial irrigation' (deficit irrigation) could be applied to other land where the incremental increase in yield was large. According to English et al., (1990) deficit irrigation has been a profitable long term strategy for those farmers who had limited water supplies (example is from Columbia Basin, USA). Alizadeh (1993) stated that more area could be cultivated by the amount of water which was saved due to deficit irrigation and therefore total benefits from the farm might increase.

Thus when water is limited the deficit irrigation may prove beneficial in both the surface irrigation system and pressurised irrigation system. In surface irrigation systems, the deficit irrigation may be beneficial due to additional net benefits obtained by spreading the saved water over an additional area while in pressurised irrigation systems additional factors described under Section 3.3 may also make deficit irrigation beneficial.

It is important to know the depth of deficit irrigation which is beneficial. For a single crop (and soil type) it may be the depth giving maximum net returns or yields per unit of water applied (depending on the objective). But when many crops (and soil types) are involved in the scheme, the deficit irrigation depth which gives the maximum net return or maximum yield per unit of water for the individual crop might not be the most beneficial depth, as the reduction or increase in water applied to one crop affects the water availability of other crops.

Optimal deficit depth of irrigation (seasonal): It is the depth of deficit or adequate irrigation (seasonal), for a certain crop, which leads to maximum net returns from the entire scheme with many crops and soils.

This depth is not constant for a particular crop but varies with the other crops to be irrigated in the project and the soil types. In single crop and homogeneous soil conditions when water is limiting, the deficit irrigation depth giving the maximum net returns from the scheme is the seasonal optimum deficit depth of irrigation. In water unlimiting condition the optimal deficit depth of irrigation may be equivalent to adequate depth of irrigation or optimal depth of irrigation. But in heterogeneous irrigation scheme, there is a need to model the response of different crops grown on different soils together to the limited water supply to know the optimum deficit depth of irrigation.

While some deficit in the irrigation depth may prove significant, and as water application is not just one time process but the crop responds differently to different amounts of water in different growth stages (Jensen, 1968; Stewart et al., 1974; Hargreaves and Samani, 1984 and Doorenbos and Kassam, 1986), the optimum spreading of limited water or deficit over a crop's growth stages becomes important. This is also strengthened by the fact that for the same amount of limited water applied to the crop over the season, different yields may be obtained due to different amounts of application during various crop growth stages (Stewart et al., 1974). Hargreaves and Samani (1984:351) also concluded

"*large differences in yield can be produced with the same water deficit due to differences in the sequencing of water stresses or deficits. Stress during a critical growth period (usually flowering, fruit setting, or grain formation stage) has a significantly larger influence on yield reduction than a deficit in other growth stages*".

The water allocation models based on the technique of dynamic programming utilise the same concept.

The seasonal depth of irrigation defined above is based on the optimum distribution of deficit over all the irrigations occurring in a crop season. However, associated with a given seasonal depth of deficit irrigation, there are many depths of irrigation for every irrigation in the crop season.

It is concluded from the considerations in this section that

(1)From the definitions of deficit irrigation given in Section 3.4 and by English and Nuss (1982) and Trimmer (1990), deficit irrigation is practised by underwatering the crop (due to failure to provide ETm)
(2)The generalised form of water production function indicates the deficit irrigation results in reduction of yield per unit area through the water stress to crop
(3)The discussion in Section 3.4.1 and 3.4.2 leads to the fact that deficit irrigation may result in higher returns than adequate irrigation when water is not limited and may give more yield and net returns when water is limited.

(4)From the stagewise water production functions (Jensen, 1968; Stewart et al., 1974; Hargreaves and Samani, 1984 and Doorenbos and Kassam, 1986), deficit irrigation should not be considered only in terms of 'underwatering' or 'applying the stress to crop' but also by the way in which the deficit is exerted .

3.5 METHODS OF APPLYING DEFICIT

Crop is subjected to stress by deficit irrigation. Hypothesis 1 states the means to cause deficit irrigation in the irrigation scheme. These are described in this section by formulating following three approaches.

(1)Approach-1 : Prolonging the interval between two applications of water beyond the interval which does not cause any stress to the crop if the soil root zone is filled up to field capacity, and then applying water to bring soil moisture in the root zone to field capacity. The crop is subjected to stress at the end of each irrigation period (English and Nuss, 1982). The full irrigation with large irrigation interval is the case of Approach-1.

(2)Approach-2 : Applying water less than the amount required to bring the soil moisture in the root zone to field capacity (Jensen et al., 1971 and Martin et al., 1989[b]), with an irrigation interval which would not cause any stress if the root zone was filled up to field capacity. The partial irrigation with a small irrigation interval is the case of Approach-2.

(3)Approach-3 : Combinations of (1) and (2) i.e. by prolonging the irrigation interval beyond the one which does not cause any stress when at each irrigation the soil root zone is filled to its field capacity, and applying water less than required to bring the soil root zone to field capacity. The partial irrigation with a large irrigation interval is the case of Approach-3.

Practising only (1) can result in a long period of 'no stress' followed by a long period of 'stress' and thus soil moisture will fluctuate within a wider range as full irrigations are applied at longer intervals. But practising (2) may result in a short period of 'no stress' followed by a short period of 'stress'. As the amount of water applied per irrigation is not adequate, soil moisture will fall to a level at which the crop will experience the stress quickly but as the next application is also applied before the crop is subjected to more stress, crop is exposed to moderate stress more or less continuously. Several combinations of period of stress and no stress can be obtained by practising (3). Various ranges of soil moisture fluctuation can be possible. If timing of water application is flexible (i.e. in an irrigation scheme with water delivery on demand or a ground water irrigated farm) and small irrigation depth and small irrigation interval are possible (sprinkler irrigation system), numerous combinations of deficit irrigation may result even for single crop. These combinations are more limited with surface irrigation method and water delivery through rotational water supply with a predecided uniform irrigation interval throughout the crop season, as in such situation the smaller irrigation depths are not feasible and shorter irrigation intervals are not possible. Shorter irrigation intervals may make the distribution system continuous rather than rotational (Bhirud et al., 1990).

The present study assumes the irrigation interval as uniform for all crops, soils and climatic conditions and predecided throughout the crop season. The assumption is valid for the HIS with rotational water supply. However the water delivery interval for different crops, soils and climatic conditions can be varied. In the case study, the irrigation interval was assumed uniform over the subseason. This is generally the practice which is followed in the irrigation commands to make the distribution schedule adaptable to the farmers (Tsakiris and Kiountouzis, 1984 and Vedula and Mujumdar, 1992). However water delivery interval is varied. This study then evaluates the influence of all three approaches of practising the deficit irrigation on crop yield and irrigation depth. This eventually led to the proposal of "variable depth irrigation" which is included in the model (Chapter V) and compared with full depth irrigation and fixed depth irrigation (applying water in same depth at ever irrigation and to different crops grown on different type of soils and in different climatic conditions) in Chapter VIII.

3.6 SOME RESULTS OF DEFICIT IRRIGATION

In this section the results obtained by some researchers by adopting the deficit irrigation are elaborated. These are also summarised in Table 3.1.

Barrett and Skogerboe (1980) concluded with the help of a model, that in a water short area the optimal irrigation policy should be to apply water close to the amount of water giving maximum yield for areas with higher irrigation application efficiencies, and less water should be applied for areas with low irrigation efficiency.

English and Nuss (1982) investigated the merits of deficit irrigation for a farm in eastern Oregon, USA. Two distinctly different irrigation systems were designed: one for full irrigation and the other for deficit irrigation for a farm of 37 hectare with the supply of 3000 lit/min for irrigating wheat. In full irrigation 58 mm gross water was applied every six days to prevent the moisture content in the soil falling below 50% of available soil moisture so that crop was not subjected to stress and there was no reduction in yield. In deficit irrigation 80 mm of water was applied every 12 days so that the crop was subjected to water stress (an example of Approach 3). Full irrigation required 815 mm of water and deficit irrigation 502 mm of water. The costs and performance of these systems were compared and it was found that deficit irrigation gave 2% more net return over full irrigation. As the irrigation system under consideration was sprinkler, the increase in the net return by deficit irrigation was mainly due to reduction in production cost partly attributable to reduced water use and lower yields (other factors are described by the authors), as the gross income was more in the case of full irrigation. However water saved through deficit irrigation of 37 hectares could be used to put additional land into production. It was estimated that the irrigated area could be increased from 37 hectare to 58 hectare and net farm income would therefore increase by 42%. The authors finally concluded that particularly in the circumstances of constrained resources, deficit irrigation could offer significant benefits. Though in this study the benefits to be realised from deficit irrigation were largely dependent on system design which in surface irrigation may not be the case, the water saved through deficit irrigation which could be used to put more area under irrigation may prove significant in surface irrigation. There was no consideration of risk in the analysis and according to the authors the uncertainty of crop model predictions, rainfall and other factors might alter the conclusion.

Kundu et al., (1982) evaluated the effect upon yield of applying irrigation water for each irrigation event in amounts such that it replenishes only a fraction of total depletion, once the optimum total allowable water (TAW) depletion level was known with the help of CORNGRO model (Childs et al., 1977 and Kundu, 1981) for Grand Junction, Colorado and Davis, California, USA. Each replenishment level consisted of irrigating the desired (10, 20, 30, 40, 50 and 60) % of the TAW after 40% of TAW was depleted below field capacity (therefore 40% replenishment level corresponded to field capacity at the completion of an irrigation event, 50 and 60% represented over irrigation and 10,20 and 30% represented under irrigation). As irrigations were based on the 40% depletion of TAW, lower replenishment levels required more irrigations (frequent irrigation) and vice versa. They found that yields were reduced and water use efficiencies were increased with decrease in replenishment levels. Thus their results indicate that the partial irrigation when coupled with frequent application results in more yield (and also less water use efficiency) but they did not comment on partial irrigation at fixed interval of time.

Stegman (1983) pointed that when water was limited compared to available land, with small depth of irrigation it was possible to bring more area under irrigation. At the same time however it increased the total cost of cultivation and did not produce sufficient yield to make it beneficial over the application of depth giving 'near maximum yield' (full irrigation depth or less or more than full irrigation depth). He further found from their studies that water supplies, whether limited or not, were frequently best managed by a goal of 'near maximum yield' attainment, particularly for relatively high application efficiency. His findings are contradictory to the findings of others but indicative of the need for investigation of deficit irrigation based on the economic criteria. His findings also emphasise the need to give due consideration to the irrigation efficiency.

Tsakiris and Kiountouzis (1984) formulated a deterministic dynamic programming model and applied it to the conditions prevailing in Greece for sorghum grown in sandy clay loam irrigated every 15 days under rotational delivery of irrigation water. They found that if 30% less water than what was required to satisfy all the irrigation needs was applied, 13.7% losses of yield were experienced. However 30% of water could be used to irrigate additional area under water limiting condition and the yield reduction due to deficit irrigation might be compensated for by the additional yields from the additional area.

Hargreaves and Samani (1984) found that deficit irrigation was beneficial even when water was unlimited and land was limited under condition of high water application cost and heavy rainfall from their simulation studies on alfalfa grown in North Coastal region of California, USA. However it was also shown that maximum net benefits for alfalfa could be made to more nearly coincide with maximum yield (per unit area) by reducing cost of irrigation, by increasing the selling prices or by improving other management practices. Maximum benefit was obtained for wheat from the data of San Joaquin Valley, California, USA where irrigation cost was low and effective rainfall was low when maximum yield (per unit area) was obtained i.e. by irrigating the crops to their potential demand. Thus when water is limited, the deficit irrigation may or may not be beneficial. They compared 'limited water' and 'unlimited water' conditions, when certain amount of water was available, by varying the depth of water to be applied for wheat in San Joaquin Valley. In limited water condition, the total amount of water was kept constant and the area irrigated was increased as less water per unit area was applied. In unlimited water condition the area was held constant and the application rate or depth was varied (thus varying the total amount of water applied also) . They studied two price levels. Generally in water limiting condition more or equivalent benefits were obtained than in water unlimiting condition for most of the time when crop price was high and effective rainfall contribution was low. However when crop prices were lowered, the net benefits were more in water limiting condition only at higher depths. Thus the benefits derived from both the conditions were price sensitive. In water limiting condition the highest benefits were obtained when irrigated below the irrigation level giving maximum yield. According to them (p. 356)

"Deficit irrigation can produce significant benefits under favourable circumstances. These benefits depend upon the interactions of several factors including the management of fertility, rainfall, crop selection, crop value, water costs etc."
and presumably the degree of deficit.

Rao et al., (1986) formulated a linear programming model for the maximisation of the net returns by considering the effect of different water levels on the yield of crop and applied it to Araniar irrigation project, Andhra Pradesh, India for allocating area and water under rice, groundnut and finger millet. Though the formulation did not consider the different optimal levels in optimal way, nor the sequencing of water deficit, it was interesting to note under water limiting condition the irrigation water levels giving lower yield appeared in the solution for all the crops indicating irrigating at below optimum level increased area under irrigation and was more beneficial than irrigating at water level giving maximum yield per unit area.

For a farm grown with four crops (dry bean, grain corn, wheat and alfalfa) in Columbia river basin, Washington state, USA on the homogeneous deep sandy loam soil and for the condition of unlimited water supply, Bernardo et al., (1988) found that the irrigated schedules selected as optimal were high water use schedules that resulted in crop yields approaching the maximum attainable. With the reduction in water supply from unlimited to 40% of that need with unlimited case, the area to be irrigated was total farm area (210 ha). 55% of reduction in water supply caused the drop in area to be irrigated to 192 hectares. Net returns decreased with reduction in total water supply. Farm level water supply reductions of 40% translated to about only 10% decrease in economic return.

According to Martin et al., (1989)[b] it is more difficult to manage a water supply that is inadequate than to produce the maximum yield on the irrigable area as several other factors (other than water deficit) also play a role. They found that maximum irrigation requirements, crop value and production costs and crop yields affected the optimal depth of deficit irrigation. They elaborated (p. 75)

"The optimal irrigation depth relative to that required for maximum yield decreases as the efficiency of irrigation decreases. Even though the optimal relative depth decreases, the actual depth may be nearly the same as for more efficient systems since the gross irrigation requirement is larger for inefficient systems. Barrett and Skogerboe (1980) concluded that, because of this compensation, there is a narrow range of optimal irrigation depths regardless of the efficiency of the irrigation system. Yet others generally recommend spreading the available water over the entire irrigable area (Stewart and Hagan, 1973)".

The results of Martin et al., (1989:75)[b] showed

"there are situations where the water should be spread over the total irrigable area and others where a small area should be irrigated".

Prasad and Mayya (1989) found by subjecting the crops to deficit (applying 20 % less water than its potential demand) during initial crop growth period increased the area under irrigation and net benefits than full irrigation.

Bhirud et al. (1990) studied the crop evapotranspiration and yield relationship with their crop-growth simulation model for wheat and cotton crops for a period of 17 crop seasons (1971-87) for on-demand and rotational schedules. The depth of water applied per irrigation was the one which brought the soil moisture to field capacity. On demand and rotational schedules of two, three, four, five and six weeks were equivalent to degree of deficit of 1, 0.92, 0.8, 0.7, 0.65 and 0.58, respectively for wheat. Thus degree of deficit was more with the longer intervals. The comparison of two and three week rotation schedules with on demand showed that it would be possible to obtain 91.5% and 78.3% of potential yield respectively and result in water saving of 20 and 40% respectively. Water use efficiency increased with the rotation period and was minimum for on demand schedule. Cotton crop also showed the similar results with different magnitude. Results of this study indicates that though the yield per unit area is more with no deficit or low deficit, it is possible to increase area under irrigation and total production with higher deficits.

English (1990) presented an analytical framework for dealing with deficit irrigation and illustrated with a case study involving a farm in the Columbia Basin of USA that has been practising deficit irrigation for some years. The optimum levels of water use (the level at which the returns to water are maximised) were found to be relatively low and the profitable deficit range (the range between the level of water at which the yield was maximised and the level at which the returns to water was maximised) was rather wide suggesting that the decision to underirrigate in these particular circumstances was potentially profitable and reasonably safe.

English et al., (1990) illustrated the concepts developed by English (1990) with data from nine co-operating farms in Columbia Basin of USA. They observed irrigation practices during 1984-86 seasons. Seven of the farms were deliberately practising deficit irrigation, motivated by a shortage of water. Some of the farms were irrigating frequently with light applications of water while others were irrigating infrequently with large applications. In some cases the farms were limiting their operations primarily to wheat while others were using deficit irrigation of wheat in rotation with full irrigation of other crops. The farms practising deficit irrigation recorded deficits on the order of 30 to 70% of the nominal water requirement. They found that the costs of production declined significantly under deficit irrigation (method of irrigation was sprinkler) and average wheat yields per unit of applied water were substantially higher for the deficit irrigated fields than for the fully irrigated fields. A comparison was made between net incomes for six farms that were raising both wheat and potatoes in rotation. Four of the six farms were underirrigating the wheat while the other two were fully irrigating the wheat. All six were fully irrigating the potatoes. Estimated net income for the years 1977-1986 indicated that the net returns to land under deficit irrigation would have been 25% less than for the fully irrigated fields and net returns to water would have been 14.5% greater under deficit irrigation. They concluded from these results that deficit irrigation has been a profitable long term strategy for those farms which has the limited water supplies. However they found that the amounts of water applied to those fields were non optimal as the returns to land were low for the deficit irrigated fields.

Steiner and Walter (1992) studied the effect of allocation and scheduling rules on equity and productivity in irrigation schemes with the help of the Irrigation Land Management (ILM) model (Keller, 1987[a]; Steiner, 1991 and Steiner and Keller, 1992) for a section of 63 fields having silt loam soil of the Bear river system, USA. They found that production differed when the fields were irrigated by different allocation rules in water short condition(with the same amount of water for each allocation rule). They tested the allocation rules viz. shortage was equally shared among all the fields and the fields at the head of the system received all their demand, with water availability equivalent to 75% of requirement calculated with 14 days irrigation interval and moisture content in the root zone reaching to field capacity with each irrigation. They found that when the shortage was equally spread the overall production was more than when the fields at the head were supplied with their potential demand. This indicates with deficit irrigation it

Table 3.1 Results obtained by some researchers by adopting the deficit irrigation and comparing with full irrigation.

Sr. No.	Researchers and year of study	Place of study	crops	Main findings
1	Barrett and Skogerboe (1980)	Colorado, USA	maize	When water is limiting,, applying water close to the amount of water giving maximum yield is beneficial for areas with higher application efficiency whereas opposite (deficit irrigation) is true for areas with low irrigation efficiency.
2	English and Nuss (1982)	Oregon, USA	wheat	Deficit irrigation gave 42% more net returns over full irrigation. (as the irrigation method was sprinkler, there was saving in energy cost also in deficit irrigation).
3	Kundu et al., (1982)	Colorado, USA	corn	partial irrigation coupled with frequent irrigations resulted in more benefits
4	Stegman (1983)	North Dakota, USA	corn	With high irrigation efficiency, the water supply is best managed by a goal of "near maximum yield" attainment whether water supply is limited or not.
5	Tsakiris and Kiountouzis (1984)	Greece	Sorghum	The yield reduction due to deficit irrigation (13.7% loss in yield if 30% less water is applied) might be compensated for by the additional production by irrigating additional area.
6	Hargreaves and Samani (1984)	California, USA	alfalfa and wheat	Deficit irrigation can produce significant benefits under favourable circumstances related to crop selection, fertility, rainfall, crop value and water cost.
7	Rao et al., (1986)	Andhra Pradesh, India	rice, groundnut and finger millet	Irrigating at below optimum level increased area under irrigation and was more beneficial than irrigating at water level giving maximum yield per unit area.
8	Bernardo et al., (1988)	Washington, USA	dry bean, grain corn, wheat and alfalfa	Farm level water supply reductions of 40% translated to about only 10% decrease in economic return.
9	Martin et al., (1989[b])	various locations in USA	corn and sorghum	They found that there are some situations where the water should be spread over the total irrigable area and others where a small area should be irrigated.
10	Prasad and Mayya (1989)	Karnataka, India	rice, finger millet, maize, wheat, sorghum, oilseeds and pulses	Subjecting the crops to deficit irrigation (applying 20% less water than their potential demand) during initial crop growth period increased the area under irrigation and net benefits than full irrigation.
11	Bhirud et al., (1990)	India	wheat and cotton	Though the yield per unit area is more with no deficit or low deficit, it is possible to increase area under irrigation and total production with

				higher deficits.
12	English (1990)	Columbia Basin , USA	wheat	Decision to underirrigate was potentially profitable and reasonably safe.
13	English et al., (1990)	Columbia Basin, USA	wheat and potato	Deficit irrigation has been a profitable long term strategy for those farms which have limited water supplies
14	Steiner and Walter (1992)	Bear River System, Utah, USA	corn, sugar beet and spring barley	With deficit irrigation it is possible to increase overall production by bringing more area under irrigation. Irrigation efficiency may shift the benefits from deficit to full irrigation, depending on other factors.
15	Alizadeh (1993)	Khorassan Province, Iran	sugar beet	With deficit irrigation, area under cultivation increased by 33% and net benefits increased by 3%.
16	Mannocchi and Mecarelli (1994)	Upper Tiber Valley, Italy	wheat, sunflower and maize	maximum profit was not attained by cultivating just a few hectares of maize and supplying irrigation to its maximum crop water requirement, but rather, by cultivating a larger area in conditions of deficit irrigation

is possible to increase overall production by bringing more area under irrigation. However the authors cautioned that this was a case when overall irrigation efficiency was high (about 85%) and soil type of the fields was silt loam. But with low irrigation efficiency, too much water would be lost in non irrigation purposes in irrigating more area and may give less overall production than full irrigation.

Alizadeh (1993) studied the effect of deficit irrigation on sugar beet yield and the net benefits of farm in arid region of Khorassan Province, Iran and found that with deficit irrigation, area under cultivation increased by 33% and net benefits increased by 3%. Mannocchi and Mecarelli (1994) found for maize grown in a farm in Upper Tiber Valley, Italy, that maximum profit was not attained by cultivating just a few hectares of maize and supplying irrigation to its maximum crop water requirement, but rather, by cultivating a larger area in conditions of deficit irrigation.

3.7 CONCLUSIONS

In this chapter the concepts of deficit irrigation water management along with some results by practising deficit irrigation were reviewed and discussed. The following conclusion are drawn in view of incorporating those into the present study.

(1)As practising the deficit irrigation may prove significant when water supplies are limited (Section 3.4.2 and 3.6), the means to develop deficit irrigation which could be incorporated in the model need to be investigated. The concept of deficit irrigation should be incorporated into area and water allocation models for the deficit irrigation water management in view of its possible advantage over the adequate irrigation.

(2)The effect of deficit irrigation was studied by many researchers by considering the single crop (see Section 3.6). However in many irrigation schemes, mostly multi-crop situation exists. Similarly deficit irrigation directly influences the soil moisture status and thus variation of soil type in the scheme also needs to be included while studying the deficit irrigation on command area basis. Therefore the attempts are required to study the deficit irrigation in relation to multi-crop and heterogeneous soils. This stresses the need to include the detailed process involved in the crop, soil and air subsystems in the model incorporated with the deficit irrigation.

(1) and (2) led to the formulation of Hypotheses 1 and 2.

(3)Deficit irrigation is not only the function of water availability and yield obtained but type of crop, rainfall and irrigation efficiency are another important parameters which might affect deficit irrigation water management policy. This emphasises the need of studying deficit irrigation water management by varying some of these parameters.

(4)Almost all the studies in relation to deficit irrigation were deterministic in nature. However the deficit irrigation involves the risk factor (English and Nuss, 1982 and Hargreaves and Samani, 1984). Therefore uncertainty in weather parameters deciding the water availability and water consumption need to be considered while making the decisions related to deficit irrigation water management.

CHAPTER IV

AREA AND WATER ALLOCATION MODEL (AWAM)
1. OVERVIEW

Summary. A method developed for planning and operation of irrigation schemes in semi-arid regions, based on hypotheses formulated and discussed in Chapters I, II and III, is presented by formulating a model, Area and Water Allocation Model (AWAM). This chapter describes certain terms used in the development of model and model as a whole. The details of different aspects involved in the development of AWAM are discussed in subsequent chapters (Chapter V to Chapter X)

4.1 IRRIGATION SCHEME

Irrigation schemes in semi-arid regions are characterised by varying climates, the existence of different types of soils, the possibility of growing multiple crops and the scarcity of water. The command area of such irrigation schemes is usually large involving a complex network of water delivery system. Such types of irrigation schemes in this study are referred as "Heterogeneous Irrigation Schemes" (HIS). The AWAM is formulated to be suitable for HIS under rotational water supply. In rotational water supply, the water is delivered from the source to the different fields at predetermined intervals, irrespective of the crop grown in the field, type of soil and climate. In AWAM also the water deliveries are assumed to follow this pattern. Therefore AWAM is not suitable for on demand type irrigation schemes, where in water is available to a farm at any time and thus the interval between deliveries to different fields may vary (Sagardoy et al., 1982). Soil moisture percentage, accumulated actual ET since previous irrigation , soil moisture depletion etc. (Bernardo et al., 1988) may influence the time of irrigation in on demand type irrigation scheme as against preset or fixed and uniform (to all crops grown on different soils) time of irrigation in rotational water supply (Sagardoy et al., 1982 and Shanan, 1992). However AWAM takes care of detailed response of soil, plant and atmospheric subsystems by varying the irrigation depth (from zero to maximum permissible) at every irrigation.

4.2 RESOURCES

The major output to be obtained from the irrigation scheme is the produce or benefits generated from the cultivation and irrigation of different crops. The inputs required to generate the output are land, water, labour, machinery, fertilisers, seeds, pesticides etc. All these inputs influence the crop yield. In the present model major emphasis is given to the allocation of land and water resources to different crops. The influence of the application of different quantities of water at different time on crop yields and net benefits, and the allocation of different quantities of water on different land area are considered, while assuming that the other inputs do not limit the production per unit area. However the total area to be irrigated under different crops can be limited by the availability of total quantity of these inputs and this is considered in AWAM.

4.3 PLANNING AND MANAGEMENT UNIT

As the irrigation scheme is heterogeneous and the extent of the scheme can be very large, the scheme is divided into smaller units in order to consider the maximum details of the system which can influence allocation, for the following two purposes

1. Allocation and operation
2. Computation

4.3.1 Allocation and Operation

The entire irrigation scheme is physically divided into a number of smaller units called "Allocation Units" (AU). The allocation unit is the part of the irrigation scheme over which land and water resources are allocated. The climate is assumed to be uniform over the AU, but the AU may include different soils and crops. The climatic conditions may be different for different AUs.

The need to divide the irrigation scheme into several allocation units arises due to the heterogeneous nature and large extent of the irrigation scheme and in order to make allocation of resources and management of the irrigation scheme efficient. Usually in most allocation models (referred in Chapter II), the resources are allocated at scheme level (single field model). But it is difficult to adopt the allocation results for operation of the scheme because it does not specify the spatial distribution of the resources allocated (as in multifield models). The spatial distribution of the resources is important due to different specifications and efficiency of different canals in the distribution system and the variability of soil and climate in the scheme. This is also necessary to allocate the resources according to certain equity criteria.

The largest possible size of the AU is equivalent to the size of the irrigation scheme itself. The smallest size of the AU is the individual farm. The intermediate sizes are the command area of the secondary, tertiary and quaternary canals or their groups. The smaller the size of the AU, the more efficient will be the planning and operation of the irrigation scheme according to the optimum allocation plan, as the smaller unit can capture more details of the water distribution system and soils and climate. However this can increase the computational difficulties. Therefore there should always be balance a between efficient allocation and operation of an irrigation scheme and computational requirements, while deciding the size or number of AUs.

The size recommended is the command area of the canals at tertiary or quaternary levels (usually outlet). In India, this is generally referred to as 'Chak'. This is usually the point in the irrigation scheme up to which the water is managed by the irrigation authority of the scheme (from the headworks). Beyond this point, the farmers are responsible for distributing the water. The size of the command area of the outlet may vary from 10 to 100 ha with 5 to 100 farmers in each outlet (The AWAM has provision to allocate the resources at a lower level such as farm level from the allocation of resources at the upper level such as tertiary level. This is achieved by running the AWAM by considering the upper level as scheme e.g. tertiary level and lower level as AU e.g. farm.). The allocation units of different sizes are schematically represented in Figure 4.1.

4.3.2 Computation

The procedure used in optimum allocation of resources in AWAM uses the generation of irrigation programmes for each crop grown on different soils which exist in different climatic regions of the irrigation scheme. Though the climate is assumed to be uniform over the AU, it can include several soils and crops. Therefore the generation of irrigation programmes at allocation unit level would need a lot of computational time. These are generated separately by dividing the irrigation scheme into number of units based on climate, soil and crop, but this is not physical division of the irrigation scheme like AU. This division is described below.

Region: As discussed earlier, the irrigation scheme may have different climates. The part the of irrigation scheme with similar climate is refereed to as "Region".

Soil Group: Several soils may exist in the irrigation scheme. The part of the irrigation scheme with similar soils is termed as "Soil Group".

Crop: Several "Crops" can be grown in the irrigation scheme.

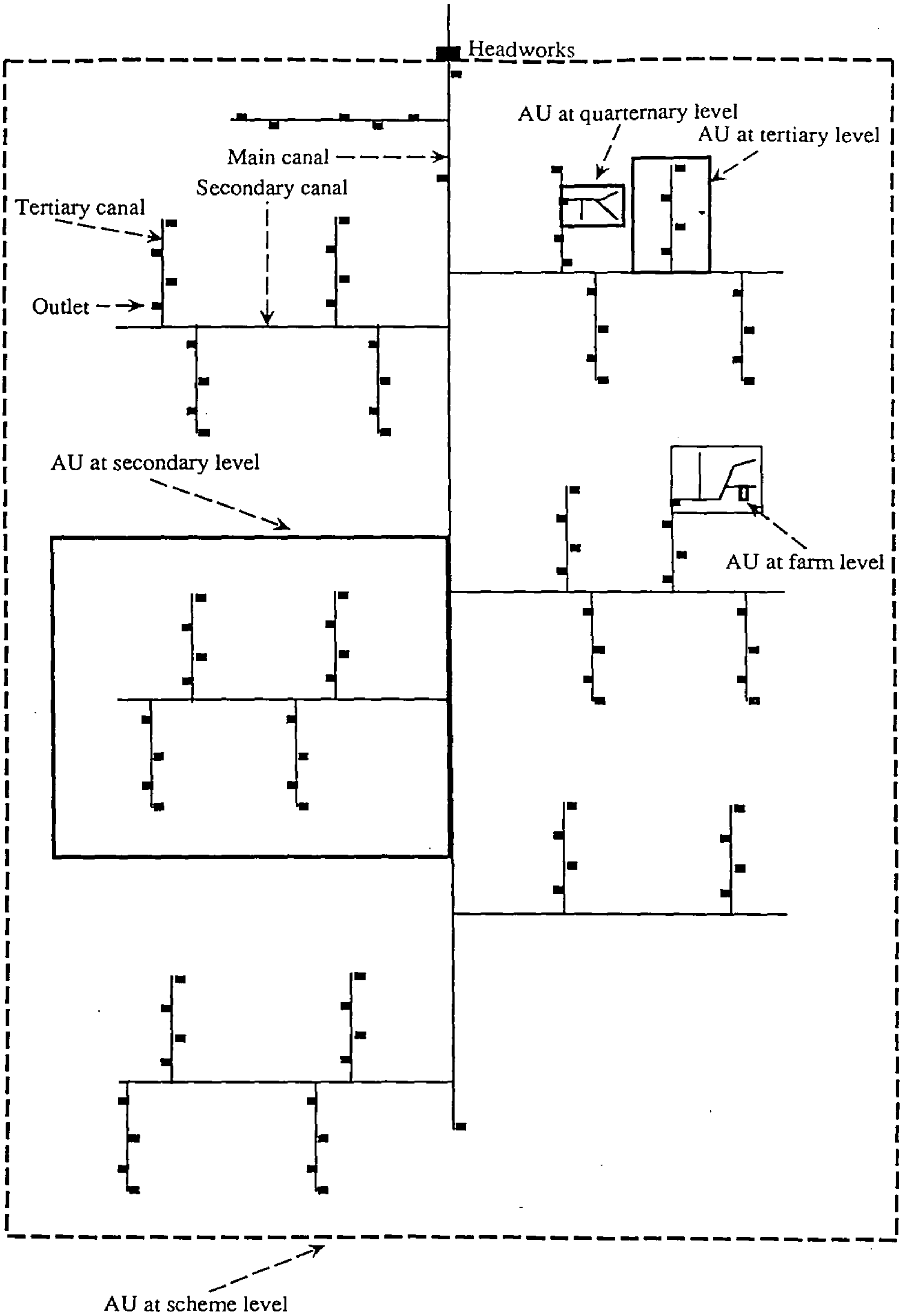


Figure 4.1 The schematic view of allocation units at different levels

The unit with similar climate (Region), soil (Soil group) and crop is termed as Crop-Soil-Region (CSR) unit. The CSR units are obtained with the combination of regions, soil groups and crops. The total number of CSR units is given by the equation (4.1).

$$NU = \sum_{R=1}^{NR} \sum_{S=1}^{NS_R} NC_{SR} \tag{4.1}$$

where

R, S and C	=	subscripts for region, soil group and crop, respectively
NU	=	number of CSR units
NR	=	number of regions
NS_R	=	number of soil groups in R^{th} region
NC_{SR}	=	number of crops in S^{th} soil group of R^{th} region

The irrigation programmes are generated over the CSR unit. Each AU may have one or more than one CSR units, but each CSR unit having the same climate (as climate is assumed same over the AU) but may have different soils and crops. Therefore CSR unit in AU is referred as Crop-Soil (CS) unit. The resources are allocated to each CS of different AUs.

4.4 IRRIGATION SEASON

The irrigation season is the season for which planning for the irrigation is done and over which the scheme is operated for irrigating the crops. It may be maximum one year and minimum equivalent to one irrigation period. The irrigation season (if equivalent to one year) can be divided in to the subseasons to represent the climatic variability over the year and vary the parameters which depend on the climate (such as number of irrigations). Generally different crops are grown in the different seasons. Some times the same crop can be grown in different seasons. Some crops may overlap different seasons.

4.5 IRRIGATION INTERVAL

It is defined as the time between the beginning of the two successive turns of water application. The irrigation interval for a particular irrigation is fixed irrespective of region, soil group or crop. However the irrigation interval can vary over the irrigation season or subseason. It can be same over the irrigation subseason but different in different subseasons (thus irrigation interval is the parameter which depends on the climatic variability over irrigation season). The irrigation interval is generally kept the same over the subseason for ease in management. Irrigation period is alternately used for irrigation interval.

4.6 WATER DELIVERY INTERVAL

It is the time between the beginning of two successive actual application of water. In the method used in the development of AWAM, some irrigations can be skipped i.e. water may not be delivered at each turn for a particular CSR unit. Thus the interval between actual water delivery is more prolonged than the interval between the turns. Water delivery interval, is therefore, a multiple of the irrigation interval (if it is uniform over the irrigation subseason), or summation of successive irrigation intervals (if it is varying over the irrigation season).

The irrigation interval (or set of irrigation intervals) is predetermined for the irrigation season but the water delivery interval is the decision variable which is the output of AWAM for different CSR units. The possibility of different water delivery interval for different CSR unit adds flexibility in application of water at different intervals to different crops grown on different soils and in different climatic patterns. Theoretically the delivery system can be used as flexible as in on demand type, by reducing the irrigation interval to one day. However the computations will be very difficult with such a small irrigation interval due to the specific approach adopted in the generation of irrigation programmes (Chapter V).

4.7 ALLOCATION PLAN

The allocation plan is the plan which contains the information on allocation of different resources (land and water) at the beginning of the irrigation season. This is also known as the irrigation plan. It consists of the area to be irrigated under different crops in different soil groups of different AUs and the water to be delivered per irrigation to these areas.

4.8 OPERATION OF MODEL

The AWAM operates in the following seven modes (Figure 4.2) to satisfy the different objectives outlined behind the development of the methodology in Chapter I.

1. Simulation
2. Calibration

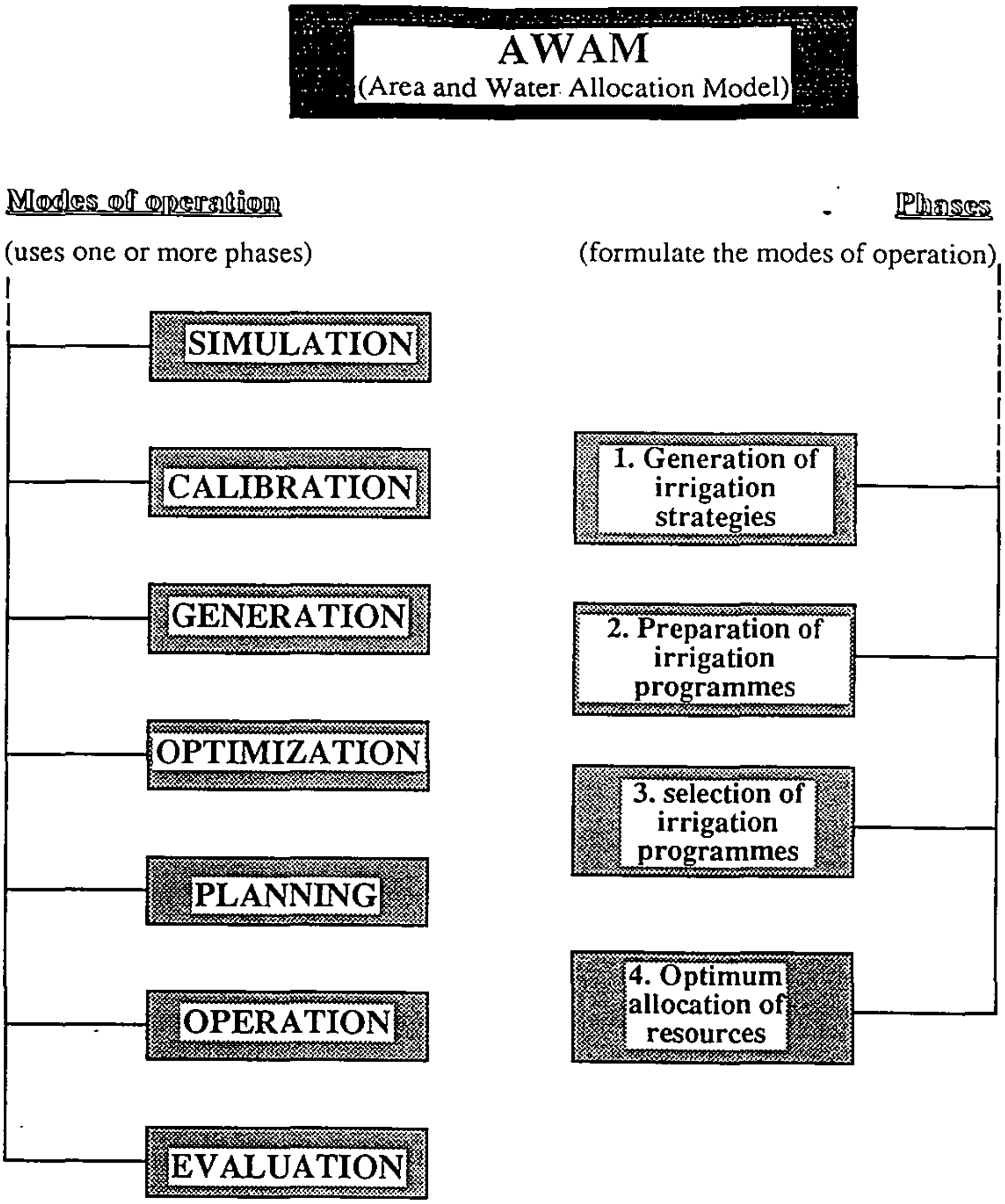


Figure 4.2 Area and Water Allocation Model (AWAM)

3. Generation
4. Optimisation
5. Planning
6. Operation
7. Evaluation

The AWAM has the following four phases formulated according to Hypotheses 1 to 5, to operate in the above seven modes. One or more than one phase is used to operate AWAM in any mode.

1. Generation of irrigation strategies
2. Preparation of irrigation programmes
3. Selection of irrigation programmes
4. Optimum allocation of resources

The four phases are described briefly below. The detailed description is presented in Chapter V and Chapter VI.

Phase 1. Generation of irrigation strategies: AWAM allocates land and water resources optimally. Optimum allocation of water needs the information on the output obtained from several ways of irrigating crop. These several ways (irrigation strategies) are generated in this phase for each CSR unit and a given set of irrigation intervals. Alternatively the irrigation strategies can be given as direct input i.e. applying a certain depth of water or deficit per irrigation.

Phase 2. Preparation of irrigation programme: The irrigation programme which consists of information on yield/benefits and irrigation requirement (depth) per irrigation is prepared for each irrigation strategy with the following two submodels.

i. SWAB: This submodel simulates soil moisture in the soil root zone and estimates the actual crop evapotranspiration and the other related parameters and the irrigation requirement (depth) per irrigation (Chapter V).

ii. CRYB: This submodel estimates crop yield and net benefits (Chapter V).

Alternately irrigation programmes can be given as direct input.

Phase 3. Selection of irrigation programmes: Phases-1 and 2 may generate several irrigation programmes. All of them are not important and all can not be used in fourth phase due to computational limitations. Therefore this phase selects a specified number of irrigation programmes which are optimal and efficient according to certain criteria for each CSR unit.

Phase 4. Optimum allocation of resources: This phase allocates land and water resources optimally to different crops grown on different soils in different allocation units, with the help of irrigation programmes obtained for different CSR units from Phases 1,2 and 3, or prescribed irrigation programmes in the following two stages.

i. Preparation of irrigation programmes for each CS unit of AU by modifying the irrigation programmes of the corresponding CSR unit with consideration to distribution and conveyance efficiencies.

ii. Allocation of the resources to each CS unit of AU with certain objectives and constraints with the Resource Allocation (RA) submodel.

The linkage among all these phases is shown schematically in Figure 4.3.

4.8.1 Simulation Mode

In this mode the different components of the soil water balance (e.g. evaporation, transpiration, deep percolation) and crop yield are simulated for the given set of crop, soil and climate and the irrigation strategy. Irrigation requirement and benefits can be estimated from the simulated parameters. In this mode the model SWAB and CRYB of second phase are used. These submodels are run for a given set of data. The flowchart of the model in this mode is presented in Figure 4.4. The AWAM in simulation mode is needed for AWAM in all other modes. AWAM in simulation mode is used in Chapter VII.

4.8.2 Calibration Mode

The second phase of AWAM includes the soil water balance and crop yield estimation (SWAB and CRYB submodels). These submodels estimate the irrigation requirement and crop yield for a given irrigation strategy and crop, soil and climate. The system over which these models are formulated should contain the details of crop, soil and climate and is therefore complex. The accurate representation of the system and hence the estimation of irrigation requirement and crop yield needs several data. As described earlier the scheme might be characterised with several soils, over which different crops can be grown in a varying climate. In most irrigation schemes it is difficult to obtain the detailed data for all such situations. The use of complex models also poses a computational problem. Therefore very simple models (discussed in Chapter V) are

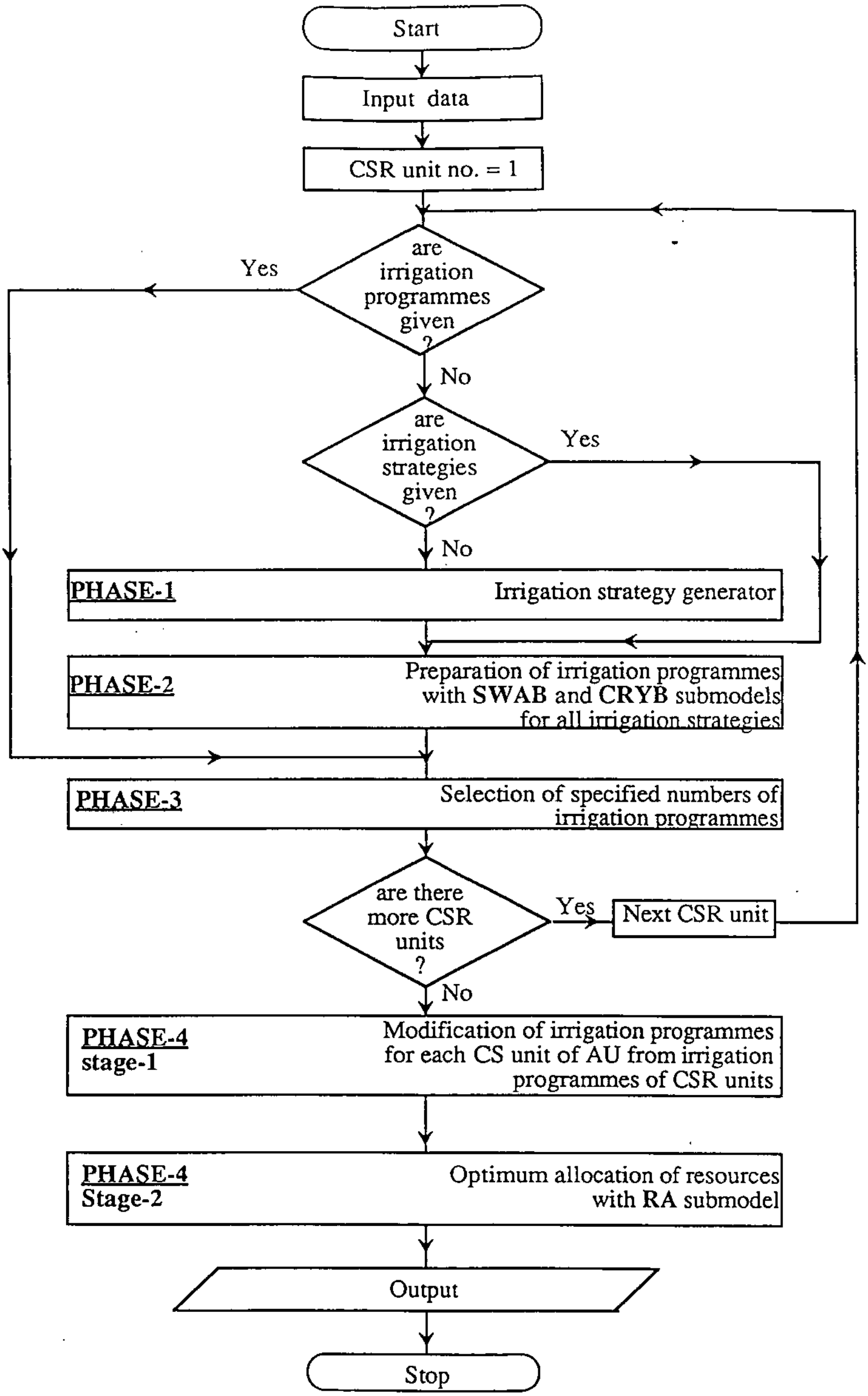


Figure 4.3 Linkage among different phases in AWAM

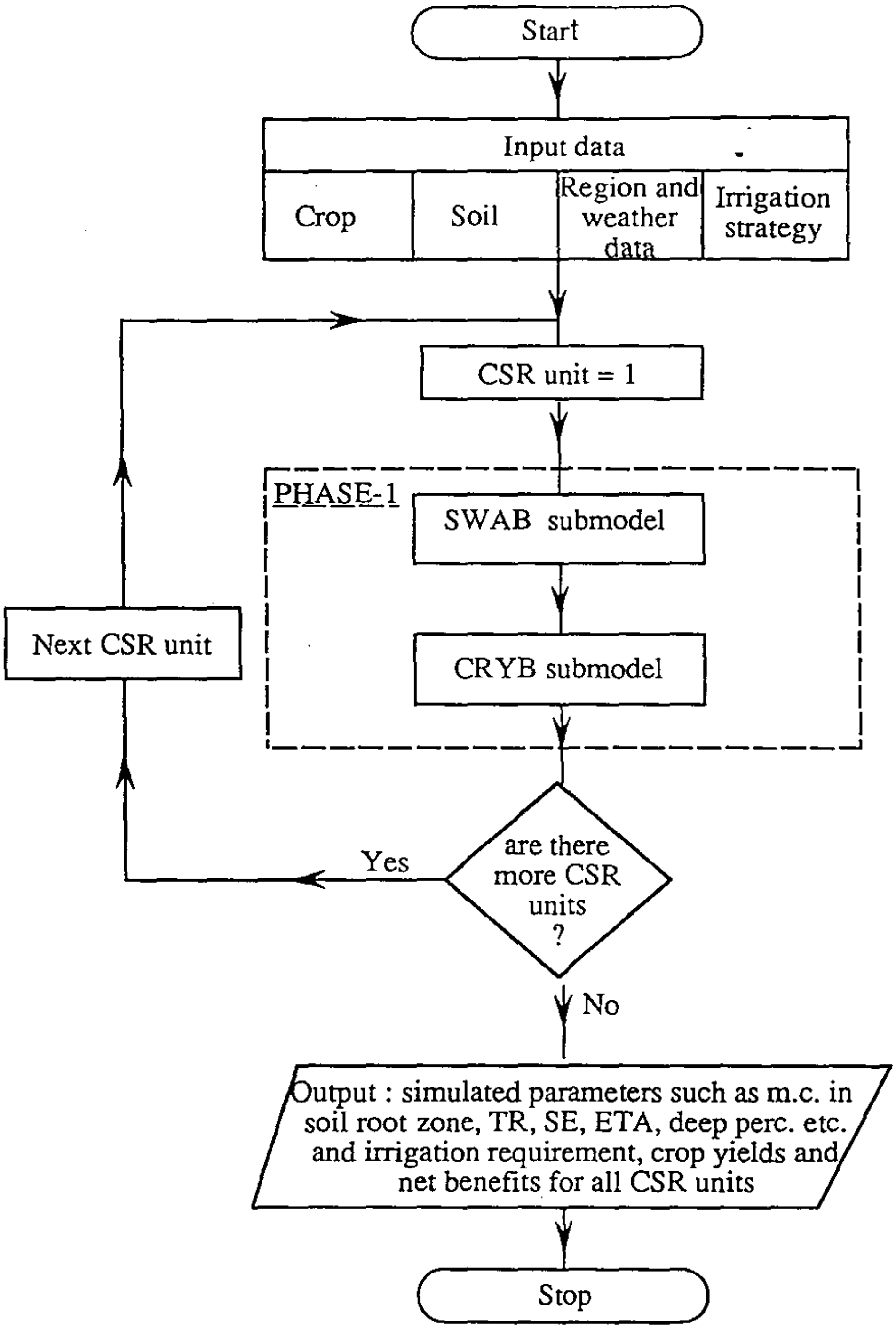


Figure 4.4 AWAM in Simulation Mode

used in many allocation studies which are described in Chapter II. These models need few data and all other parameters are either not considered or assumed to be the same for all the crops. In fact these models also assume the soil to be homogeneous over the scheme and along the depth. This type of simplification may not estimate the irrigation water requirement and crop yield properly. Therefore in AWAM most of the important parameters influencing irrigation requirement and crop yield are considered. If all these required data are not available at the scheme, these can be estimated by calibrating the model for given CSR unit for some parameters. This helps to model the system with few data and little experimentation in the scheme.

The deficit irrigation is included in AWAM for the generation of irrigation programmes and subsequently for the allocation of the land and water resources. It is stated by the Hypothesis-1 that the detailed process in the soil-plant-atmospheric system can be modelled accurately to include deficit irrigation in a computer program. The addition of component of calibration in the process of allocation of land and water resources for HIS is the way to address Hypothesis-1.

The input data, the values of which are to be estimated are known as calibration parameters. The value of a calibration parameter is to be selected from the given range. The test parameters are those parameters which are to be tested by comparing simulated and observed values for a given set of calibration parameters. The test criterion is the one which should be satisfied for the selection of a set of calibration parameters. In this mode the calibration parameters and the range over which these should vary are determined for a given set of data and CSR unit. For each set of calibration parameters, the observed and simulated values of test parameters are compared with test criteria. The set of calibration parameters is selected which satisfies the test criteria for which the value of test criteria is the most optimum. This mode uses AWAM in simulation mode for each set of calibration parameters. The flow chart of the model in this mode is presented in Figure 4.5. The use of AWAM in this mode is described in Chapter VII.

4.8.3 Generation Mode

Irrigation programmes are to be generated for the AWAM in optimisation and operation modes. Several irrigation programmes are required for the optimum allocation of the land and water resources. These irrigation programmes also need to be stored for testing several allocation plans in the optimisation mode. In this mode irrigation strategies are generated for each CSR unit (Phase-1) and irrigation programmes are prepared for each irrigation strategy with SWAB and CRYB (Phase-2). The required number of irrigation

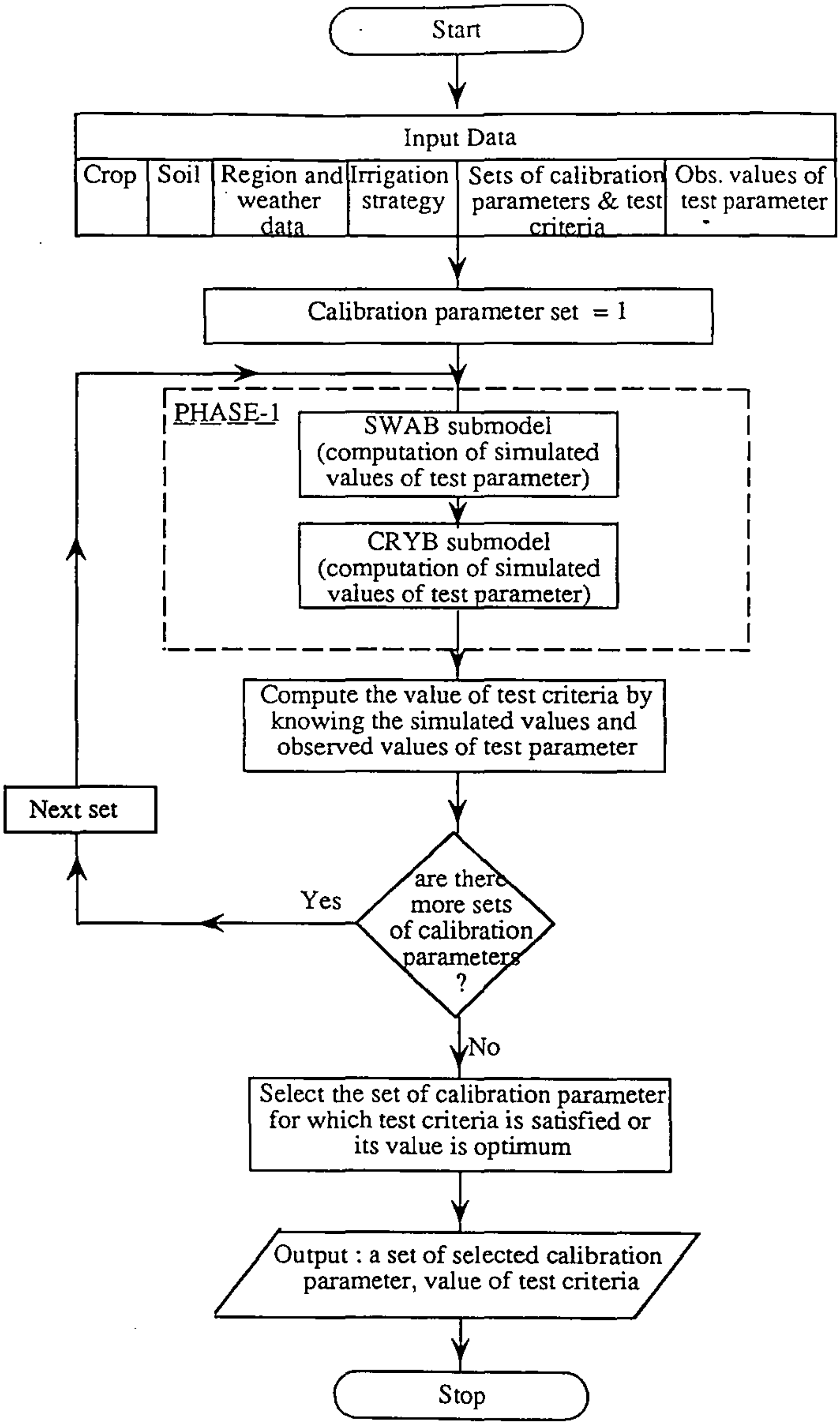


Figure 4.5 AWAM in Calibration Mode

programmes are selected with certain criterion (Phase-3). This mode is described with flow chart in Figure 4.6. The AWAM in this mode is described in Chapter VIII and used in Chapters VIII, IX and X.

4.8.4 Optimisation Mode

AWAM in optimisation mode allocates the resources optimally to different crops and soils in each AU for achieving a certain objective under the influence of given constraints. This is needed for AWAM in planning and operation modes. This mode needs the input of irrigation programmes for each CSR unit. The irrigation programmes for each CS unit of AU are obtained with the irrigation programmes of corresponding CSR unit and other scheme data (Stage-1 of Phase-4). In this stage the losses in conveyance and distribution of water are considered. Then the resources are allocated optimally to different crops grown on different soil groups of each allocation unit for a given objective and set of constraints (stage-2 of phase-4) with the RA submodel. This is described with a flow chart in Figure 4.7. The model in this mode is used in Chapters VIII, IX and X.

4.8.5 Planning Mode

AWAM is operated in this mode to obtain the optimum allocation of land and water resources to different crops grown in different soil groups of each AU, and a set of irrigation intervals for a given objective and a set of constraints. In fact this is the combination of AWAM in generation mode and AWAM in optimisation mode and operating the combination for different sets of irrigation intervals. The irrigation and allocation plans at the start of the irrigation season are obtained with AWAM in planning mode. In this mode irrigation programmes for each CSR unit are obtained by generating irrigation strategies (AWAM in generation mode) or irrigation programmes are prepared for given irrigation strategies. Alternately the set of irrigation programmes for a particular CSR unit might be given as direct input. The irrigation programmes for each CS unit of AU are obtained with the irrigation programmes of corresponding CSR unit, and resources are allocated optimally (AWAM in optimisation mode). The procedure is repeated for all sets of irrigation intervals. The set of irrigation intervals and corresponding irrigation and allocation plans are selected based on optimum value of the output. The flow chart in Figure 4.8 represents the AWAM in planning mode. The model in this mode is used in Chapters VIII, IX and X.

4.8.6 Operation Mode

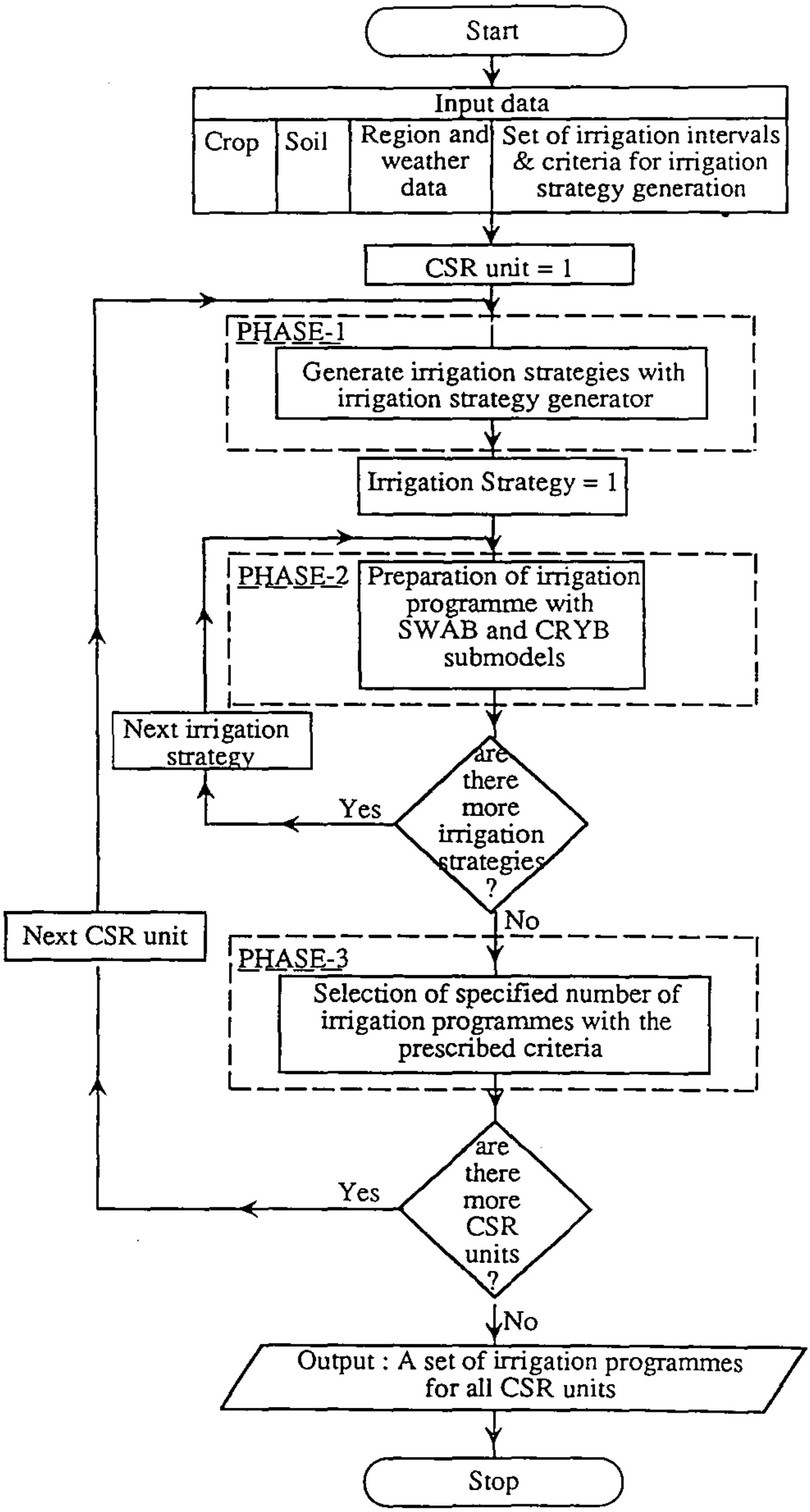


Figure 4.6 AWAM in Generation of Irrigation Programmes Mode

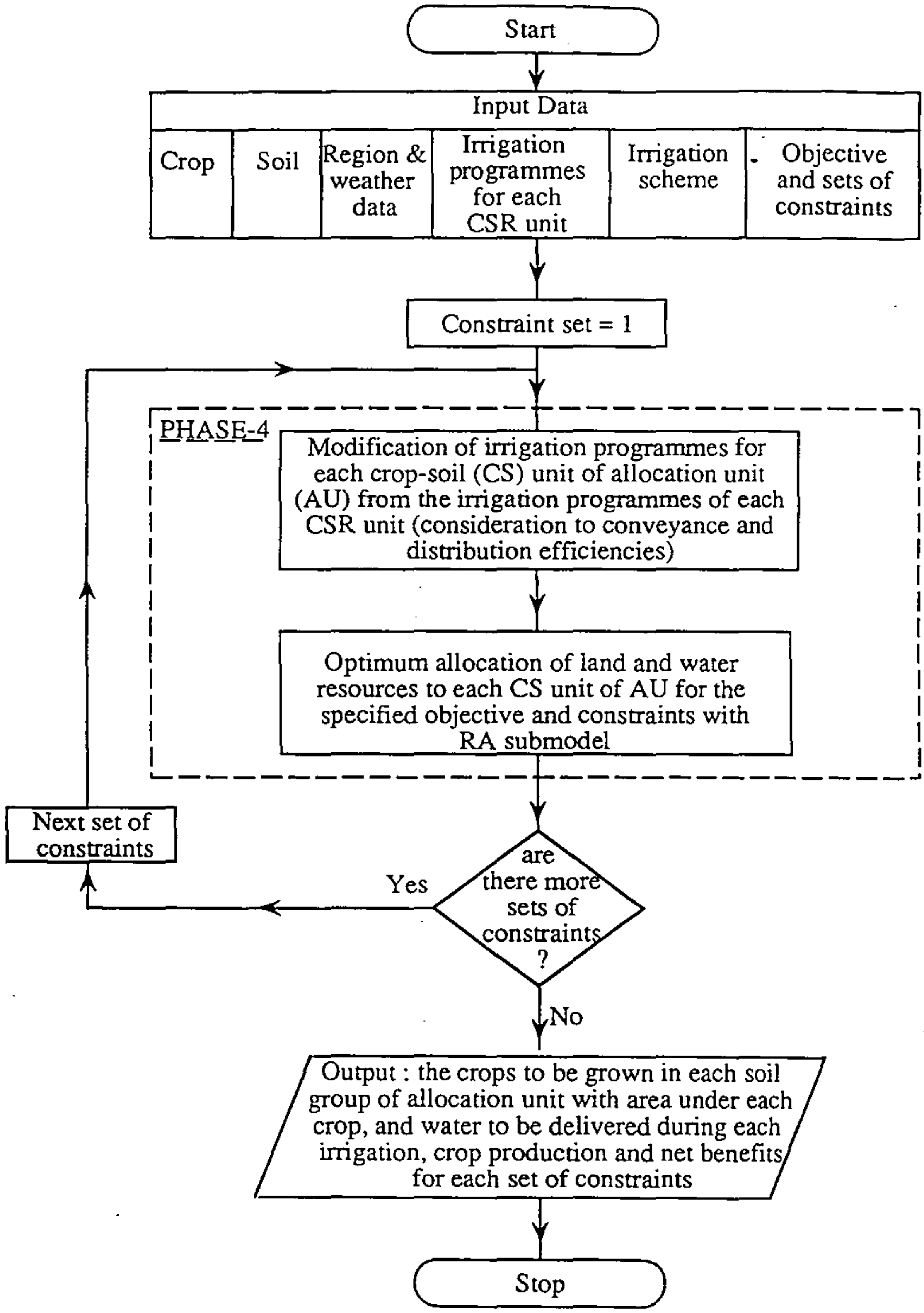


Figure 4.7 AWAM in Optimisation Mode

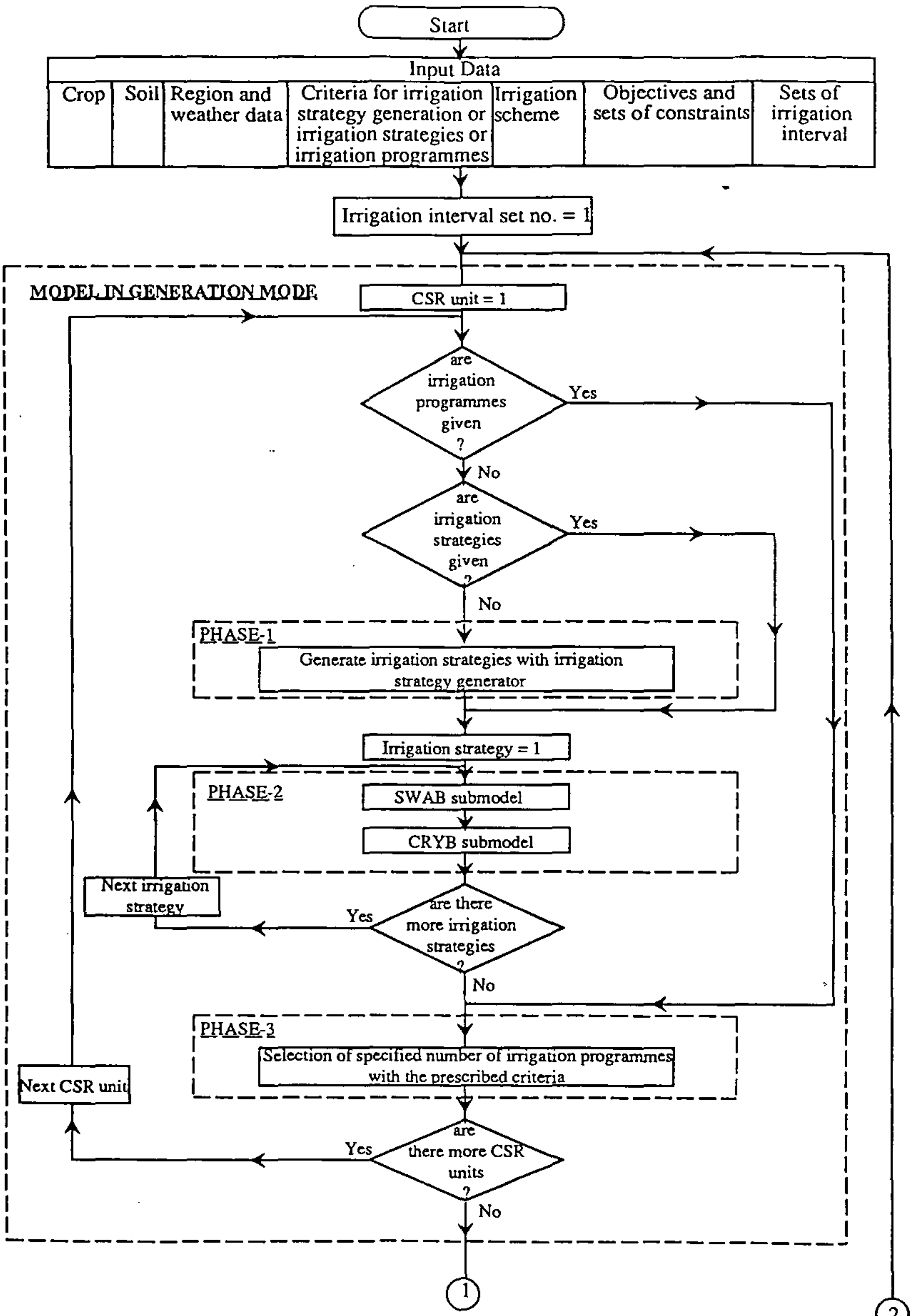
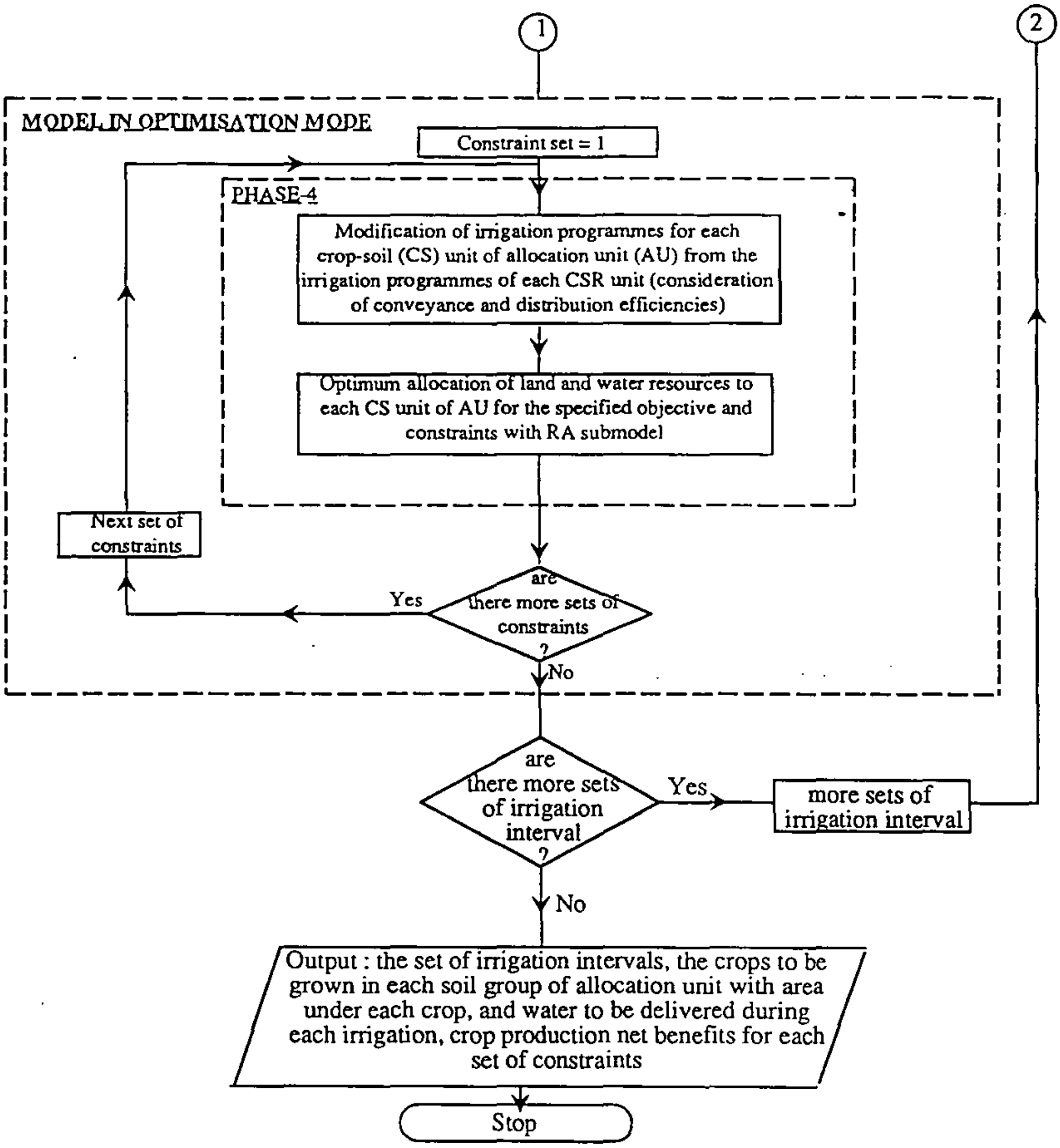


Figure 4.8 AWAM in Planning Mode (contd..)


1
2
MODEL IN OPTIMISATION MODE
Constraint set = 1
PHASE-4
Modification of irrigation programmes for each crop-soil (CS) unit of allocation unit (AU) from the irrigation programmes of each CSR unit (consideration of conveyance and distribution efficiencies)
Optimum allocation of land and water resources to each CS unit of AU for the specified objective and constraints with RA submodel
Next set of constraints
are there more sets of constraints ?
Yes
No
are there more sets of irrigation interval ?
Yes
more sets of irrigation interval
No
Output : the set of irrigation intervals, the crops to be grown in each soil group of allocation unit with area under each crop, and water to be delivered during each irrigation, crop production net benefits for each set of constraints
Stop

AWAM in planning mode gives the irrigation and allocation plans at the start of irrigation season. The irrigation plans are obtained for a certain set of climatological and river runoff (streamflow) data. When the irrigation season has started and the plans are being executed, the conditions will change depending on the deviation of the actual climatic conditions from those used in planning mode. Therefore the irrigation plans for the remaining irrigation season may also change for optimal output. If the original plans are continued for the remaining season, the final output may not be optimum. Therefore the plans are modified at every irrigation (except the irrigation interval) with the help of modified conditions, observed climatological and streamflow data (previous) and estimated climatological and streamflow data (next) for optimum output. The modified plans are adopted for the subsequent irrigations. The modified plans can be obtained from current irrigation or some irrigations before current irrigations (lag). The lag is provided to get sufficient time for communications.

In this mode at any irrigation, the modified conditions are obtained from the previous data with SWAB for all CS units of AUs and reservoir. For the modified conditions, the irrigation programmes are prepared (Phases 1,2 and 3) and resources are reallocated (Phase 4) with the given objective and set of constraints. If certain constraints prove to be active in obtaining the unfeasible solution, these are modified and then plans are again obtained. The process is repeated until the last irrigation in the irrigation season. The area already being irrigated and being prepared for planting is not removed from irrigation, but its irrigation programme is modified according to changed conditions. However the area which is yet to be prepared for planting can be removed from the irrigation or additional area can be brought under irrigation for the crops to be planted later in the season. The AWAM in operation mode is indicated in Figure 4.9. The AWAM in this mode is summarised in Chapter X.

4.8.7 Evaluation Mode

It is often necessary to test the performance of the allocation plan derived from other considerations for the irrigation scheme, or to test the allocation plan prepared for one year against the another year for studying the effect of climatic variability and to obtain a steady optimum allocation plan. The AWAM in evaluation mode is used for these purpose.

The mode operates in a reverse manner to the planning mode. The crop yields and net benefits are simulated for each CS unit of AU from the corresponding area and water

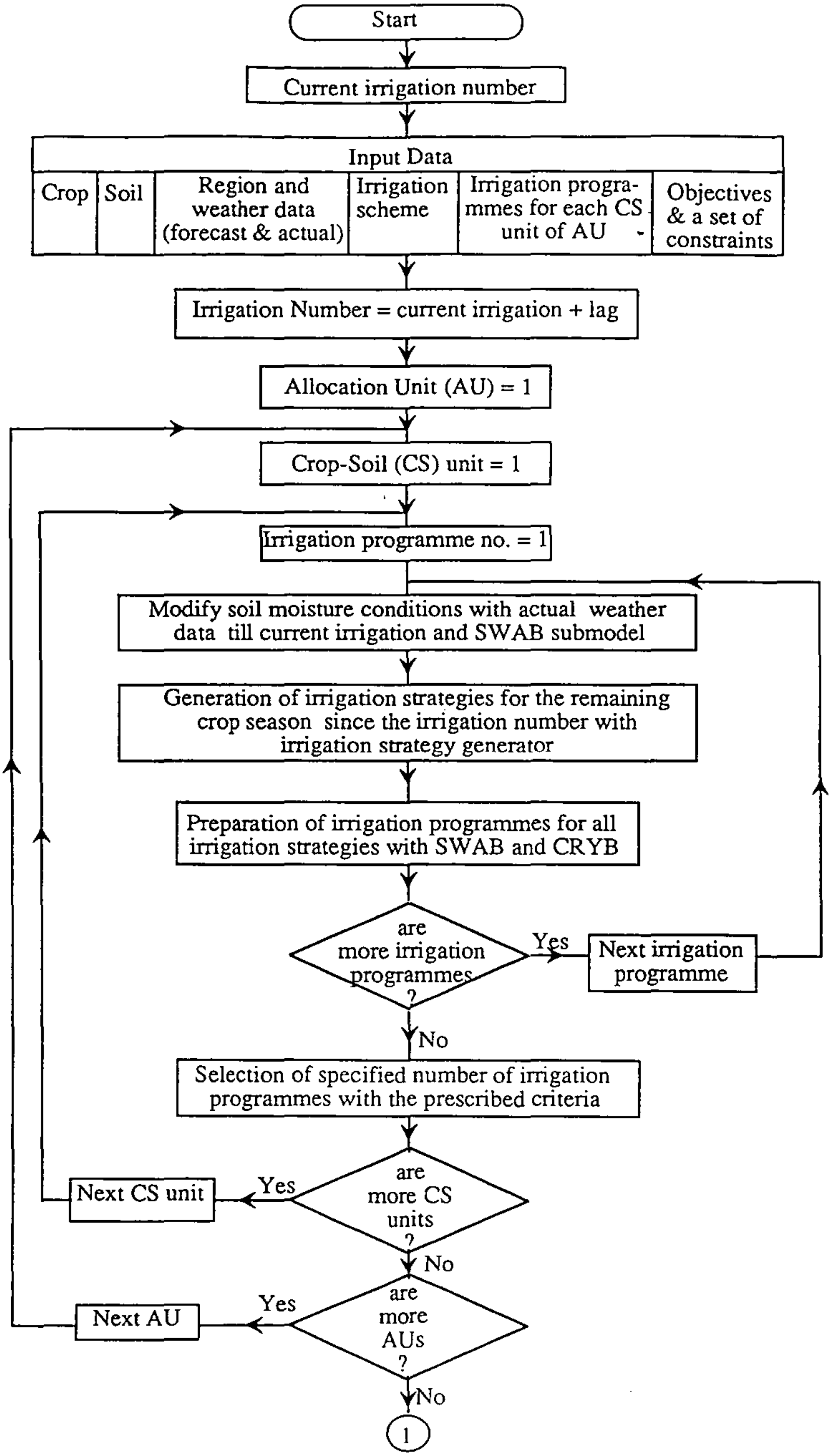
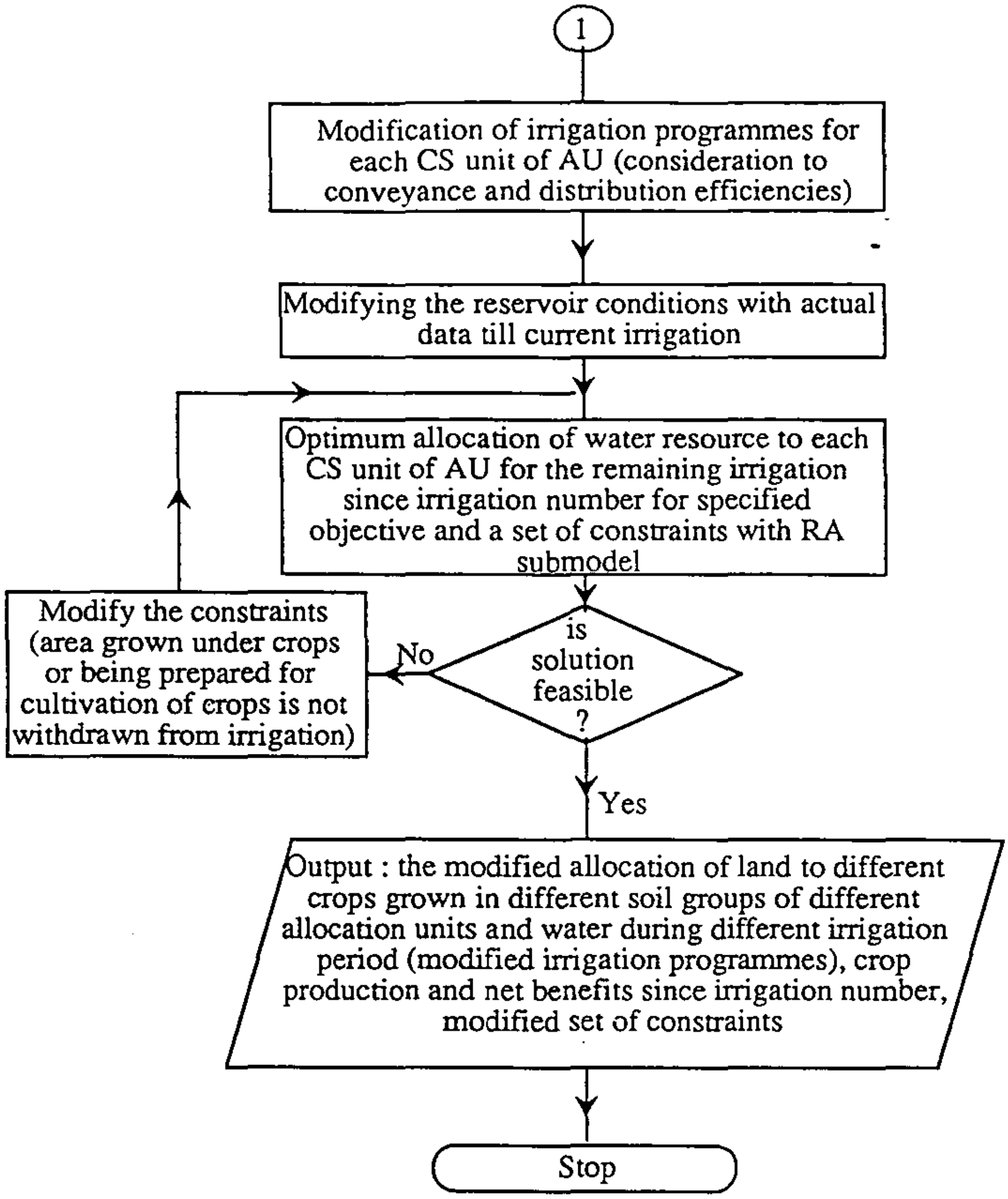


Figure 4.9 AWAM in Operation Mode (contd..)


1
Modification of irrigation programmes for each CS unit of AU (consideration to conveyance and distribution efficiencies)
Modifying the reservoir conditions with actual data till current irrigation
Optimum allocation of water resource to each CS unit of AU for the remaining irrigation since irrigation number for specified objective and a set of constraints with RA submodel
is solution feasible ?
No
Modify the constraints (area grown under crops or being prepared for cultivation of crops is not withdrawn from irrigation)
Yes
Output : the modified allocation of land to different crops grown in different soil groups of different allocation units and water during different irrigation period (modified irrigation programmes), crop production and net benefits since irrigation number, modified set of constraints
Stop

delivered per irrigation. In this way the total benefits that could be obtained from the irrigation scheme under the given allocation plan are obtained. The restrictions on water available are not considered.

When used for testing the allocation plan of one year against another year, this mode operates differently. In this situation the water availability may not be equivalent to water consumption estimated according to the given allocation plan (restrictions on water available are considered). Water is delivered according to the allocation plan. If water shortage occurs, water is delivered to those CS units which are first in queue and no water is delivered to those units which are last in the queue (queue is either formed from head to tail of the system or tail to head of the system, depending on the option provided). The water delivered for every irrigation to each CS unit of AU is determined and the net benefits are computed. The schematic representation of AWAM in evaluation mode is shown in Figure 4.10.

When it is needed to test the performance of a certain irrigation strategy or irrigation programme given for each CSR unit for the irrigation scheme, the irrigation programmes are formulated for each CSR unit for the given irrigation strategy with SWAB and CRYB submodels (this is skipped if irrigation programme is given). The irrigation programme for each CS unit of AU is prepared including consideration of the conveyance and distribution efficiencies. The total crop production and net benefits are obtained with the RA submodel by equating the area under each CS unit of AU with those prescribed with or without physical constraints (water availability, canal and outlet capacities). The AWAM in this evaluation mode is shown schematically in Figure 4.11. The AWAM in this mode is summarised in Chapter X.

4.9 CHARACTERISTICS OF THE IRRIGATION SCHEME

Though the purpose of irrigation schemes is to make water available and distribute for irrigation to different crops, the several local conditions guide to fulfil this purpose. Therefore different irrigation schemes have different characteristics. The characteristics of an irrigation scheme for which AWAM can be used for planning and operation purposes are described below.

1. The irrigation scheme may be heterogeneous.
2. The irrigation scheme is located in a semi-arid region and the distribution of water in the canal network follows rotational water supply.

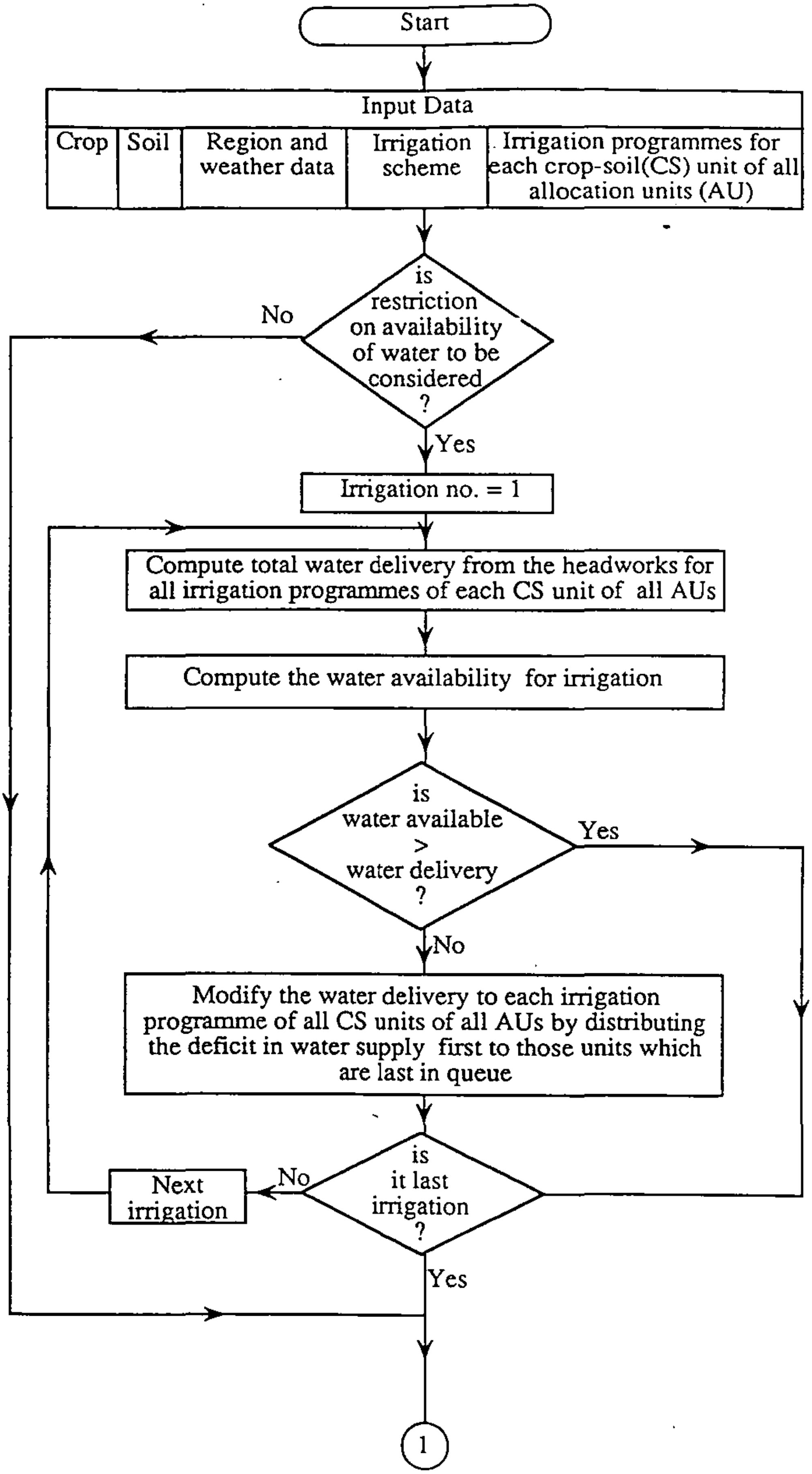
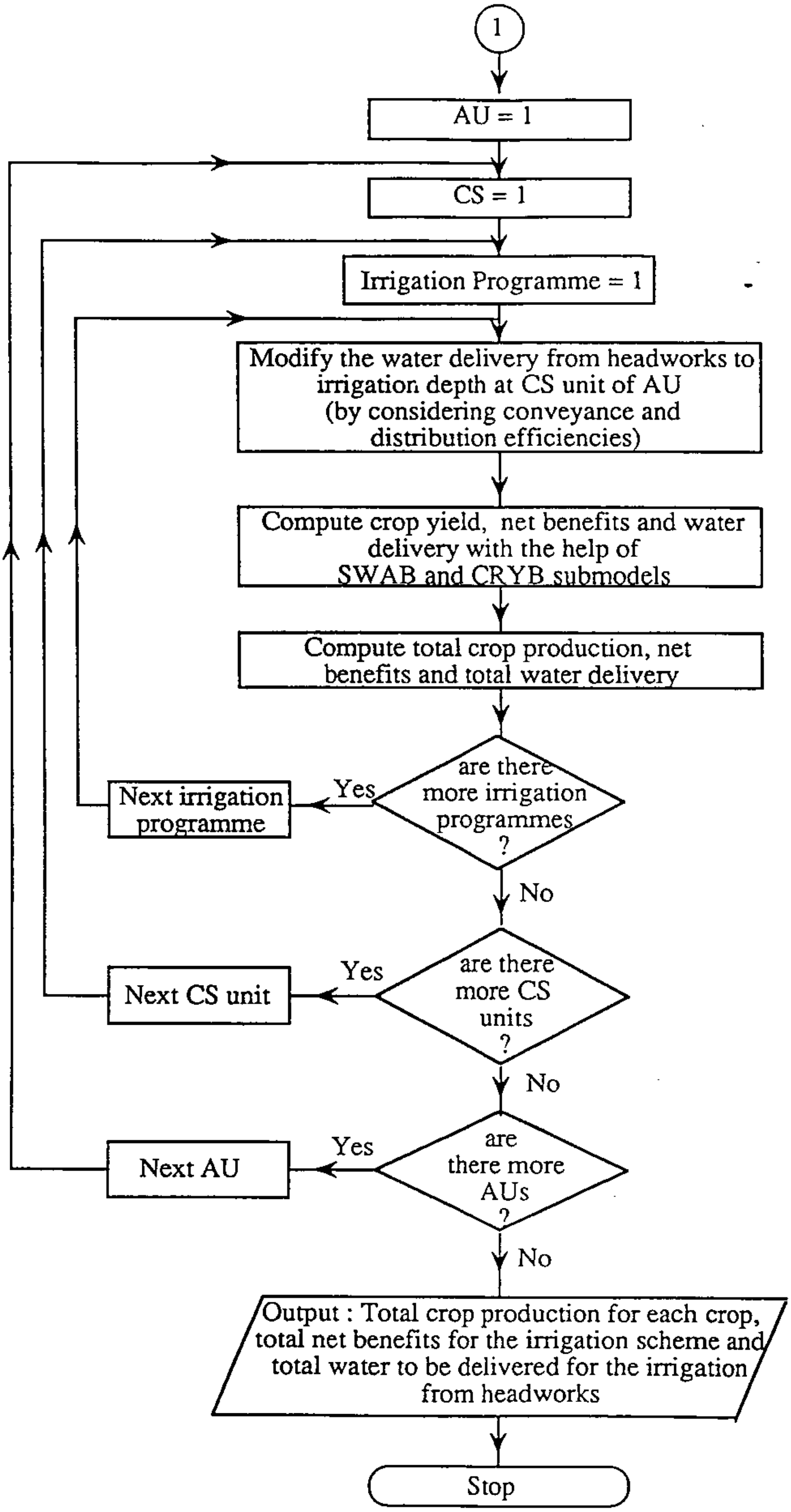


Figure 4.10 AWAM in Evaluation Mode (a) (contd..)


1
AU = 1
CS = 1
Irrigation Programme = 1
Modify the water delivery from headworks to irrigation depth at CS unit of AU (by considering conveyance and distribution efficiencies)
Compute crop yield, net benefits and water delivery with the help of SWAB and CRYB submodels
Compute total crop production, net benefits and total water delivery
are there more irrigation programmes ?
Yes
Next irrigation programme
No
are there more CS units ?
Yes
Next CS unit
No
are there more AUs ?
Yes
Next AU
No
Output : Total crop production for each crop, total net benefits for the irrigation scheme and total water to be delivered for the irrigation from headworks
Stop

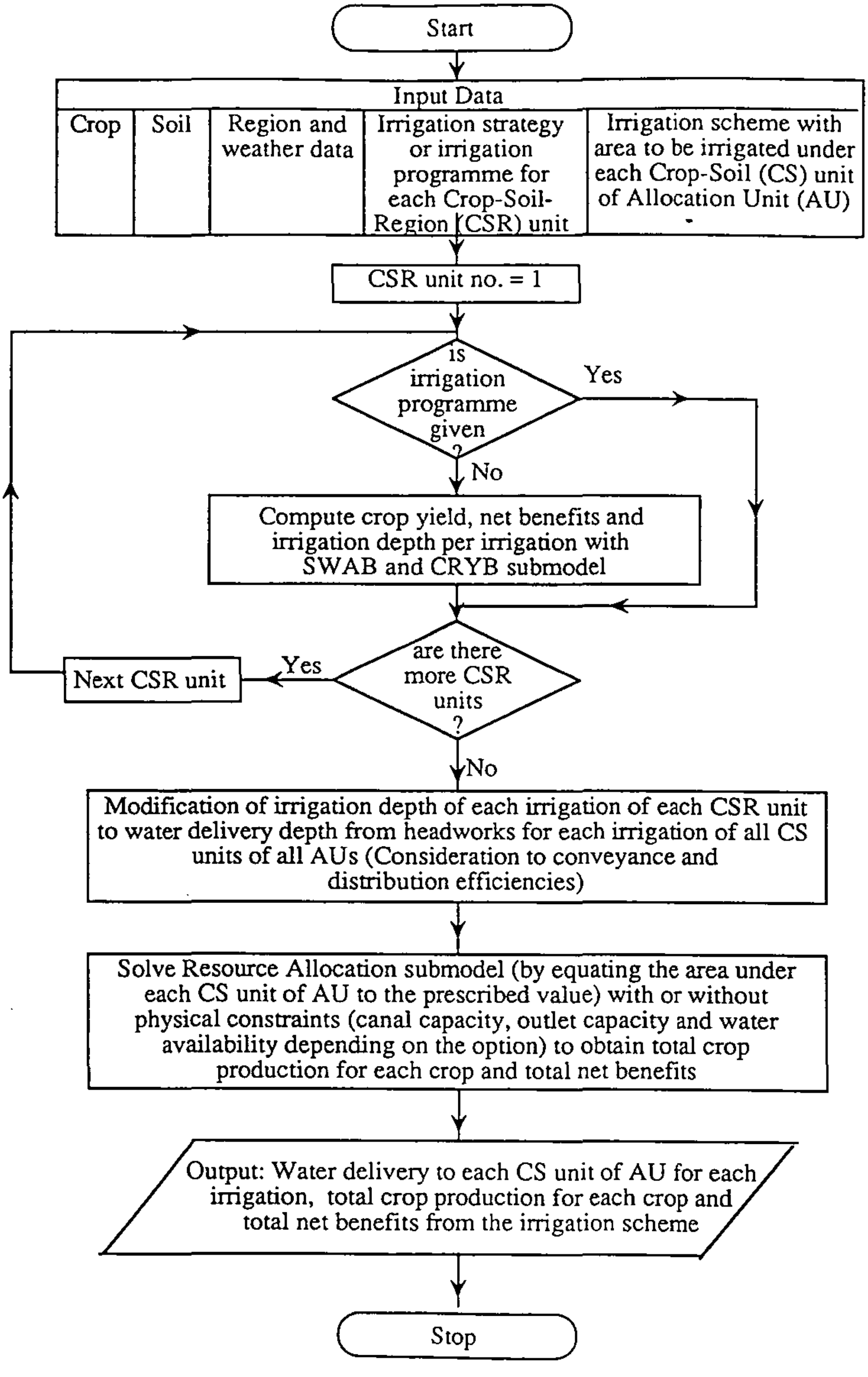


Figure 4.11 AWAM in Evaluation Mode (b)

3. The objective of the irrigation scheme is to obtain maximum output to the water users (farmers) in the scheme, which may be constrained by the capacity of the scheme to store and deliver water and the social issues among the users in the scheme.

4. There is an authority (irrigation authority) which is responsible for managing, operating and maintaining the irrigation scheme at least up to tertiary level.

5. The irrigation interval for a particular irrigation is fixed in the scheme irrespective of region, soils and crops grown in the scheme.

6. The farmers in the irrigation scheme follow the irrigation schedules fixed by the irrigation authority and these schedules are known to them in advance.

7. All the required data are available and constantly collected.

8. The supply of irrigation water to allocation unit level or below AU level can be controlled and measured.

9. The irrigation authority knows the demand of water or the area to be irrigated under different crops from the farmers in advance.

10. The irrigation authority can decide upon the allocation of different area to different crops and to different farmers (within the guidelines from the government and demand from the farmers).

In most of the irrigation schemes, some of these conditions are generally met and remaining could be met. The irrigation schemes in semi-arid regions of developing countries generally follow the conditions 1 to 6 (refer to irrigation water management models in Chapter II; Chambers, 1988; Burton, 1992; Shanan, 1992 and Jurriens and Kuper, 1995). Conditions 7 and 8 can be met by developing the infrastructure for data collection and control and measurement of water. Such development is already being under consideration in some irrigation schemes in view of their recognised importance in irrigation water management (Kathpalia, 1990). However the irrigation schemes which follow conditions 1 to 6 may or may not follow condition 9 and 10. The example is the irrigation schemes in India. In irrigation schemes in northern India, the rotational water supply system called "Warabandi" is followed. In this system, the water is delivered to the farmers in proportion to their holdings in the outlet command and farmers are free to choose their cropping pattern (Malhotra, 1982) So irrigation authority needs not to know demand from farmers. On the other hand, in the irrigation schemes in southern India the rotational water supply system called "Shejpali" is practised. In this system, the water is delivered to the farm according to the cropping pattern sanctioned by the irrigation authority depending on the water availability, the demand of water from farmers and other factors in the irrigation scheme (Shanan, 1992). Thus irrigation schemes in southern India suit to conditions 9 and 10. However it should be noted that the condition 9 and 10 are placed to satisfy the condition 3. Model under consideration can also be applied to irrigation schemes not fulfilling conditions 9 and 10 but in violation of condition 3.

4.10 CONCLUSIONS

This chapter described the overview of Area and Water Allocation Model (AWAM) and how it operates in different modes. The ability of AWAM to operate in several modes makes it useful in planning and operation of irrigation scheme. One of the objectives (Objective 1) of the study was to develop such model. The detail development of AWAM according to the formulated hypotheses and its usefulness for irrigation scheme are described in next chapters.(Chapter V to Chapter X).

CHAPTER V

AREA AND WATER ALLOCATION MODEL
2. GENERATION OF IRRIGATION STRATEGIES AND PREPARATION AND SELECTION OF IRRIGATION PROGRAMMES

Summary. In this chapter, three phases of AWAM are discussed. These are (i) generation of irrigation strategies, (ii) preparation of irrigation programmes and (iii) selection of irrigation programmes. The purpose of the first phase is to generate several possible irrigation strategies depending on the requirement. This phase is discussed with its need, previous works and the method used in the study. In the second phase, irrigation programmes are prepared for the generated irrigation strategies. These are prepared by formulating Soil WAter Balance (SWAB) and CRop Yield Benefit (CRYB) submodels. The basis of development of SWAB and CRYB is discussed by reviewing several types of earlier models developed from literature, and then formulation of SWAB and CRYB is presented by citing appropriate supporting theory. SWAB and CRYB submodels model the soil, plant and atmospheric subsystems and deficit irrigation is considered while generating the irrigation strategies and preparing the irrigation programmes. The methods used to select the appropriate irrigation programmes from those generated in second phase are discussed in the third phase. Thus this chapter addresses the Hypothesis 1 and fulfil the part of Objective 1.

5.1 CROP IRRIGATIONS

The total number of crop irrigations is computed from the planting and harvesting days of the crop within the irrigation season. The planting day may fall in the irrigation season or the crop might have already been planted before the start of the irrigation season and needs irrigations during irrigation season. Similarly the harvesting day may be in the irrigation season or the crop might be harvested after the end of the irrigation season and needs irrigation during the irrigation season. AWAM considers all such crops to be included in the allocation plans. The starting day of the irrigation season and ending day of the irrigation season are used as the planting day and harvesting day for the crops which have been planned before the start of irrigation season, and the crops which are expected to be harvested after the end of irrigation season, respectively. This is done for the sake of computation of crop irrigations for the generation of irrigation strategies (Phase-1), and computations in SWAB submodel (Phase-2).

The planting day is adjusted for the number of days required to wait for planting since the irrigation (due to excessive top soil wetting after the irrigation, which is not suitable for planting) and the number of days since the irrigation after which planting should not be done (due to excessive dry top soil, which is not suitable for planting). These are referred to as 'wet limit' and 'dry limit', respectively in this study. The irrigation just before planting (or at planting for the crops which are planted before the start of irrigation season) is termed as first crop irrigation.

1. If the planting day falls within in the wet limit, it is adjusted to the wet limit by equation (5.1).

$$pld = SI_{if} + Wc \qquad \text{if } SI_{if} < pld < SI_{if} + Wc \tag{5.1}$$

2. If the planting day falls after the dry limit, it is adjusted to the dry limit after the current irrigation or to the wet limit after the next irrigation, depending on whether advance in planting or delay in planting is preferred (equation 5.2).

$$pld = SI_{if} + Dc \qquad \text{if } EI_{if} > pld > SI_{if} + Dc \qquad \text{(advance in planting is preferred)}$$

$$pld = SI_{if+1} + Wc \quad \text{if } EI_{if} > pld > SI_{if} + Dc$$
$$if \rightarrow if + 1 \qquad \text{(delay in planting is preferred)} \tag{5.2}$$

where

pld	=	planting day (days since the beginning of irrigation season)
if	=	number of first crop irrigation (irrigations since the beginning of irrigation season)
SI_{if}	=	starting day of if^{th} irrigation (days since the beginning of irrigation season)
EI_{if}	=	ending day of if^{th} irrigation (days since the beginning of irrigation season)
Wc	=	wet limit (days)
Dc	=	dry limit (days)

The harvesting day is adjusted accordingly so that the total crop growth period is not changed.

The number of crop irrigations is computed by considering the irrigation at planting or just before planting as the first crop irrigation and the irrigation just after harvesting as the last crop irrigation. If the irrigation period of the last crop irrigation (for the crop) is within the minimum prescribed limit of extending the irrigation period of the previous crop irrigation without causing stress to the crop, the number of crop irrigations is reduced by one (omitting the last crop irrigation).

The presowing irrigation, if given, is the irrigation which is applied prior to the first crop irrigation. It is not considered as a crop irrigations for the purpose of generating irrigation strategies.

It is considered that the particular crop within a region is planted or irrigated on the same day, irrespective of the location of the area occupied by the crop (for computation purpose). In actual practice the lag in planting and the day of irrigation are assumed to be same. This takes care of different planting dates within a region during the same irrigation period but not during different irrigation periods. However the different planting days (and thus irrigation days) for the same crop can be considered for the different regions.

5.2 GENERATION OF IRRIGATION STRATEGY

5.2.1 The Need for Generation

Irrigation strategy is the way of scheduling irrigation for a given crop-soil-region (CSR) unit and given set of irrigation intervals. There are several ways of scheduling irrigation for a given set of irrigation intervals by varying the amount of water to be delivered in field at every irrigation, and therefore there are several irrigation strategies. In land and water allocation models, the optimum irrigation strategy (strategies) can not be decided before observing all possible irrigation strategies. This is possible in a land allocation model where the allocation is based on certain predecided rule or strategy such as to obtain the maximum crop yield per unit area by delivering water equivalent to the maximum crop water requirement. This strategy is considered as the optimum in such models. Therefore there is a need to generate the irrigation strategies, to select the optimum irrigation strategy or strategies among those for optimum allocation of land and water resources in the irrigation scheme which is heterogeneous in nature and short of irrigation water.

5.2.2 The Previous Work

The water allocation models described in Chapter II (Section 2.4.2) makes use of several irrigation strategies among which the optimum one is selected by optimisation procedure which is generally dynamic programming. In many studies, the basis for generating the irrigation strategies is the available soil moisture (Bras and Cordova, 1981; Rees and Hamlin, 1983; Tsakiris and Kiountouzis, 1984; Rao et al., 1988[a]; Rao et al., 1990; Vedula and Mujumdar, 1992). In some studies the other parameters such as evapotranspiration and/or rainfall are also considered either separately (Houghtalen and Loftis, 1988) or along with soil moisture (Rhenals and Bras, 1981 and Bras and Cordova, 1981). The range of these parameters is discretised in to several intervals at each irrigation. The irrigation water needed at each irrigation and the corresponding yield or net benefits are computed for each combination of parameters and the discretised interval of these parameters. The optimum one is selected by a dynamic programming approach. The approach is discussed in Chapter II for its limitation in heterogeneous irrigation schemes.

Matanga and Marino (1979), Yaron and Dinar (1982), Bernardo et al., (1988) and Manocchi and Mecarelli (1994) generated several irrigation strategies to allocate the land and water resources optimally. The procedures adopted by these authors to generate the irrigation strategies are described in Chapter II (Section 2.4.3.4). The procedure used by Matanga and Marino (1979) does not consider the effect of ET deficit during the growth stage on crop yield. Yaron and Dinar (1982) used dynamic programming for generating additional irrigation strategies each time, with the limitation discussed in Chapter II (Section 2.4.2). The procedures used by Bernardo et al., (1988) and Manocchi and Mecarelli (1994) are suitable for the irrigation schemes with water delivery on demand. These procedures also do not evaluate the full range of irrigation strategies. In this study the irrigation strategy generator is developed which is only suitable for irrigation schemes with rotational irrigation. The generator generates the full range of irrigation strategies. Various options are included for generation of irrigation strategies in the generator.

5.2.3 Irrigation Strategy Generator

In the present study the irrigation strategies are generated for a set of fixed irrigation intervals. The procedure to generate all the possible irrigation strategies used in the model is described in this section. However in actual study the number of irrigation strategies to be generated and considered in the optimisation process depends on the accuracy required and computational facility available.

The irrigation strategy is a set containing the deficit ratios for each irrigation. If there are 'Ic' number of crop irrigations (excluding presowing irrigations, if any) for a given unit and 'β_i' is the deficit ratio for i^{th} irrigation then a set of deficit ratio which is represented by β is given by equation (5.3).

$$\beta = \{\beta_i, i = 1, Ic\} \tag{5.3}$$

The deficit ratio can be varied in the certain range (βmin to βmax, where βmin is the lowest possible value of deficit ratio and βmax is the highest possible value of deficit ratio). The lowest value of βmin is zero meaning no irrigation water is to be applied or the irrigation is to be skipped. βmax can be one, which means that the full irrigation is to be applied (however it can be more than one, where an extra amount of water is required for satisfying leaching requirements, but this aspect is not considered in the present study). The deficit ratio can be varied from βmin to βmax by a certain increment ($\Delta\beta$) at each irrigation. The number of deficit ratio ($n\beta$) can be computed by equation (5.4).

$$n\beta = \{(\beta\max - \beta\min) / \Delta\beta\} + 1 \tag{5.4}$$

In the present study the irrigation strategies are generated in combination of deficit ratio and irrigation by varying the deficit ratio in the given range (obtained with the given βmin, βmax and $\Delta\beta$) at each irrigation. This results in generating the full range of irrigation strategies (or all the possible ways of scheduling irrigation for a given set of irrigation intervals) for the given values of βmin, βmax and $\Delta\beta$. The total number of irrigation strategies (nis) generated is given by equation (5.5).

$$nis = (Ic)^{n\beta} \tag{5.5}$$

For first irrigation, the deficit ratio can be varied in the full range (βmin to βmax), can be only 1 (generally when no presowing irrigation is given), can be only 0 (generally when presowing irrigation is given) or can be 0 or 1 (generally when no presowing irrigation is given and irrigation before planting is optional). When the deficit ratio varies in full range, nis is given by equation (5.5). For other situations, nis is computed by equations (5.6) (when nis for first irrigation is only 1 or only 0) and (5.7) (when nis for first irrigation is either 1 or 0).

$$nis = (Ic - 1)^{n\beta} \tag{5.6}$$

$$nis = 2(Ic - 1)^{n\beta} \tag{5.7}$$

Sometime it is necessary to keep the value of the deficit ratio for a few irrigations (e.g. the first few irrigations) the same in all irrigation strategies (e.g. zero for first few irrigations) or to limit the values of deficit ratio (e.g. 0, equivalent to minimum possible irrigation depth and 1 for few irrigations). When the deficit ratio for a certain irrigation is predecided, the nis is given by equation (5.8).

$$nis = n\beta 1(Ic - I1)^{n\beta} \tag{5.8}$$

where

I1	=	the number of irrigations for which deficit ratio is predecided
nβ1	=	the number of predecided deficit ratios

The number of irrigation strategies can be very high. For example for the crop period of 120 days and a uniform irrigation interval of 21 days, the number of irrigations is 6. If Δβ is 0.2, βmin = 0 and βmax=1, nβ = 6, the number of irrigation strategies nis = 46656. However for first few irrigations, the depth of water applied is small even with β=1 and irrigation depth needs to be adjusted to the minimum possible irrigation depth. So there is no need to consider the different combinations of deficit ratios from the given range of deficit ratio. Thus it can be assumed to consider the values of deficit ratio for first few irrigations as either 0 (for skipping the irrigation) or 1(for applying the irrigation). In the present example, if the first irrigation is given to fill the root zone to field capacity (β=1) and the second irrigation is either to be skipped or given fully, the nis is reduced to 2592.

As such the feasible irrigation strategies may be much less than nis, as the deficit ratio of some of the irrigations do not consider its full range, for the following reasons.

(1) For some of the irrigations, some lower values of deficit ratio may result in the same depth of irrigation due to limitation by minimum possible irrigation depth. Similarly for some of the irrigations, some higher values of deficit ratio may result in the same depth of irrigation due to limitation by the maximum possible irrigation depth. For such cases only one value among those higher or lower values of deficit ratio is relevant.

(2) Many irrigation strategies can be unfeasible due to the possibility of dropping the soil moisture in the root zone below wilting point or some allowable limit. This will happen especially when the set of deficit ratios contains the values of lower deficit ratios in succession.

If $\Delta\beta$ is reduced, more accuracy is achieved but at the cost of computational time.

5.3 PREPARATION OF IRRIGATION PROGRAMMES

This is the second phase of AWAM. Irrigation programmes which contain the information on the depth of irrigation water to be applied in field at every irrigation, the crop yield and the net benefits are prepared for each irrigation strategy generated in first phase, by estimating the daily soil water content in the soil root zone and the actual evapotranspiration or transpiration. In the present study this is done by formulating the simulation model. This section describes the purpose, past work done and development of the simulation model used in the study.

5.3.1 Purpose

Irrigation scheduling studies need the knowledge of soil moisture status at various instances of time during the crop growth period to know how much and when to irrigate. Similarly optimisation studies (for allocating the resources) in irrigation water management use the information on irrigation water requirement and corresponding crop yield (net benefits) as influenced by different crop, soil and climatic parameters. This information can be known either by conducting experiments or estimated by simulating individual processes in the crop-soil-climate system. Experiments may produce accurate results but have severe limitations. The important limitations are that the results are not transferable between locations and years (Rasmussen and Hanks, 1978), conducting experiments is time consuming and expensive, and it is almost impossible to generate information on numerous alternatives available in the optimisation process by experiments. On the other hand in a simulation technique, all the intricate processes involved in the crop-soil-climate system can be modelled mathematically using known principles, empirical relations and basic data. It is, therefore, possible to quantify different physical aspects of the system for different alternatives. The estimation can be approximated to accuracy by calibrating the simulation model with a test set of experimental data. The solutions can be obtained quickly for different locations, time and alternatives. Therefore the simulation technique has gained enormous popularity in irrigation water management. In the present study the simulation model (SWAB-CRYB) is developed to generate the information needed for allocating the resources in third and fourth phases of AWAM. Specifically the purpose of SWAB-CRYB in the present study in accordance with Hypothesis 1, can be summarised as

(1) To estimate the soil water content over the depth of the soil root zone, actual crop evapotranspiration, soil evaporation, actual transpiration and deep percolation at various instances of time during the crop growth period.
(2) To estimate the depth of irrigation water to be applied at different irrigations during the crop growth period according to the predetermined irrigation strategy (estimation is not necessary if the depth of irrigation water to be applied is predetermined).
(3) To estimate the crop yield and net benefits.

The information in (1) is necessary for calibration and testing of the model and to generate information in (2) and (3). The information in (2) and (3) which constitutes the irrigation programme is necessary for the third and fourth phases of AWAM (screening of irrigation programmes and allocation of the resources).

The SWAB-CRYB model is presented in two submodels

1. Soil WAter Balance (SWAB) submodel
2. CRop Yield Benefit (CRYB) submodel

5.3.2 System Details

The SWAB-CRYB model is formulated to represent a system which generates benefits through crop production in response to application of various inputs (water and other resources such as seeds, fertiliser etc.). This system in the present study is termed the irrigated agricultural system. The irrigated agricultural system is further divided into three main and two auxiliary subsystems from the point of studying the influence of irrigation water (one of the inputs) application on crop yield and net returns. These subsystems are listed below.

Main subsystems
(1) Soil subsystem,
(2) Crop subsystem,
(3) Atmospheric subsystem,

Auxiliary subsystems
(1) Irrigation subsystem,
(2) Economic subsystem and
(3) Other subsystems

Other auxiliary subsystems include all subsystems related to crop production, excluding the irrigation subsystem (e.g. fertiliser application, capital supply etc.), and are assumed to be at standard or optimum level in the present study. The characteristics of all the five subsystems are described below. The aim of this section is not to describe all the characteristics of these subsystems but only those related to irrigation and considered for building the SWAB and CRYB sub-models.

5.3.2.1 Soil subsystem

The soil zone with depth equivalent to the maximum length of crop roots (soil root zone) forms this subsystem. Water required by the plant for its growth (transpiration) is available through this subsystem. The plant extracts water from only that part of the soil subsystem in which its roots are spread. Some water is lost to the atmosphere from this subsystem evaporation. The combination of the two processes (evaporation and transpiration) taking water out from the subsystem is known as evapotranspiration. Not all the water stored in this subsystem is available to the plant. The water held in the soil above and below certain limits is not available to the plant. These limits are field capacity and wilting point, respectively. The depth of the water stored in the soil between these two limits is available soil water.

If sufficient amount of water is available in this subsystem all the time, the plant can abstract water according to its need and its growth is not hampered due to shortage of water through water stress. However due to the particular nature of the irrigation subsystem considered (rotational water supply, surface irrigation method and limited water supply), water may not be made available in sufficient amount all the time and crops may suffer from shortage of water. When the water available in this subsystem is reduced below a level from which plant can draw water easily, the plant is subjected to stress due to shortage of water in the plant subsystem to meet atmospheric demands, which effects the output of the crop subsystem. This level is known as soil water depletion level and depends on the type of crop, the atmospheric demand and soil type. This is represented by equation (5.9).

$$\theta p_t^R = \theta w^R + (\theta f^R - \theta w^R)(1 - p_t) \quad (5.9)$$

where

θp_t^R = volumetric soil moisture content in the entire root zone at depletion level (mm/mm) on t^{th} day

θf^R	=	volumetric soil moisture content in the entire root zone at field capacity (mm/mm)
θw^R	=	volumetric soil moisture content in the entire root zone at wilting point (mm/mm)
p_t	=	depletion factor on t^{th} day
R	=	superscript to indicate the values are over entire root zone.

The water content in this subsystem is often required not to drop below a certain level (to act as safety factor while applying the results of the model in real time operation or to obtain expected minimum level of crop yield) which may be above or below the depletion level. This level is known as allowable level of soil moisture and is represented by equation (5.10).

$$\theta\omega^R = \theta w^R + (\theta f^R - \theta w^R)\,\omega \tag{5.10}$$

where

$\theta\omega^R$	=	volumetric soil moisture content in the entire root zone at allowable level (mm/mm)
ω	=	allowable level factor

Different types of soils can be encountered in the scheme and these may have different field capacity and wilting point and thus water available to crop. As the water in the system is limited, there is a possibility, that soil moisture will drop below depletion the level (θp_t^R). The magnitude of depletion and its occurrence for the given irrigation schedule depend on soil type (other factors being constant) and the same crop may respond differently to different amount and occurrence. Therefore for the same irrigation schedule in the limited water situation, different responses can be expected from the same crop grown in different soils.

The water is added to this part of the system by the irrigation subsystem or atmospheric subsystem. The water can also be transferred from and to the other parts of the soil subsystem by capillary rise and deep percolation, respectively.

5.3.2.2 Crop subsystem

The plant which forms this subsystem abstracts water through its roots from the soil subsystem, transports it upwards through its stem, and finally releases it into the atmosphere through the stomatal openings of the leaves in the form of water vapour.

The supply of energy to vaporise water comes from the atmosphere (solar or wind energy). This flow of water is transpiration and is controlled by the atmospheric demands. If the water available in the soil subsystem is above the depletion level, the plant meets the atmospheric demand fully, and the actual water transfer from the soil subsystem to the atmospheric subsystem by the process of transpiration, TR (or evapotranspiration, ET) i.e. actual TR (or actual ET) is equal to the potential TR (or maximum ET) of the given crop. But if water available in the soil subsystem falls below the depletion level, resistance to flow of water from soil subsystem to plant subsystem increases, and therefore less water is transferred through the crop subsystem to the plant subsystem. Thus the actual TR (or actual ET) is less than the potential TR (or maximum ET). The result of resistance to water flow is the development of water stress in the plant and its growth is affected and the yields are reduced. This also indicates that when actual TR (or actual ET) drops below potential TR (or maximum ET), the yields are affected. The response of plant growth to drop in water level in the soil subsystem below the depletion level also depends on its growth stage. Thus the actual TR (or actual ET) and crop yields are dependent on both the potential TR (or maximum ET) and also the water level present in the soil subsystem during the plant's different growth stages. If there is no water available for the plant in the soil subsystem, the plant may start to wilt and may not recover with the addition of water in the soil subsystem.

The length of plant roots is different during different crop growth periods and hence the water available from the soil subsystem is also different even when other conditions are similar.

5.3.2.3 Atmospheric subsystem

This subsystem transfer water to or from the soil subsystem. The water is removed from soil subsystem directly by the process of evaporation and through the plant subsystem by the process of transpiration. The sources of energy for these processes are solar and wind which are variable with time and space. Therefore the loss of water through the evaporation from the soil, or transpiration through plant, is not the same over the entire crop period. The atmospheric subsystem adds water to the soil subsystem by the effective part of the rainfall. Rainfall is also a time dependant process. In semi arid and arid regions little rainfall is received in some part of irrigation season so that the addition of water by the effective rainfall is less than the removal of water by the process of evapotranspiration. The atmospheric subsystem supplies water to the irrigation subsystem directly by rainfall or through the runoff from the river.

5.3.2.4 Irrigation subsystem

When the rainfall is not sufficient to meet the ET requirements, the artificial application of water is required in the soil subsystem so that plant can survive. The irrigation subsystem does this. The irrigation subsystem may have the stored water in the reservoir received before the start of irrigation season, and may receive the water during the irrigation season by river runoff. This subsystem consists of the conveyance and distribution network to bring the water to the farm from its headworks and some method of application to add the water into the soil subsystem. The distribution network may operate continuously or intermittently and may supply water to the farm on demand or at some fixed instances of time. The irrigation method may add water to the soil subsystem continuously (drip) or intermittently (other methods). The irrigation subsystem under consideration consists of the conveyance network, the lower level canals (secondary and tertiary) which operate on rotation and deliver water to the farm at fixed instances of time, and the method of application which adds water to the soil subsystem at discrete time intervals (at the instance when water is delivered to the farm). Alternately pipelines may be used instead of canals.

5.3.2.5 Economic subsystem

This subsystem converts the crop yield into benefits and also computes the total cost of inputs required to derive the benefits. The water transferred from the irrigation subsystem to the soil subsystem controls the benefits and total costs (when other auxiliary subsystems are at optimum level) and thus the net returns.

A pictorial representation of the inter relationship among various subsystems in the system is shown in Figure 5.1. The detail description of SWAB and CRYB submodels are given in the Sections 5.3.3 and 5.3.4, respectively. The SWAB and CRYB submodels in the form of flow charts are shown in Figures 5.2 and 5.3, respectively.

5.3.3 The Soil Water Balance (SWAB) Sub-model

The SWAB sub-model generates the information listed in purposes (1) and (2) (Section 5.3.1). The maximum and actual crop evapotranspiration and transpiration estimated by this model act as the input to CRYB sub-model. Various types of simulation model developed for this purpose and the development of SWAB model are discussed in this section.

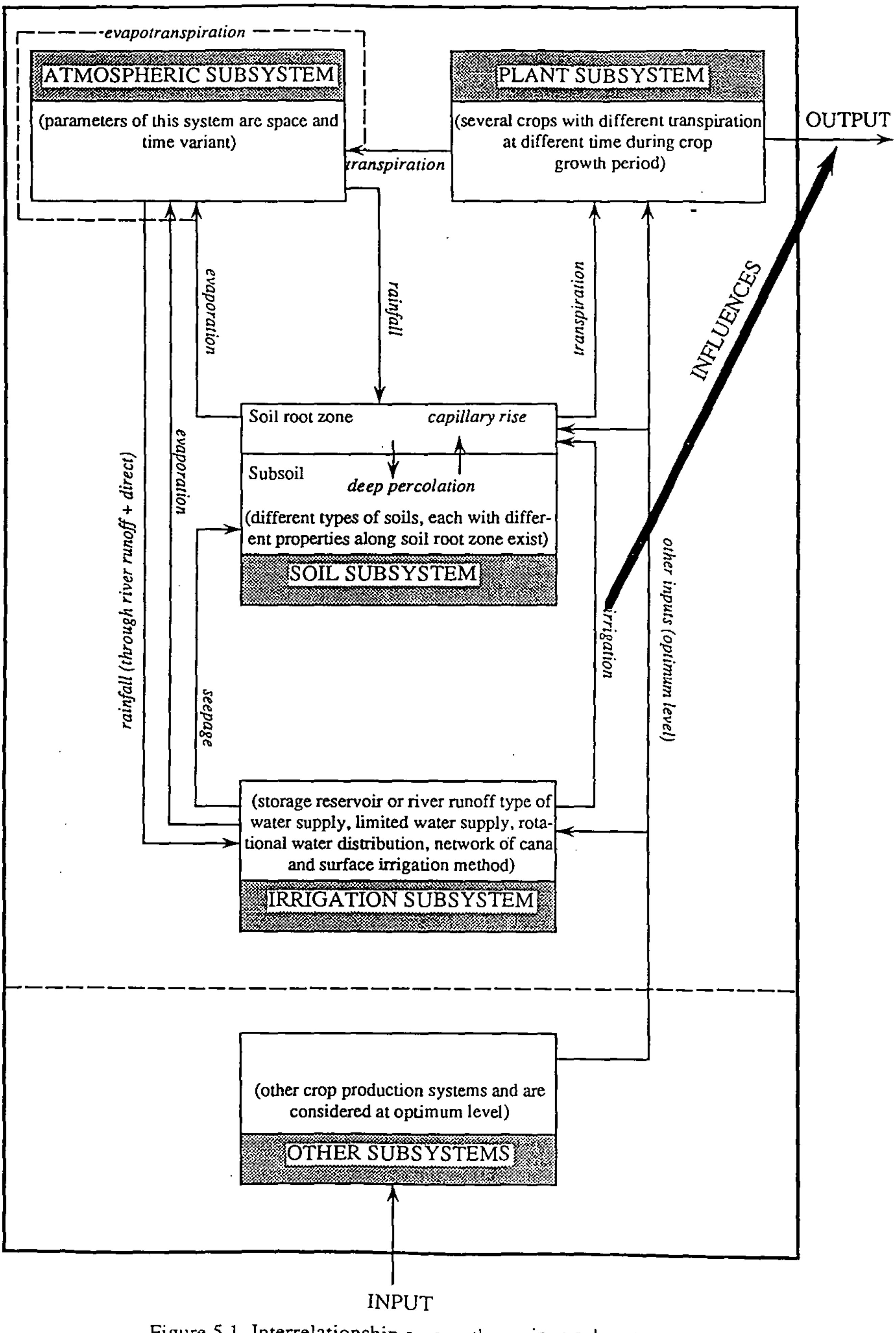


Figure 5.1 Interrelationship among the various subsystems

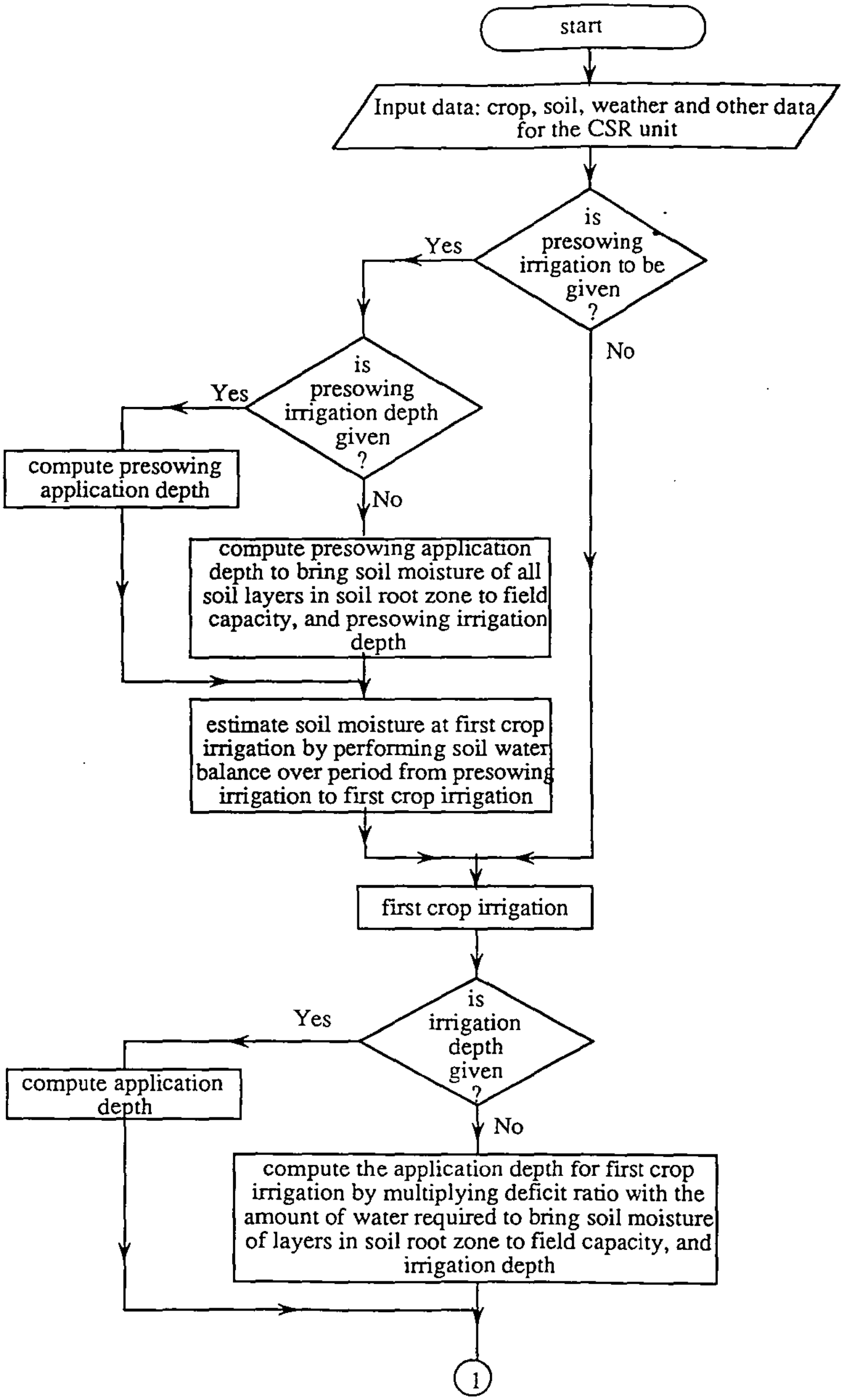
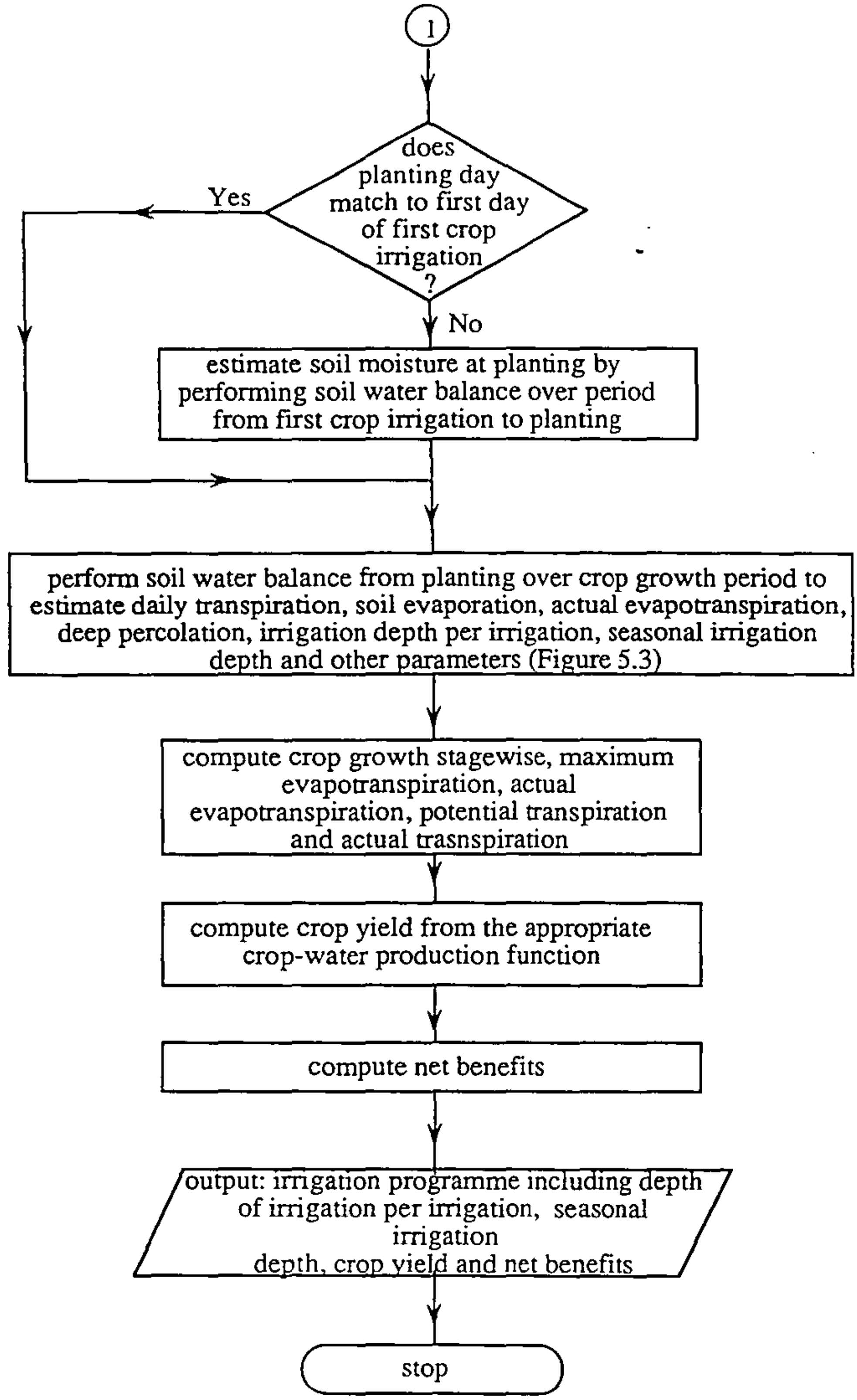


Figure 5.2 The schematic representation of SWAB and CRYB submodels for preparation of irrigation programmes for the CSR unit (contd..)


1
does planting day match to first day of first crop irrigation ?
Yes
No
estimate soil moisture at planting by performing soil water balance over period from first crop irrigation to planting
perform soil water balance from planting over crop growth period to estimate daily transpiration, soil evaporation, actual evapotranspiration, deep percolation, irrigation depth per irrigation, seasonal irrigation depth and other parameters (Figure 5.3)
compute crop growth stagewise, maximum evapotranspiration, actual evapotranspiration, potential transpiration and actual trasnspiration
compute crop yield from the appropriate crop-water production function
compute net benefits
output: irrigation programme including depth of irrigation per irrigation, seasonal irrigation depth, crop yield and net benefits
stop

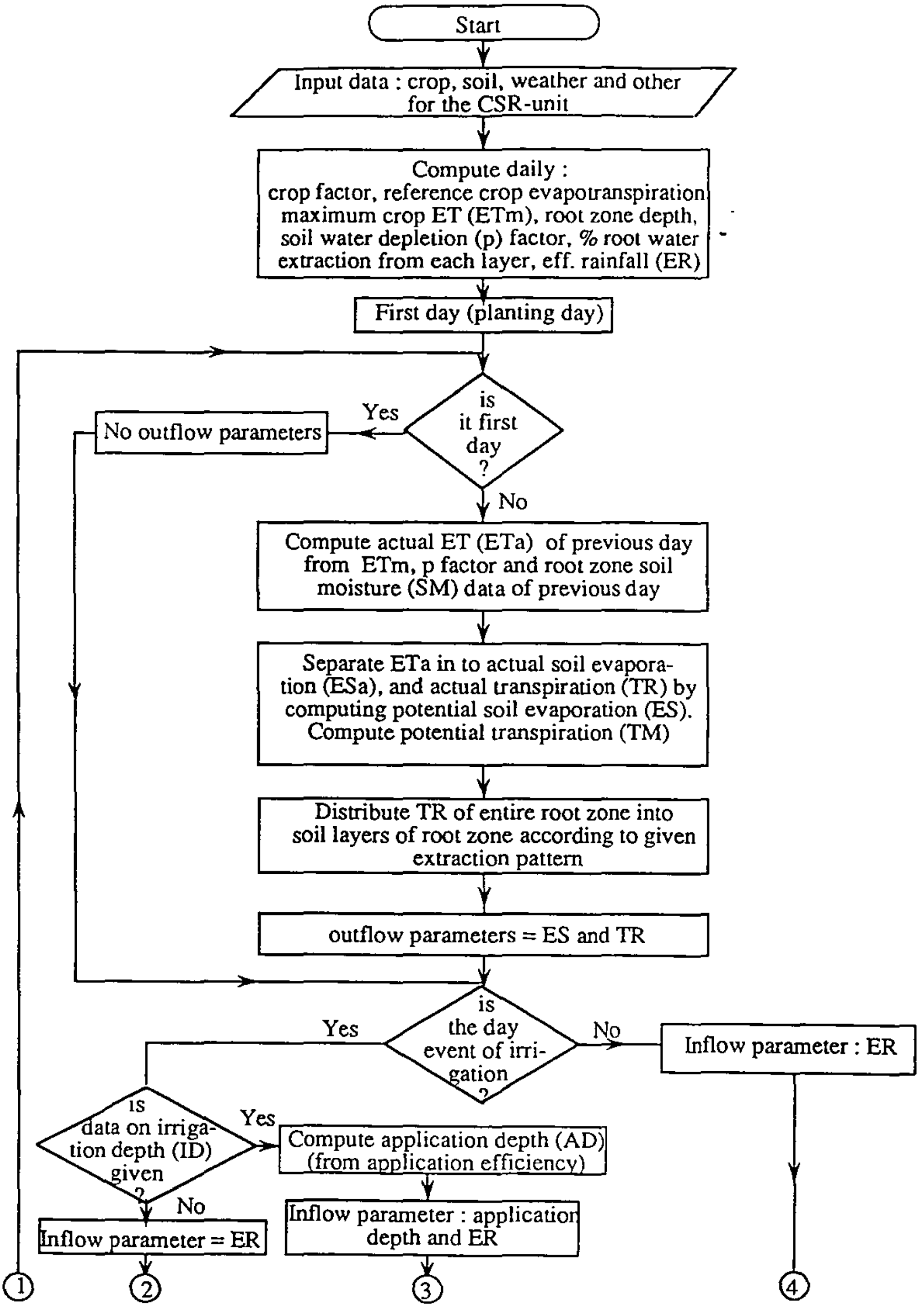
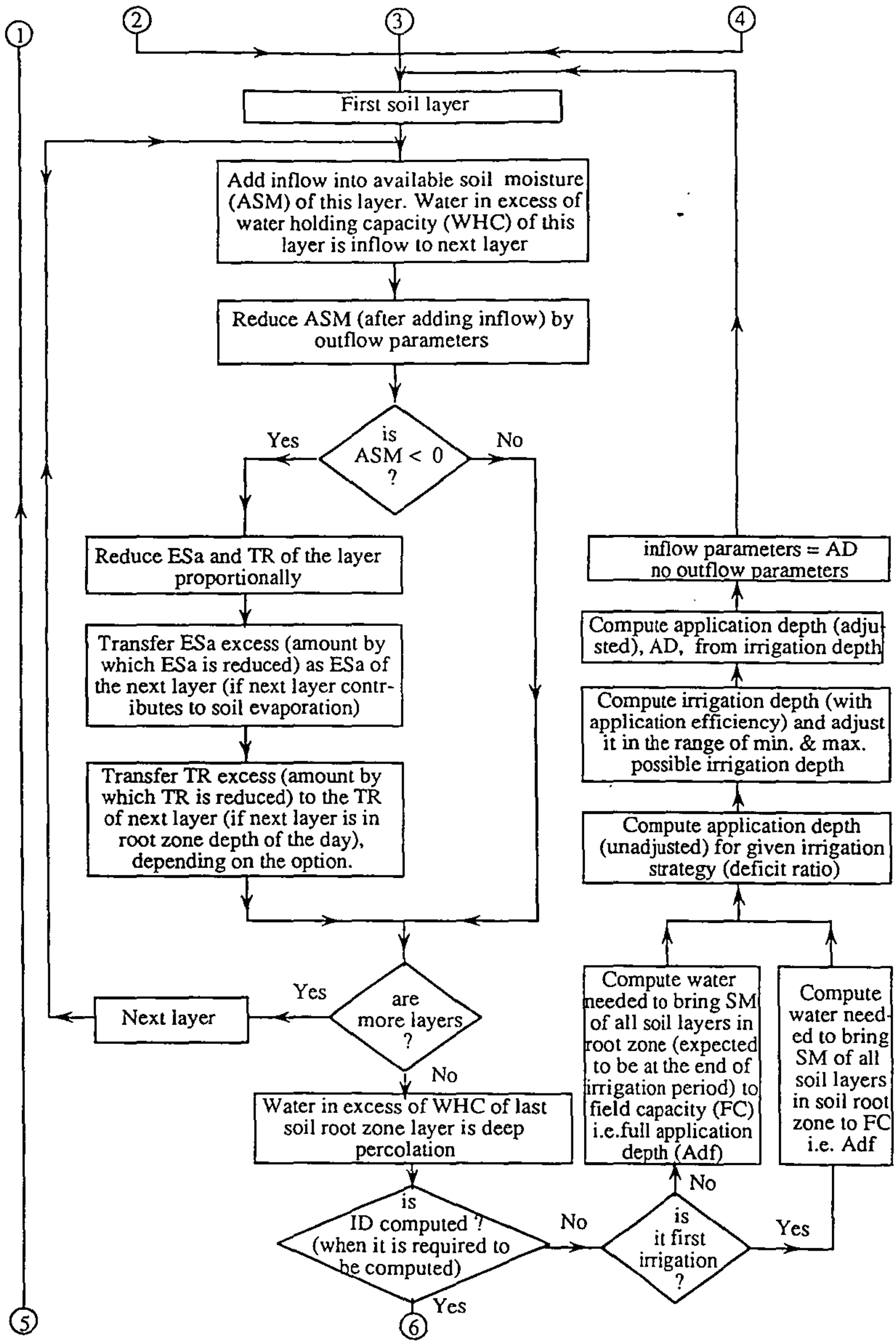
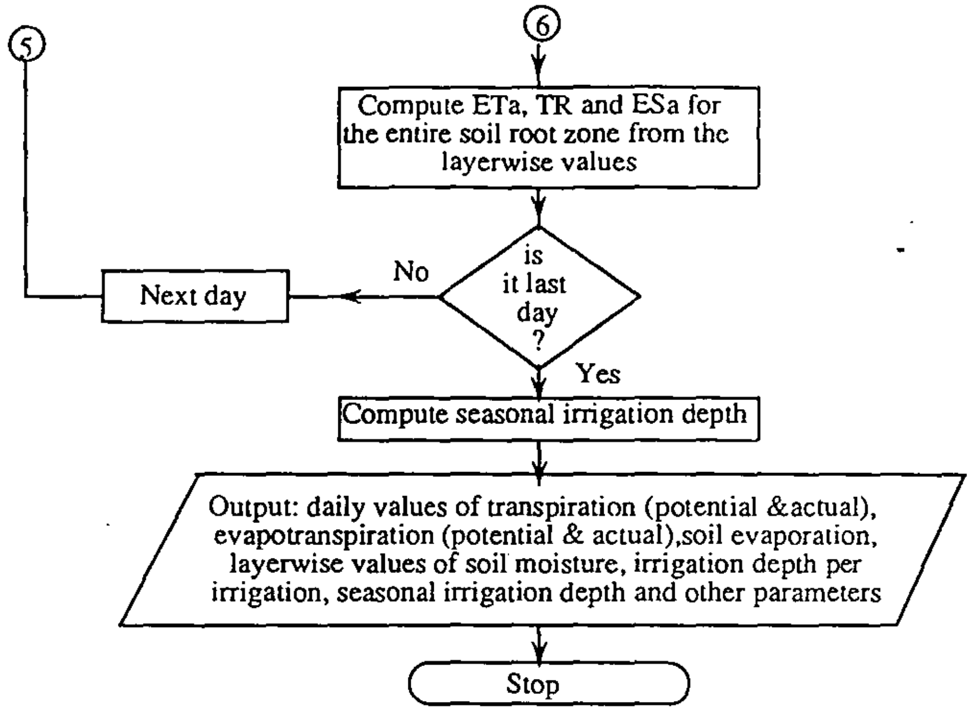


Figure 5.3 : The flow chart of SWAB submodel over the crop period (contd..)


1
2
3
4
First soil layer
Add inflow into available soil moisture (ASM) of this layer. Water in excess of water holding capacity (WHC) of this layer is inflow to next layer
Reduce ASM (after adding inflow) by outflow parameters
is ASM < 0 ?
Yes
No
Reduce ESa and TR of the layer proportionally
Transfer ESa excess (amount by which ESa is reduced) as ESa of the next layer (if next layer contributes to soil evaporation)
Transfer TR excess (amount by which TR is reduced) to the TR of next layer (if next layer is in root zone depth of the day), depending on the option.
inflow parameters = AD no outflow parameters
Compute application depth (adjusted), AD, from irrigation depth
Compute irrigation depth (with application efficiency) and adjust it in the range of min. & max. possible irrigation depth
Compute application depth (unadjusted) for given irrigation strategy (deficit ratio)
Next layer
Yes
are more layers ?
No
Water in excess of WHC of last soil root zone layer is deep percolation
Compute water needed to bring SM of all soil layers in root zone (expected to be at the end of irrigation period) to field capacity (FC) i.e.full application depth (Adf)
Compute water needed to bring SM of all soil layers in soil root zone to FC i.e. Adf
No
is ID computed ? (when it is required to be computed)
No
is it first irrigation ?
Yes
Yes
5
6


6
5
Compute ETa, TR and ESa for the entire soil root zone from the layerwise values
is it last day ?
No
Next day
Yes
Compute seasonal irrigation depth
Output: daily values of transpiration (potential &actual), evapotranspiration (potential & actual),soil evaporation, layerwise values of soil moisture, irrigation depth per irrigation, seasonal irrigation depth and other parameters
Stop

5.3.3.1 Simulation models

The estimation of soil moisture by simulation technique consists of studying the flow of water in the soil root zone, which may be saturated, unsaturated or both, and various sources and sinks. The flow of water in the soil is non-linear as both the hydraulic conductivity and soil water pressure head depends on the soil water content (Feddes et al., 1988). The various sources are rainfall, irrigation water and capillary rise, and sinks are soil evaporation and transpiration or root water uptake. Each of these is governed by different laws and has influence on soil water content. Besides these, soil, crop and climate have complex characteristics. All these factors are discussed in detail by Walley (1983). Therefore the simulation of soil water becomes extremely difficult if the system is to be represented truly. Several simplifying assumptions are made in the simulation model to estimate the soil water content, depending on the accuracy required, availability of data, computational facility and purpose. The models can be as simple as involving only just one equation containing addition and subtraction of different parameters in the process (Jensen et al., 1971 and Stegman, 1983) to involving the numerical methods to solve differential equations to obtain the solutions (Feddes et al., 1988 and Braud et al., 1995).

Models based on simulation technique can be broadly classified into two groups depending on one important assumption made :

"The input of water in to the entire soil zone (or soil layers) is instantaneously distributed and similarly the removal of water from soil in response to any demand from soil is instantaneous."

The models which do not operate under the influence of this assumptions are complex to solve due to presence of non-linear differential flow equations. In this study these models are called 'soil water flow and balance models'. Under the influence of the above assumption the estimation of soil water reduces to the determination of various parameters influencing the soil water content in the soil zone and their balance. The various equations governing the flow of water are not considered. Therefore these models are simple in computation but are physically limited as they do not allow water flow to be influenced by time and thus may not be accurate in estimation. These models are refered to as 'soil water balance models' in this study. The concepts behind these models, methods of obtaining the solutions and brief review are presented in the following sections.

The Soil Water Flow and Balance Models

The flow of water in saturated or unsaturated soil zone is modelled by mathematical models, and solutions in respect of water content at various instances of time along the depth of soil zone are obtained. A mathematical model is a mathematical expression, or group of expressions that describes the various relations (hydraulic relations) within the system (soil root zone-time region). It is usually in the form of a differential equation or set of differential equations together with the auxiliary conditions. The differential equations which provide the basis for specification of the system functioning are based on the laws governing system variables such as flows or soil water potentials. Auxiliary conditions describe the system geometry, hydraulic characteristics of the system matrix, or system parameters and initial and boundary conditions. Richards (1931) presented the differential equation for soil water flow which forms the basic mathematical expression that underlines unsaturated flow phenomenon. The equation describing one dimensional vertical water movement in isotropic non swelling soils with sink term is represented by equation (5.11).

$$\frac{\delta\theta}{\delta t} = \frac{\delta[\phi(\theta)\frac{\delta\theta}{\delta z}]}{\delta z} - \frac{\delta K(\theta)}{\delta z} - S(\theta) \qquad (5.11)$$

where

t	=	time
z	=	vertical distance from soil surface
θ	=	volumetric soil moisture content
$K(\theta)$	=	unsaturated hydraulic conductivity as a function of soil moisture, θ
$\phi(\theta)$	=	soil moisture diffusivity = $K(\theta)\frac{\delta\psi}{\delta\theta}$
ψ	=	pressure head
$S(\theta)$	=	sink term (normally water uptake by plant)

Feddes et al., (1988) reviewed extensively the principles underlying soil water dynamics in unsaturated zone under different situations.

The matrix characteristics of interest describe the capacity of the flow region to transmit water and store water. These are described by hydraulic conductivity and soil water content at field capacity and wilting point, respectively. Some of these may vary from point to point (non-homogenous) and with direction (anisotropic).The initial conditions are the values of pertinent system variable at the initial time such as the initial soil water content or soil water content at t=0 along the depth of soil root zone and boundary conditions which describes the conditions at geologic boundaries such as soil water content at upper and lower boundaries of soil water zone. The sink term represents the soil water extraction by roots. The solutions are obtained for the values of soil water potential throughout the system at all times. Solutions to governing equations can be obtained by analytical or numerical methods (finite difference or finite elements). However the numerical method with finite difference approach is extensively used to obtain the solutions to such models. The finite element approach was used in some models. These approaches are described in short below.

In finite difference approach, a grid is superimposed on the region of interest (soil depth-time). Each point of intersection is called as 'node' or 'mesh point'. Then the derivatives at each of a number of mesh points is replaced by ratios of the change of soil water potential over a small but finite interval by forward difference scheme, backward difference scheme or central difference scheme (Crank-Nicholson method). This along with initial and boundary conditions results in a set of algebraic equations which can be solved by different methods to obtain the solution at each node at various instances of time.

Several models are developed in this category. These are based on two approaches : (1) microscopic and (2) macroscopic (Afshar and Marino, 1978). In microscopic approach, the water uptake or flow is considered to or from single root (Philip, 1957; Gardener, 1960; Molz et al., 1968 and Molz, 1976). However this approach is difficult to test experimentally and is not directly applicable to field because of consideration of single root (Afshar and Marino, 1978 and Feddes et al., 1988). In macroscopic approach, the removal of moisture from the entire soil root zone as whole (with the help of volumetric sink term) is considered (Gardener, 1964, Whisler et al., 1968; Molz and Remson, 1970; Nimah and Hanks, 1973; Feddes et al., 1974; Feddes et al., 1976; Neumann et al., 1975; Afshar and Marino, 1978). This approach was used for studying the flow of water in soil root zone and simulating the soil water content in irrigation related studies (Narda and Curry, 1981; Belmans et al., 1983; Norman and Campbell, 1983; Yaron and Bresler, 1983; Jain and Murty, 1985; Stockle and Campbell, 1985; Dierckx et al., 1988; Malik et al., 1989; Workman and Skaggs, 1990; Kemachandra and Murty, 1992; Murty et al., 1992; Binh et al., 1994 and Braud et al., 1995).

In finite element method the flow region is descretised in to the finite elements, each corner of element acting as node at which the value of stated variable of interest (soil water potential) is to be computed. The co-ordinates of each node are specified. The appropriate equations are defined over each set of nodal points and written in terms of the unknown nodal value. The equations are written for all elements. The set of differential equations are obtained by the application of variational or weighted residual principles. These are solved to obtain the solution.

Marino and Tracy (1988) and Witono and Bruckler (1989) (for bare soil) developed the models using finite element approach.

Soil Water Balance Models

The soil root zone-time region is assumed as finite system. The principle of continuity is applied to the system which states that difference between inflow and outflow to or from the system is change in water content over the considered time period and is represented by the equation (5.12).

$$\theta_t^Z \, ZT = \theta_{t-1}^Z \, ZT + INF_t - OTF_t \tag{5.12}$$

where

θ_t^Z	=	volumetric water content at the end of period t in soil root zone (mm/mm)
INF_t	=	inflow of water into the system during period t (mm)
OTF_t	=	outflow of water from the system during period t (mm)
t	=	index for time period
ZT	=	depth of soil root zone (mm)
Z	=	superscript to indicate that the values are over the soil root zone

The solution to equation (5.12) is obtained by solving the individual components over the considered time interval.

The simplicity and complexity of these models vary depending on the inflow/outflow parameters considered, methods of estimation used in computing the values of these parameters, discretization of soil root zone and period of balance. Numerous models are developed under this category. Though it is difficult to categorise these models under different types, the essential features represented in different models vary according to

(1) Time step : Time period of water balance is one day, one week, a decade (ten days), month or irrigation period.

(2) Discretization of soil zone : Soil root zone is considered as homogeneous or divided in to number of layers, with each layer having different properties influencing irrigation.
(3) Partitioning of evapotranspiration : Evapotranspiration is split in to evaporation and transpiration or considered as whole.
(4) Root zone : Static root zone or growing root zone.

Besides these, the methods to compute and models to represent root growth, moisture extraction, evapotranspiration, soil evaporation, transpiration, crop factors, soil water depletion factor vary in different soil water balance models.

The soil water balance models are generally developed for following purposes.

(1) To know when and how much to irrigate so that the plant is not subjected to more stress than prescribed.
(2) To estimate irrigation water requirement and crop yield.
(3) To include in allocation model, where in land and water resources are optimally allocated to different crops.

In many studies several criteria are evaluated to satisfy the given objective.

The simplest form of soil water balance model is the one which includes addition and subtraction of different inflow and outflow parameters over certain period (Jensen et al., 1971; Fereres et al., 1981; Pleban and Israeli, 1989; Stegman, 1983; Shayya et al., 1990; Clarke et al., 1992 and Foroud et al., 1992) and is used for purpose (1).

The estimation is improved by incorporating the procedure to estimate actual evapotranspiration and representing root growth over the crop period by a suitable model. In some such type of models all the parameters are either computed at midpoint of irrigation period or assumed to be uniform or lumped over the irrigation period (Rhenals and Bras, 1981; Tsakiris and Kiountouzis, 1984; Rao et al., 1988[a]; Rao et al., 1990; Vedula and Mujumdar, 1992). All of these studies used dynamic programming in the optimisation part and therefore considered the time period corresponding to the irrigation period and soil as homogeneous. The soil water balance models used by Schmidt and Plate (1980), Rees and Hamlin (1983), Hiessl and Plate (1990), Jian (1990) and Hales (1994) in water allocation studies operated on daily basis. Some such models used for estimating soil moisture or predicting crop yield are formulated by Rao (1987), Raes et al., (1988), Bhirud et al., (1990), Ahmad and Heermann (1992) and Teixeira and Pereira (1992). The more rigorous analysis and more details (such as soil as multilayer, daily or hourly time step, separation of evapotranspiration in to evaporation and transpiration) were not considered in those models to minimise the time requirement to obtain the solution and to keep the number of state variables within a manageable limit. Some soil water balance models considering most of these details are reviewed below. These are mostly used for irrigation scheduling studies or in optimisation models which do not need soil water balance model in iterative mode. The examples of these models are those developed by Hanks (1974), Rasmussen and Hanks (1978), Retta and Hanks (1980), Sudar et al., (1981), Wally and Hussein (1982), Martin et al., (1984), Smith et al., (1985),. Chesness et al., (1986), Sammis et al., (1986), Arora et al., (1987), Schouwenaars (1988), Vilalobos and Fereres (1989), Tuzet et al., (1992), Majeed et al., (1994), Shanholtz and Younos (1994) for scheduling and estimation purposes and by Swaney et al., (1983) and Steiner (1991) in optimization models.

5.3.3.2 Criteria for development of model

The proposed SWAB sub-model which is a part of SWAB-CRYB sub-model is needed in AWAM in which numerous irrigation strategies are evaluated over the various allocation units in an irrigation scheme. As discussed earlier, each allocation unit may be characterised with different soils over which various crops can be grown. Similarly different allocation units may have different soils, crops and climatic conditions. Therefore it was thought appropriate to develop the model

- which needs the data which can be found or obtained in the irrigation scheme at various levels,
- is computationally efficient,
- represents important processes influencing the soil water content, irrigation water requirement and crop yield and
- suitable for calibration for different situations.

The water flow-balance type of models are, therefore, not suitable as it consumes a lot of computer time and needs a large amount of data to get the solution. Therefore for the present study the model of water balance type is developed by incorporating the important process and giving consideration to availability of data at different points in the irrigation scheme. Most of the processes considered in the study are modelled by adopting the appropriate theories developed in soil water balance studies. The criteria discussed above influence the choice of the particular method. For some of the processes, satisfactory methods were not available to suit the above criteria. In such cases (separation of transpiration and evaporation, soil water uptake pattern), the appropriate relationships have been devised.

5.3.3.3 Model description

Assumptions

As described earlier, the irrigated agricultural system is complex and variable with space and time. The model is based on certain simplifying assumptions. These are listed below.

(1) Water added into the soil root zone is instantaneously distributed into the soil root zone and water removal from soil root zone is also instantaneous.
(2) The water content in the soil root zone at the beginning of the growing period is known.
(3) Water is added into the soil root zone by rainfall and irrigation and removed from the soil root zone by transpiration, soil evaporation and deep percolation.
(4) Water table is deep enough not to cause any rise of water due to capillary process.
(5) The processes such as evaporation from soil, transpiration, rainfall are assumed to occur in a lumped manner at the end of the time period and irrigation is applied at the beginning of the time period.
(6) The soil root zone and irrigation water is free from salinity.

Other assumptions used in the formulation of model are described wherever they are used.

Effective Rainfall

The effective rainfall is computed as certain fraction of total rainfall. This fraction can vary with soil and crop but not with soil moisture status, crop growth parameters and intensity and duration of rainfall. The detailed computation of effective rainfall is not included for the following reasons.

(1) The model is developed for the irrigation schemes in arid and semi-arid regions. In such regions little or no rainfall is expected during the most part of irrigation seasons. The fields in the irrigation schemes are usually designed for surface irrigation methods. Therefore they have little slope. Similarly the fields are generally small in size and bunded. In such situations, entire rainfall can be considered to be infiltrated in to the soil, if the evaporative loss of rainfall intercepted by vegetation is assumed to be negligible.

(2) The detailed analysis of effective rainfall on the basis of soil moisture status, crop growth stage and intensity and duration of rainfall may increase the computational time, without adding much to the accuracy.

The effective rainfall is computed by the equation (5.13) (Dastane, 1974)

$$RFe_t = (1-\alpha)RF_t \tag{5.13}$$

where

RFe_t	=	effective rainfall amount on t^{th} day (mm)
RF_t	=	total rainfall amount on t^{th} day (mm)
α	=	runoff coefficient

Reference Crop Evapotranspiration

Various methods to compute reference crop evapotranspiration (ETr) are available in literature and used in the allocation models. Which one to use depends on data availability, data accuracy, accuracy needed in estimation and its suitability to the climatic condition (Doorenbos and Pruitt, 1984; Jensen et al., 1990 and Smith, 1991). In the present study, four different methods are considered. These are listed below.

1. Penman-Monteith method (Smith, 1991)
2. Modified Penman method (Doorenbos and Pruitt, 1984 and Smith, 1991)
3. Hargreaves-Samani (temperature) method (Hargreaves et al., 1985 and Samani and Pessarakli, 1986)
4. Pan evaporation method (Doorenbos and Pruitt, 1984)

The basis for selecting these four methods are discussed below.

Comparison among various methods at different locations (Jensen, 1973; Dugas and Ainsworth, 1985; Samani and Pesarakli, 1986; Tsakiris, 1986; Jong and Tugwood, 1987; Abderrhman et al., 1989 and Jensen et al., 1990) showed that combination method in form of some Penman equation and Penman-Monteith equation and Hargreaves-Samani method were the methods which performed better than other methods at many locations. Combination methods are based on a theoretical concept considering most of the parameters influencing evapotranspiration. The modified Penman method is presently being used in most of the irrigation schemes in India and other developing countries for computing reference crop evapotranspiration. The Penman-Monteith method was recently recommended by FAO as the best performing combination equation to compute ETr (Smith, 1991). The Hargreaves-Samani and pan evaporation method needs relatively less of data which are readily available at most of the irrigation schemes. Many studies related to allocation of resources (reviewed in Chapter II) either preferred modified Penman or pan evaporation method to compute ETr.

The input of ETr computed from other methods can also be given in the SWAB model.

Maximum Crop Evapotranspiration

Maximum crop evapotranspiration (ETm) which is the ET when water is not limited and is different from ETr due to effect of crop characteristics and weather conditions is computed by equation (5.14).

$$ETm_t = Kc_t \, ETr_t \tag{5.14}$$

where

ETr_t	=	reference crop evapotranspiration on t^{th} day (mm)
ETm_t	=	maximum crop evapotranspiration on t^{th} day (mm)
Kc_t	=	crop factor on t^{th} day

Crop factors values specified for different crop growth stages or in equation form can be used. If the stage wise crop factor values are used, the daily crop factor values can be the crop factor value corresponding to the stage for the day or can be obtained by interpolation. The equation form of crop factor values are represented by the polynomial equations (5.15) and (5.16).

$$Kc_t = m_0 + m_1 t + m_2 t^2 + \ldots\ldots + m_n t^n \tag{5.15}$$

$$Kc_t = m_0 + m_1(t/T) + m_2(t/T)^2 + \ldots\ldots + m_n(t/T)^n \tag{5.16}$$

where

T	=	crop period (days)
n	=	order of equations
$m_o, m_1, \ldots\ldots m_n$	=	coefficient of equations
t	=	days since planting

The direct input of daily crop factor values can also be given. In the absence of appropriate crop factor values, the crop factors are estimated by adopting the values of stage wise crop factors and the method proposed by Doorenbos and Pruitt (1984).

Actual Evapotranspiration

The plant transpires at its potential rate until the water available in the soil root zone is above the critical level, below which the soil water conditions begin to limit the transpiration process. Therefore when soil water content drops below the critical level, water removed by the process of evapotranspiration (actual ET or ETa) becomes less than the ETm (Hanks, 1974; Rijetma and Aboukhaled, 1975; Slabbers, 1980 and Doorenbos and Kassam, 1986). Based on the formulation of Rijetma and Aboukhaled (1975), Doorenbos and Kassam (1986) proposed that ETa equals to ETm until the readily available soil water (fraction of available soil water) has been depleted. Beyond this depletion ETa becomes increasingly smaller than ETm until the next application of water and its magnitude depends on remaining soil water content and ETm. The mathematical representation included in the model based on the formulation of Doorenbos and Kassam (1986) is given by equation (5.17).

$$\begin{aligned} ETa_t &= ETm_t \\ &\quad \text{if } (\theta_t^R - \theta w^R) Z_t \geq (1 - p_t)(\theta f^R - \theta w^R) Z_t \\ ETa_t &= [(\theta_t^R - \theta w^R) Z_t \, ETm_t] / [(1 - p_t)(\theta f^R - \theta w^R) Z_t \\ &\quad \text{if } (\theta_t^R - \theta w^R) Z_t < (1 - p_t)(\theta f^R - \theta w^R) Z_t \end{aligned} \tag{5.17}$$

where

ETa_t	=	actual crop ET on t^{th} day (mm)
θ_t^R	=	volumetric soil moisture content in the root zone depth (mm) on t^{th} day
p_t	=	soil water depletion factor t^{th} day
Z_t	=	depth of root zone on t^{th} day

Soil Water Depletion Factor

The values of p depends on crop, magnitude of ETm and soil. The p values for different crop and ETm are adopted from Doorenbos and Kassam (1986). The p values can also be computed by the function given by equation (5.18).

$$p_t = p2 - \frac{p2 - p1}{ETm1 - ETm2}(ETm1 - ETm_t) \tag{5.18}$$

where

ETm1 = maximum value of ETm (mm/d)

ETm2 = minimum value of ETm (mm/d)

p1 = p value corresponding to ETm1

p2 = p value corresponding to ETm2

$p1 \leq p2$

The equation represents the linear variation of p from p1 at maximum ETm to p2 at minimum ETm. The p is constant over the entire crop period if p1=p2.

Separation of Evaporation and Transpiration

Actual evapotranspiration constitutes the actual transpiration and actual soil evaporation. Transpiration returns the water to atmosphere through the root zone while the soil evaporation takes place from soil near the surface (Hanks, 1974). In some studies ET is not separated in to evaporation and transpiration, especially those which considered entire soil root zone homogeneous in soil and used crop growth models which related actual crop ET with crop yield (Jensen et al., 1971; Raes et al., 1988; Rao, 1987; Pleban and Isreli, 1989; Ahmad and Heermann, 1992; Bhirud et al., 1992; Shanholtz and Younos, 1994 and many water allocation models reviewed in Chapter II (Section 2.4.2). Chesness et al., (1986), though considering the soil as layered, did not separate evaporation and transpiration.

Different approaches have been used to separate soil evaporation and transpiration in soil water balance models. All these approaches involve computing potential transpiration (or potential soil evaporation) and then subtracting it from potential evapotranspiration to obtain potential evaporation (or potential transpiration). The relationship between potential soil evaporation and potential transpiration is governed by the amount of solar radiation reaching the soil surface and solar energy intercepted by plant canopy. The method to separate potential transpiration and potential soil evaporation is based on the fact that during the plant growth, initially the transpiration is less and evaporation is more due to less plant cover and transpiration increases up to full cover. From full cover to harvesting transpiration again decreases due to leaf senescence and shading effects (Retta and Hanks, 1980). This phenomenon is represented by variation of crop factor over plant growth period (potential transpiration is assumed to be influenced by stage of crop growth) or leaf area index (potential transpiration is assumed to be influenced by leaf area development). Ritchie (1972), Sudar et al., (1981), Swaney et al., (1983), Smith et al., (1985), Arora et al., (1987), Schouwenaars (1988) and Kemachandra and Murty (1992) separated potential transpiration and potential soil evaporation from potential evapotranspiration by leaf area index. Hanks (1974), Rasmussen and Hanks (1978), Retta and Hanks (1980) and Martin et al., (1984), Sammis et al., (1986) used the crop factor to split potential transpiration and potential soil evaporation from potential evapotranspiration. Actual transpiration was considered as a function of soil water content in the soil root zone. The actual transpiration was computed on the assumption that transpiration is not influenced by the soil water status as long as the ratio of actual soil water storage to available water is greater than some threshold value and then decreases. In a layered soil this was done by either splitting potential transpiration into different layers and then computing actual transpiration for different layers (Hanks, 1974; Retta and Hanks, 1980 and Arora et al., 1987) or computing actual transpiration for the entire soil root zone and then splitting it in to actual transpiration of different layers (Rasmussen and Hanks, 1977; Sudar et al., 1981; Martin et al., 1984 and Sammis et al., 1986). Threshold value in these cases was assumed constant and 0.5 in most cases (0.7 by Swaney et al., 1983). The threshold value which was assumed as constant in previous studies, however, depends on crop, soil and climatic conditions. Doorenbos and Kassam (1986) published the threshold values below which if the ratio of actual soil water storage to available water drops, actual evapotranspiration drops below maximum crop evapotranspiration.

Actual soil evaporation in most cases was computed as a function of soil type, potential soil evaporation and the days since the last wetting occurred by following the procedure given by Ritchie (1972). He assumed that evaporation from soil occurs in two stages (constant rate and falling rate). In the constant rate stage, the soil can transmit water at a rate equal to evaporative demand. In the falling rate stage, the surface layer has dried and the soil can no longer transmit water at a rate to meet the atmospheric demand.

In the present model actual crop evapotranspiration is computed first with the help of values of depletion factor published by Doorenbos and Kassam (1986) or given values of depletion factor and the actual soil evaporation and actual transpiration are separated from actual crop evapotranspiration. The procedure is described below.

The potential soil evaporation is computed using the crop factor approach by equation (5.19).

$$ES_t = \left[1 - \left\{\frac{Kc_t}{Kc\max} - \frac{Kc\min}{Kc\max}\right\}\right] ETm_t \qquad (5.19)$$

where

ES_t = potential soil evaporation on t^{th} day (mm)

Kcmax= highest value of crop factor in crop growth period

Kcmin= lowest value of crop factor in crop growth period

Actual soil evaporation is assumed to be related to potential soil evaporation and the time since last wetting by the equation (5.20).

$$ESa_t = ES_t \qquad \text{if } tw \leq tp$$
$$ESa_t = ES_t\left(\frac{tp}{tw}\right)^{cs} \qquad \text{if } tw > tp \tag{5.20}$$

where

ESa_t = actual soil evaporation on t^{th} day (mm)

tp = the time since wetting till $ES_t = ESa_t$ (days)

tw = time since the last wetting in days

cs = exponent representing the decay of soil evaporation rate since the wetting.

Ritchie (1972), Hanks (1974), Rasmussen and Hanks (1978) Retta and Hanks (1980) Hanks and Hill (1980) and Martin et al., (1984) assumed cs as 0.5 whereas Arora et al., (1980) assumed cs as 0.3. The above studies assumed the value of tp as 1. It was assumed in these studies that all water for soil evaporation comes from top soil layer or layers.

In the present study, the soil layers existing in top few cms contribute to the soil evaporation. The soil evaporation from any layer is assumed to cease when soil moisture of that layer reaches wilting point.

Actual transpiration is computed by equation (5.21).

$$TR_t = ETa_t - ESa_t \tag{5.21}$$

where

TR_t = actual transpiration on t^{th} day (mm)

The potential transpiration is computed by equation (5.22).

$$TM_t = ETm_t - ES_t \tag{5.22}$$

where

TM_t = potential transpiration on t^{th} day (mm)

Root Growth Model

The transpiration needs are met by the water uptake by the roots, the depth of which varies over the crop season. Therefore the information of the development of depth of roots with time is necessary. The root growth is dependent on crop, soil type and management strategies. But in this study the root growth is assumed to be dependent on crop only.

In most cases the root growth variation with time follows the sigmoidal or some non-linear pattern (Rasmussen and Hanks, 1978; Borg and Grimes, 1986; Schouwenaars, 1988 and Subbaiah and Rao, 1993). However the linear model is widely used in the scheduling models and allocation studies. The linear model and sigmoidal model of Borg and Grimes (1986) are the function of maximum rooting depth and the time at which the crop attains the maximum rooting depth. The other models additionally need some empirical coefficients which are to be determined locally. In view of the assumption that root growth depends on crop type and to avoid the need of site specific empirical constants, the linear root growth and sigmoidal (Borg and Grimes, 1987) models are adopted for the present study. The sigmoidal model of Borg and Grimes is modified to include the depth of sowing. These are described by equations (5.23) and (5.24).

$$Z_t = Zo + (Zm - Zo)(t / tm) \tag{5.23}$$

$$Z_t = Zo + (Zm - Zo)[0.5 + 0.5\sin(3.03t / tm - 1.47)] \tag{5.24}$$

where

Z_t = depth of root zone on t^{th} day (mm)

Zm = maximum depth of root zone during crop growth period (mm)

Zo = initial depth of root zone (depth of sowing, mm)

tm = the day at which crop attains Zm since sowing

The specific information on root growth with time or results from other types of root growth model can be used in the model by directly giving the input of daily root zone depth.

The Extraction Pattern

It is assumed that the root water uptake is equal to the transpiration of the plant. The extraction of soil water by roots (transpiration) is different along the vertical root length mainly due to variation in root density (Prasad, 1988 and Stewart et al., 1985). Therefore the information on water uptake by roots at various depths is necessary to estimate the water depleted from the root zone at various depths.

In previous studies, two approaches were used to model the distribution of root water uptake in the soil root zone. These are

(1) Extractable water profile
(2)Variation of root density with respect to time and length

Extractable water profile

This approach is based on the assumption that the soil water is not extracted to the wilting point even though the crop suffers severe water stress, but up to the plant extractable water limit (above wilting point). This limit is the empirical function of water holding capacity and root density. The water held between field capacity and plant extractable water limit is known as extractable water. The extractable water varies (decreases) with root length by the function which defines the plant extractable limit. Soil water is removed from the wettest soil layer first. If the extractable water in the layer is insufficient to meet the demands, the water is extracted from the next wettest layer. This process continues until the actual transpiration was satisfied or all extractable water is used. This approach was used by Hanks (1974), Retta and Hanks (1980) and Martin et al., (1984).

Variation of root density with respect to time and length

In this approach the water is extracted from each layer in relation to the mass of root density present in the layer. This is well represented by the functions of root density with root length and time. This approach was used in some soil water flow-balance models (Molz and Remson, 1970; Afshar and Marino, 1978; Narda and Curry, 1981;

Yaron and Bresler, 1983; Malik et al., 1989 and Braud et al., 1995) and by Arora et al., (1987). The major difficulty associated with this approach is to obtain the data on root density. Therefore this approach was simplified by considering root water extraction as a function of root length, which combines the effect of variation of root density with root length and moisture extraction with root density (Feddes et al., 1975). Feddes et al., (1975) considered equal extraction of soil moisture from each soil layer (Feddes et al., 1976; Chesness et al., 1986; Jain and Murty, 1985; Workman and Skaggs, 1990; Kemachandra and Murty, 1992; Murty et al., 1992 and Binh et al., 1994) whereas Hoogland et al., (1981), Prasad (1988), Hayhoe and De Jong (1988) assumed that the water extraction decrease linearly with root length (Belman et al., 1983 and Dierckx et al., 1988). Constant rate of extraction is the oversimplified assumption as the root density is much greater near the surface than near the tip of roots. In that way the assumption of linearly decreasing rate is more realistic. However the root density function indicates that distribution of roots can be non-linear (Zhang et al., 1993) and therefore extraction of water with respect to root length can be non-linear.

Therefore in this study parabolic and other types of extraction patterns are used and a model for root extraction is developed which is valid for all types of extraction pattern, first by developing equations for constant, linear and parabolic extraction patterns, and then by generalising those equations for all the patterns.

Constant Extraction Pattern : It is given by equation (5.25)

$$e_t = c \tag{5.25}$$

where

e_t = extraction rate on t^{th} day (mm/mm)

c = constant

Integrating equation (5.25) over entire root zone depth gives the total transpiration from the entire root zone (TR_t)

$$\int_0^{z_t} e_t \, dz = TR_t \tag{5.26}$$

From (5.25) and (5.26)

$$c = \frac{TR_t}{Z_t} \tag{5.27}$$

From (5.25) and (5.27)

$$e_t = \frac{TR_t}{Z_t} \tag{5.28}$$

Linear Extraction Pattern : Linearly decreasing extraction pattern (Hoogland et al., 1981 and Prasad, 1988) can be represented by equation (5.29).

$$e_t = c_t - b_t z \tag{5.29}$$

where

c_t and b_t = constants

when $z = Z_t$, $e_t = 0$, from (5.29)

$$c_t - b_t Z_t = 0$$

Therefore,

$$c_t = b_t Z_t \tag{5.30}$$

Integrating equation (5.29) over the entire root zone

$$\int_0^{Z_t} (c_t - b_t z)\, dz = TR_t \tag{5.31}$$

$$c_t Z_t - b_t \frac{Z_t^2}{2} = TR_t \tag{5.32}$$

From equations (5.30) and (5.32)

$$b_t = 2\frac{TR_t}{Z_t^2} \tag{5.33}$$

From equations (5.30) and (5.33)

$$c_t = 2\frac{TR_t}{Z_t} \tag{5.34}$$

From equations (5.29), (5.33) and (5.34)

$$e_t = 2\frac{TR_t}{Z_t^2}(Z_t - z) \tag{5.35}$$

Parabolic Extraction Pattern : Parabolically decreasing extraction pattern can be represented by equation (5.36).

$$e_t^2 = 4c_t(Z_t - z) \tag{5.36}$$

Integrating equation (5.36) over the entire root zone

$$\int_0^{Z_t} \{4c_t(Z_t - z)\}^{1/2} = TR_t \tag{5.37}$$

and solving

$$a_t = \frac{9TR_t^2}{16Z_t^3} \tag{5.38}$$

From equations (5.36) and (5.38)

$$e_t = \frac{(3/2)TR_t}{Z_t^{3/2}}(Z_t - z)^{1/2} \tag{5.39}$$

From equations (5.28), (5.35) and (5.39), the general form of equation for the extraction pattern is represented by the equation (5.40).

$$e_t = \frac{ce\,TR_t}{Z_t^{ce}}(Z_t - z)^{(ce-1)} \tag{5.40}$$

where

ce = the exponent to represent the moisture extraction pattern.

ce =1, 1.5 and 2 are the cases of constant, parabolic and linear moisture extraction patterns. The moisture extraction pattern for the different values of ce are shown in Figure 5.4. The figure is for the unit value of TR_t and Z_t.

The Moisture Extraction

To find out the extraction of moisture for the different soil layers for a given extraction pattern, total actual transpiration and the depth of root zone on the particular day, the entire root zone depth is divided in to different sections called the extraction layers. The number and thickness of extraction layers either correspond to the soil layers or equal to division of the root zone according to given data. In the first case, the number and thickness of extraction layers are the number and thickness of soil layers which are effective (in the root zone) on the particular day. The thickness of the last layer is adjusted according to the root zone depth. In the second case, the number of extraction layers is assumed to be known and the same for all the days during crop growth period. The thickness of the extraction layer in this case is computed by dividing the root zone depth on the particular day by the number of extraction layers. Thus the thickness of all extraction layers is same on a particular day but may vary over the crop season. The amount of water extraction from a particular extraction layer (TR_t^e) is computed by integrating the extraction rate over the thickness of that layer.

$$TR_t^e = \int_{Z_{e,t}-\Delta Z_{e,t}/2}^{Z_{e,t}+\Delta Z_{e,t}/2} e_t \, dz \tag{5.41}$$

where

TR_t^e	=	transpiration from e^{th} extraction layer on t^{th} day (mm/day)
e	=	superscript to represent the values over the extraction layer
e	=	the subscript for the extraction layer
z	=	the depth of the midpoint of extraction layer from the soil surface (mm)
Δz	=	the thickness of the extraction layer (mm)

From equations (5.40) and (5.41)

$$TR_t^e = \frac{TR_t}{Z_t^{ce}}[(Z_t - z_{e,t} - \Delta z_{e,t}/2)^{ce} - (Z_t - z_{e,t} + \Delta z_{e,t}/2)^{ce}] \tag{5.42}$$

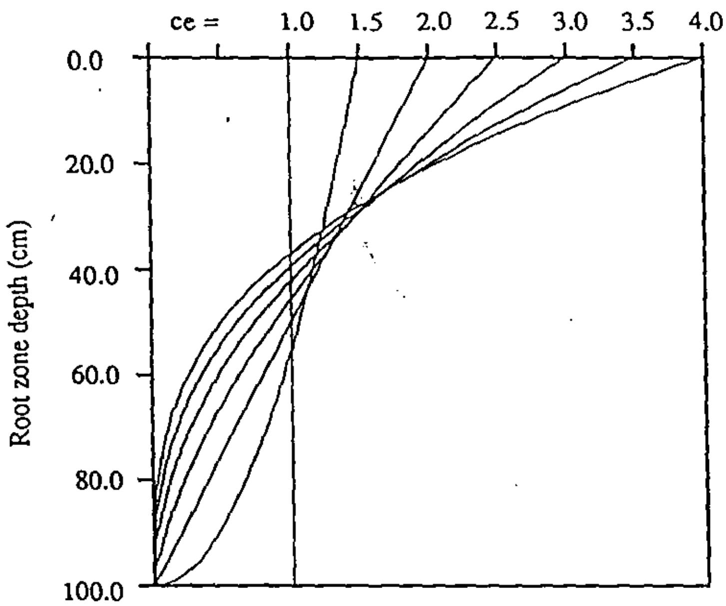


Figure 5.4 Root water extraction patterns for different values of ce

Water extraction computed by first case gives the water removed form the soil layer directly. However by second case, the water removed from the soil layer is computed from water removed form matching extraction layers using the interpolation. This gives water removed by each soil layer ($TR^{l}_{l,t}$, where l is the superscript to indicate that the values are over the soil layer).

Initial Soil Moisture and Presowing Irrigation

Initial soil moisture is either considered as known and its input is given, or it is assumed. When presowing irrigation is not performed, the initial soil moisture is assumed at field capacity, 50% available moisture and wilting point for the planting in rainy, winter and summer seasons, respectively. If the presowing irrigation is performed, the soil moisture content before presowing irrigation is assumed at wilting point (if not known). The soil is considered as bare from presowing irrigation to irrigation at or just before planting (first crop irrigation). The bare soil evaporation is computed (if not given as direct input) by Penman equation (Penman, 1948). The actual soil evaporation is computed by equation (5.20). The initial soil moisture (at first crop irrigation) is computed by carrying out a water balance over the period from presowing irrigation to first crop irrigation with the help of equations similar to equations (5.45) and (5.46) and by setting transpiration equal to zero. The depth of presowing irrigation is either given or computed in the model so that the soil moisture content at the presowing irrigation is brought to field capacity and adjusting it for application efficiency and minimum and maximum possible irrigation depths.

Irrigation Depth

If irrigation depth is given, then the application depth is computed by the equation (5.43).

$$Ad_i = Id_i \, \eta a \tag{5.43}$$

where

Ad_i	=	application depth for i^{th} irrigation (mm)
Id_i	=	irrigation depth for i^{th} irrigation (mm)
ηa	=	application efficiency (fraction)

If irrigation depth is not given, then the soil water balance calculations are done with Ad_i=0 to obtain the soil water status on the day of irrigation. Then the irrigation depth and application depth are computed for the given irrigation strategy (deficit ratio). The soil water balance computations are again done to update the soil water status in the soil root zone with the computed application depth and without considering other inflow and outflow parameters. The procedure for computing the irrigation depth is described after the soil water balance equation.

Soil Water Balance Equation

The soil water balance equation is formulated on the basis of the law of conservation of mass, which states that the sum of all inflows should be equal to the sum of all outflows and change in storage. The entire soil root zone is considered as the reservoir. The day is chosen as the time period for comparing inflows and outflows and estimating the soil water content and other parameters (such as transpiration, soil evaporation and deep percolation). The lateral flows are ignored and only the vertical movement of water is considered for the water balance. The water intercepted by vegetation and capillary rise of water are assumed to be negligible. Therefore, the rainfall (effective) and irrigation water applied (in the soil root zone) constitute inflow parameters. The outflow parameters comprise soil evaporation, transpiration and water percolated out of the soil root zone. Therefore the general soil water balance equation is written by the equation (5.44). All water added due to effective rainfall on the previous day is considered in lumped amount on the beginning of the next day. Irrigation water is assumed to be added at the beginning of the day. The water removed due to transpiration and soil evaporation during the previous day are considered in lumped amount at the beginning of the next day. The deep percolation is also considered in lumped amount at the beginning of the day.

$$RFe_{t-1} + AD_t = ESa_{t-1} + TR_{t-1} + PD_t \pm \Delta\theta_t^Z \qquad (5.44)$$

where,

PD_t	=	deep percolation on t^{th} day (mm)
$\Delta\theta_t^Z$	=	change in soil water storage on t^{th} day (mm)

In the present study, as the soil is considered as layered with each layer characterised by its own physical soil properties (which can influence irrigation), the layer wise soil water balance model is proposed to estimate soil water content and other parameters. The water added through rainfall and irrigation (inflow) is assumed to be distributed instantaneously to soil layers using a piston flow approach. The amount of water in excess of field capacity in any layer is percolated to the next layer (inflow for this layer) and the water in excess of field capacity of the last layer is considered as the deep percolation. Soil evaporation is assumed to take place from soil layers existing in prescribed depth of soil, beginning from top soil layer.

The different input and output processes are shown in Figure 5.5

The soil moisture of any layer on a particular day ($\theta_{l,t}$)is computed by subtracting transpiration corresponding to that layer and evaporation of the previous day, from soil moisture of the same layer on the previous day and inflow from the top layer. The inflow from the top layer is the moisture in excess of field capacity of the top layer. The inflow for the topmost layer is the water added due to irrigation on the same day and the rainfall on the previous day. If the soil moisture in any layer tends to drop below the wilting point, the transpiration and evaporation losses through the corresponding layer are appropriately (proportionally) adjusted. The evaporation excess (the soil evaporation remaining to be subtracted when the soil has reached wilting point) is transferred to the next layer, if it is within the prescribed limit of soil depth from the soil surface. The transpiration excess (the transpiration remaining to be subtracted when soil has reached wilting point) is either transferred to the next layer or deducted from the transpiration of the same layer, thus causing the deficit in transpiration for the layer under consideration and so the deficit in evapotranspiration. The layer wise soil water balance is mathematically expressed by the equation (5.45) and related conditions.

$TR_{l,t}^{l}$ is unadjusted transpiration of l[th] soil layer and will be adjusted in soil water balance and therefore this is referred to as unadjusted ($TR_{l,t}^{lu}$) in soil water balance. After adjustments, this is again referred to as $TR_{l,t}^{l}$.

$$\theta_{l,t} = \max[\{\min(\theta_{l,t-1}D_l + IN_l - ESa_{l,t-1}^{l} - TR_{l,t-1}^{l}), \theta f_l D_l\}, \theta w_l D_l] / D_l \qquad (5.45)$$

Conditions :

$$IN_{l+1} = \max[\{(\theta_{l,t-1}D_l + IN_l - ESa_{l,t-1}^{l} - TR_{l,t-1}^{l}) - \theta f_l D_l\}, 0 \qquad (5.46)$$

when

$$\left(\theta_{l,t-1}D_l + IN_l - \theta w_l D_l\right) \geq \left(ESa_{l,t-1}^{lu} + TR_{l,t-1}^{lu}\right.$$

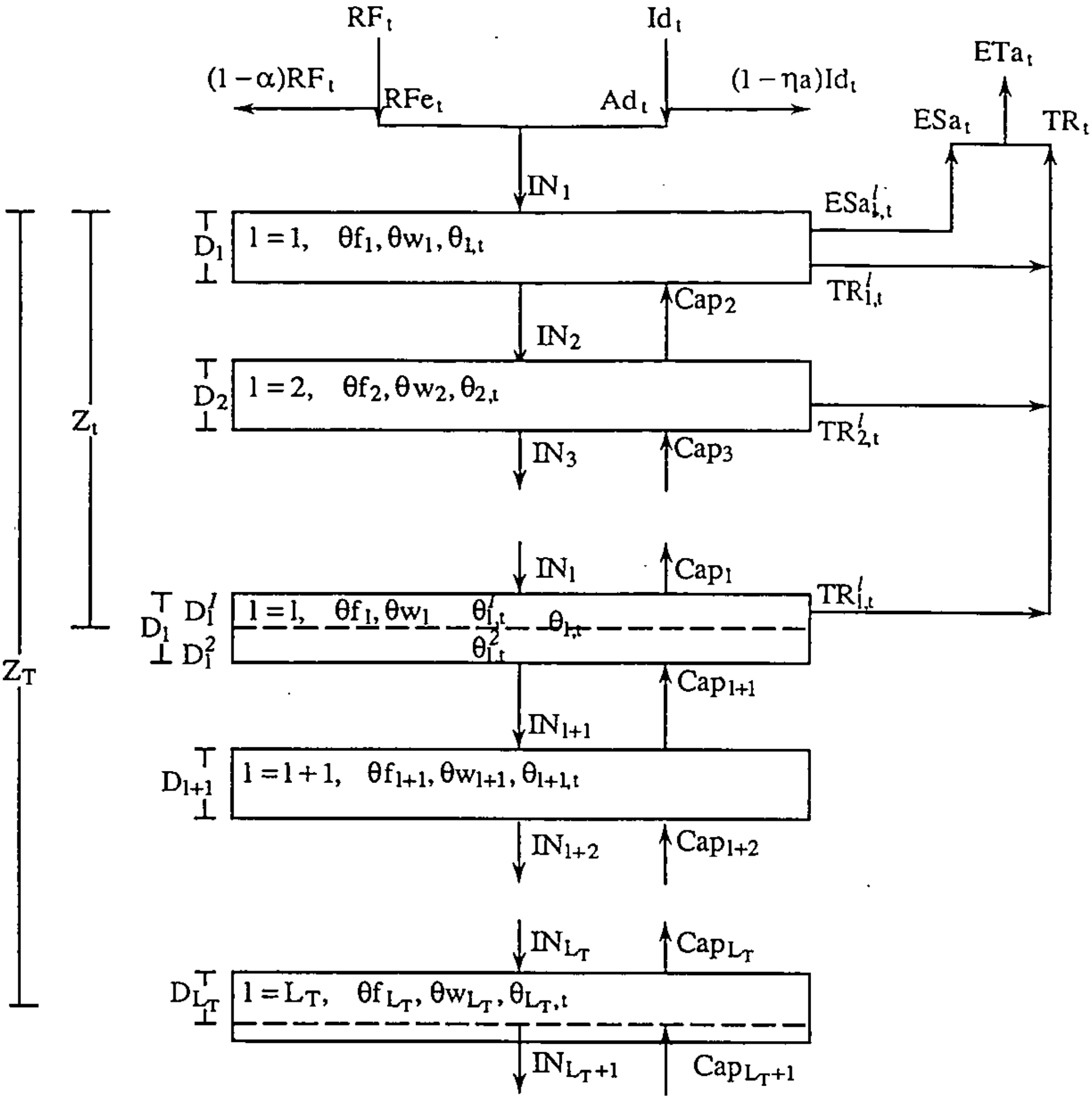


Figure 5.5 Inflow and outflow processes

$$TR^{l}_{l,t-1} = TR^{lu}_{l,t-1}$$

$$ESa^{l}_{l,t-1} = ESa^{lu}_{l,t-1}$$

$$ESa^{lu}_{l+1,t-1} = 0$$

$$\Delta TR^{lu}_{l+1,t-1} = 0$$

when

$$\left(\theta_{l,t-1}D_l + IN_l - \theta w_l D_l\right) < \left(ESa^{lu}_{l,t-1} + TR^{lu}_{l,t-1}\right)$$

$$TR^{l}_{l,t-1} = \frac{\left(\theta_{l,t-1}D_l + IN_l - \theta w_l D_l\right) TR^{lu}_{l,t-1}}{\left(TR^{lu}_{l,t-1} + ESa^{lu}_{l,t-1}\right)}$$

$$ESa^{l}_{l,t-1} = \frac{\left(\theta_{l,t-1} + IN_l - \theta w_l D_l\right) ESa^{lu}_{l,t-1}}{\left(TR^{lu}_{l,t-1} + ESa^{lu}_{l,t-1}\right)}$$

$$ESa^{lu}_{l+1,t-1} = ESa^{lu}_{l,t-1} - ESa^{l}_{l,t-1}$$

$$\Delta TR^{lu}_{l+1,t-1} = TR^{lu}_{l,t-1} - TR^{l}_{l,t-1}$$

If transpiration excess is to be transferred to the next layer

$$TR^{lu}_{l,t-1} \rightarrow TR^{lu}_{l,t-1} + \Delta TR^{l}_{l,t-1}$$

when t=1

$$\theta_{l,t-1} = \theta o_l$$

$$RFe_{t-1} = 0$$

$$ESa^{l}_{l,t-1} = 0$$

$$TR^{l}_{l,t-1} = 0$$

when $t \neq I$

$$Ad_t = 0$$

when l=1

$$IN_l = RFe_{t-1} + Ad_t$$

$$ESa_{l,t-1}^{lu} = ESa_{t-1}$$

$$\Delta TR_l^l = 0$$

when $l > L_t$

$$TR_{l,t-1}^l = 0$$

when $l > L_V$

$$ESa_{l,t-1}^l = 0$$

when $l = L_T$

$$D_l = Z_T - \sum_{l=1}^{L_T - 1} D_l$$

when $l = L_t$

$$\theta_{l,t} = \frac{\theta_{l,t}^l D_t^l + \theta_{l,t}^2 D_t^2}{D_l}$$

$\theta_{l,t}^l$ and $\theta_{l,t}^2$ are computed with equation (5.45)with following conditions

for $\theta_{l,t}^l$

$$D_t^l = Z_t - \sum_{l=1}^{l_t - 1} D_l$$

for θ_l^2

$$TR_{l,t-1}^l = 0$$

$$D_l^2 = D_{l,t} - D_t^Z$$

Transpiration (adjusted)

$$TR_t = \sum_{l=1}^{L_t} TR_{l,t}^l$$

Soil evaporation (adjusted)

$$ESa_t = \sum_{l=1}^{l_e} ESa_{l,t}^{1}$$

Evapotranspiration (adjusted)

$$ETa_t = TR_t + ESa_t$$

deep percolation

$$P_{D_t} = IN_{L_T+1}$$

where

$\theta_{l,t}$	=	volumetric soil water content in l^{th} layer and at the beginning of $(t-1)^{th}$ day (mm/mm)
θf_l and θw_l	=	volumetric soil water content in l^{th} layer (mm/mm) at field capacity and wilting point, respectively
D_l	=	thickness of l^{th} soil layer (mm)
IN_l	=	inflow into l^{th} soil layer (mm)
$ESa_{l,t-1}^{1}$	=	soil evaporation from l^{th} soil layer on $(t-1)^{th}$ day (mm)
P_{D_t}	=	deep percolation on t^{th} day (mm)
i	=	index for irrigation number
l	=	index for soil layer
L_t	=	total number effective soil layers on t^{th} day
L_v	=	total number effective soil layers for soil evaporation
L_T	=	total number soil layers in root zone
1,2	=	superscripts to indicate the part of soil layer with roots and without roots, respectively

The soil water balance from first crop irrigation to planting is performed like soil water balance from presowing irrigation to first crop irrigation, by considering soil as bare and transpiration equal to zero.

Irrigation Depth Computations

The application depth (depth of water to be applied in the root zone) for a particular irrigation is computed by multiplying the deficit ratio associated with that irrigation with the depth of application requirement. The depth of application requirement for any irrigation is the depth which brings the soil moisture content in the root zone or of all the effective soil layers during the irrigation period of that irrigation to field capacity. It is computed by the equation (5.47).

Depth of application requirement for irrigations other than first irrigation

if t is the day of i^{th} irrigation
(to bring the moisture content in the soil layers existing in the depth of root zone at the end of i^{th} irrigation period to field capacity)

$$\begin{aligned} Adf_i = & \sum_{l=1}^{L_t-1} (\theta f_l - \theta_{l,t}) D_l + \\ & (\theta f_l - \theta^1_{L_t,t}) D^1_{L_t} + (\theta f_l - \theta^2_{L_t,t}) D^2_{L_t} \\ & + \sum_{l=L_t+1}^{L_{(t+IP_i)}} (\theta f_l - \theta_{l,t}) D_l \end{aligned} \tag{5.47}$$

$$D^1_{L_t} = Z_t - \sum_{l=1}^{L_t-1} D_l$$

$$D^2_{L_t} = D_{L_t} - D^1_{L_t}$$

$$D_{L_{(t+IP_i)}} = Z_{(t+IP_i)} - \sum_{l=1}^{L_{(t+IP_i)}-1} D_l$$

$$L_{(t+IP_i)} = L_T \quad \text{if} \quad i = I$$

where

Adf_i = depth of application requirement for i^{th} irrigation (mm)
IP_i = irrigation period of i^{th} irrigation (days)

All the four terms in equation (5.47) represents the water required to bring the soil moisture to field capacity in respective soil layers. The first term is for the layers with roots. The second and third terms are for the last layer with roots, where in some part is with roots (second term) and remaining is without roots (third term). The fourth term is for the layers without roots.

If $L_t = 1$, the first term is not necessary and if $L_t = L_{(t+IP_i)}$, the last term is not necessary.

Depth of application requirement for first irrigation

(to bring the soil moisture in the soil layers existing in the entire soil root zone to field capacity)

$$Adf_i = \sum_{l=1}^{L_T} (\theta f_l - \theta o_l) D_l \tag{5.48}$$

$$D_{L_T} = Z_T - \sum_{l=1}^{L_T - 1} D_l$$

where

θo_l = initial volumetric soil moisture content in the soil l^{th} layer (mm/mm)

The application depth (unadjusted) is computed by the equation (5.49)

$$Ad_i^u = \beta_i \, Adf_i \tag{5.49}$$

where

Ad_i^u = application depth (unadjusted) for i^{th} irrigation (mm)

The irrigation depth (unadjusted for minimum and maximum possible irrigation depths) is computed with the application efficiency by equation (5.50).

$$Id_i^u = Ad_i^u \, / \, \eta a \tag{5.50}$$

where

Id_i^u = unadjusted irrigation depth for i^{th} irrigation (mm)

Application efficiency is either given as input or computed as a function of soil type, irrigation method and the application depth following the procedure and data given by Bos and Nugteren (1990).

The irrigation depth is now adjusted for minimum and maximum possible irrigation depths by equation (5.51).

$$Id_i = \min(\max(Id_i^u, Id\min), Id\max) \quad \text{if} \quad Id_i^u > 0$$
$$Id_i = 0 \qquad \text{if} \quad Id_i^u = 0 \tag{5.51}$$

where

Idmin = minimum possible irrigation depth (mm)

Idmax = maximum possible irrigation depth (mm)

Irrigation is skipped or depth of irrigation is zero when β=0 and irrigation depth is the full irrigation depth when β=1 (subjected to the limits of minimum and maximum possible irrigation depths).

Application depth is now adjusted for including it into the soil water balance equation by equation (5.52).

$$Ad_i = Ad_i^u \quad \text{if} \quad Id\min \le Id_i^u \le Id\max \tag{5.52}$$
$$Ad_i = Id_i\,\eta a \quad \text{otherwise}$$

5.3.4 CRYB Submodel

This submodel takes the input of daily actual evapotranspiration, number of irrigations and depth of irrigation water to be applied per irrigation from SWAB submodel and estimates the crop yield and net benefits.

5.3.4.1 Crop yield

The purpose of this sub model is to estimate the crop yield and net benefits obtained as the result of applying water according to the given irrigation strategy. This sub model takes the input of daily actual evapotranspiration or transpiration from the SWAB sub model and estimates crop yield and net benefits.

The crop yields can be estimated based on two approaches : (1)physiological approach and (2)semi-empirical approach.

Physical approach

In this approach the plant responses are the results of the complex interaction of many physiological processes. Each of these processes may be affected differently by water deficits (Vaadia and Waisel, 1967). These processes are cell division and enlargement, leaf area and its development for intercepting light and carrying out photosynthesis, stomatal behaviour, respiration, translocation and partitioning of assimilates etc (Vaux Jr. and Pruitt, 1983). Dierckx et al., (1988) and Williams et al., (1989) used the models based on this approach for estimating crop yield in irrigation water management. These models need a large amount of data.

Semi-empirical approach

In this approach, the crop yield is related directly to the water deficit (in form of some measures) occurring in the crop growth period through empirically developed constants. This type of relationship is also known as a crop production function or yield response function. These are discussed in detail below.

Several types of functions are available to estimate crop yield. These functions vary depending on the type of measure of water used by the plant used in the function. These measures are generally soil moisture (soil moisture deficit), evapotranspiration (relative ET or relative ET deficit), transpiration (relative transpiration or relative transpiration deficit), stress days and irrigation water applied.

Whenever the soil moisture content in the soil decreases, the effective hydraulic resistance for extracting water from the soil for plant growth increases (Jensen, 1968). Thus due to shortage of water in the soil root zone, water stress is developed. Therefore, if the soil moisture drops below a certain limit (critical level), the plant can not extract all the water needed to satisfy the atmospheric demands for its full growth. The water extracted by the plant (actual transpiration) is less than the maximum water that plant should have extracted (potential transpiration). The amount of water extracted depends on the soil moisture present in the soil. The result of this resistance is in reduction of crop yield and its quantity depends on water stress. The resistance continues in greater degree till the soil root zone is replenished by water. The water stress is related to crop yield through the measures described above.

Thus the crop yield or reduction in crop yield can be related to the soil moisture deficit (the difference between the soil moisture at critical level and soil moisture present in the soil). Such type of functions are used and developed by Moore (1961); Hall and Butcher (1968) and Yaron et al., (1973). In a stress day concept, a "stress day" is defined as the one where the soil moisture is below the soil moisture at critical level. The crop yields are related to the number of such stress days in the crop growing period (Hiler, 1969;

Hiler and Clark, 1971; Hiler et al., 1974; Evans et al., 1990 and Evans et al., 1991). The depth of irrigation water applied is directly related to crop yield (Stewart and Hagan, 1973; Musick et al., 1976 and Barret and Skogerboe, 1978). The soil moisture deficit and stress day approaches, are not widely accepted in irrigation water management, but many models which use other approaches such as evapotranspiration or transpiration, make use of relationships between soil moisture and these measures. The irrigation water applied is very much site specific and therefore of not much use in irrigation planning.

The evapotranspiration or transpiration approach has wide acceptability in irrigation water management as this approach considers the plant which is affected due to shortage of water more directly than other measures. This approach considers the evapotranspiration or transpiration deficit resulting from the resistance to extract water by the plant due to dropping of soil moisture below a critical level, and relate this to crop yield. Several crop production functions have been developed to relate relative crop yield ratio or relative yield reduction to relative ET ratio or relative ET deficit (Hanks et al., 1969; Downey, 1972; Stewart et al., 1974 and Martin et al., 1989[b]).

The crop yield or reduction in crop yield is not only a function of quantity of the measures but also of the crop itself and climatic conditions. The different crops respond differently to the shortage of water or stress. Therefore these crop production functions relate crop yield to certain measures of water deficit through a factor called the yield response factor. The yield response factor is different for different crops and at different locations.

The effect of water stress on yield is not only a function of crop and degree and duration of stress but also a function of stage of plant growth when stress is imposed. (Grimes et al., 1969). The crop production function described above relates the total water stress in a crop growth period to the crop yield. Therefore these functions can not be used for analysing the effect on crop yield of application of water at various instances and in various amounts at those instances during the crop growth period. Realising this fact many researchers proposed the functions which take in to account the effect of water stress in different crop growth stages on yield. These functions are termed as stage wise yield response functions or crop production functions or dated water production functions. The stage wise water production functions are formulated in two ways depending on the nature of interstage dependence, that is the effect of water stress in one stage on the effect of water stress on yield in subsequent stages. Some researchers considered that the crop growth in one stage depends on the growth and stress conditions imposed in previous stages and the yield is reduced in multiplicative way (Jensen 1968; Hanks 1974; Minhas et al., 1974 and Rao et al., 1988[b]). These functions are known as the stage wise crop production function in multiplicative form. These types of function were used by Rees and Hamlin (1983), Tsakiris and Kiountouzis (1984), Rao et al., (1988[a]) and Rao et al., (1990) by relating yield to evapotranspiration. Other researchers considered that the growth in various crop growth stages is independent and proposed the additive type of crop production functions (Flinn and Musgrave, 1967; Hiler and Clark, 1971; Stewart et al., 1974; Blank, 1975[a] and Sudar et al., 1981). These functions are known as crop production function in additive form. These types of functions were used by Bras and Cordova (1981), Rhenals and Bras (1981) and Vedula and Mujumdar (1992) by relating yield to evapotranspiration.

All these functions require the coefficient relating relative ET or ET deficit to the relative reduction in crop yield and relative yield for each growth stage of each crop. These coefficients are generally termed as yield reduction ratio or yield response factor. These can vary with location also due to effect of climatological parameters.

Citing Misra (1973), Vaux Jr. and Pruitt (1983) pointed out that a complete general relationship between yield and evapotranspiration is not possible but a series of yield and evpotranspiration relationships is required to capture the effects of evapotranspiration deficit sequencing. The choice of suitable crop production function and the availability of appropriate yield response factors are important in irrigation water management. At a particular location, the yield response factor may be available for several or any one type of crop production function. Therefore the five types of crop production functions are included in the model. These are represented by equations (5.53) through (5.57).

(1) Stewart et al., (1976): Crop production function in additive form (ET as measure of water stress)

$$\frac{Ya}{Ym} = 1 - \sum_{s=1}^{ns} Ky_s \left(\frac{ETm_s - ETa_s}{ETm}\right) \tag{5.53}$$

(2) Jenson (1968): Crop production function in multiplicative form (ET as measure of water stress)

$$\frac{Ya}{Ym} = \prod_{s=1}^{ns} \left(\frac{ETa_s}{ETm_s}\right)^{Ky_s} \tag{5.54}$$

(3) Hanks (1974): Crop production function in multiplicative form (transpiration as measure of water stress)

$$\frac{Ya}{Ym} = \prod_{s=1}^{ns} \left(\frac{TRa_S}{TRm_S}\right)^{Ky_s} \tag{5.55}$$

(4) Stewart and Hagan (1973) seasonal crop production function in multiplicative form: Crop production function in multiplicative form (ET as measure of water stress)

$$\frac{Ya}{Ym} = \prod_{s=1}^{ns} [1 - Ky_S(1 - \frac{ETa_S}{ETm_S})] \tag{5.56}$$

(5) Stewart and Hagan (1973) seasonal crop production function in additive form: Crop production function in additive form (ET as measure of water stress)

$$\frac{Ya}{Ym} = 1 - \sum_{s=1}^{ns} Ky_S(1 - \frac{ETa_S}{ETm_S}) \tag{5.57}$$

where

Ya	=	actual crop yield (Kg/ha)
Ym	=	potential crop yield (Kg/ha)
s	=	subscript for crop growth stage
Ky_S	=	yield response factor of s^{th} stage
ns	=	number of stages
ETm_S	=	maximum crop ET of s^{th} stage (mm)
ETa_S	=	actual crop ET of s^{th} stage (mm)
ETm	=	maximum crop ET of entire crop growth period (mm)

Doorenbos and Kassam (1986) presented the values of Ky during different crop growth stages for several crops based on the evaluation of numerous research results covering wide range of growing conditions. Many allocation models used these values either using equation (5.57) (Vedula and Mujumdar, 1992) or equation (5.56) (Tsakiris, 1982; Rees and Hamlin, 1983; Bernardo et al., 1988; Rao et al., 1988[a] and Mannocchi and Mecarelli, 1994). In the present model, the values of Ky proposed by Doorenbos and Kassam (1986) are used with equation (5.56) or equation (5.57), if the values of Ky are not locally available.

According to Jensen (1968), crops such as grass can tolerate severe stress for a period of a week during the growing season and completely recover following application and maintenance of adequate soil water during the remainder of the season with only a small decrease in total dry matter production. Downey (1972) also suggested that there was no evidence that alfalfa or other forage crops have growth stages which are particularly sensitive to water stress. Therefore for forage crops, the water production represented by equations (5.53) to (5.57) can be used with number of stages as one and seasonal yield response factor, if the stage wise Ky values are not available.

Certain crops (sorghum, maize, wheat, millet etc.) produce the fodder along with grains. In such cases, the function relating grain yield to fodder yield represented by equation (5.58) is used in the model to obtain fodder yield.

$$Yfa = fa + fb\,Ya \tag{5.58}$$

where

Yfa	=	fodder yield (Kg/ha)
fa & fb	=	the coefficient of equations.

fa and fb are to be found out with data of grain yield and fodder yield.

The daily values of actual evapotranspiration or actual transpiration over the crop growth period are transferred from SWAB sub model to CRYB sub model and these are summed up over the crop growth stage period. The crop yield is estimated with the appropriate crop production function, maximum crop yield and yield response factors. The fodder yield of the crops producing grain is estimated from the equation (5.58).

Two options are provided for the crops which were already planted before the start of the irrigation season and the crops which are expected to be harvested after the end of the irrigation season, for estimating water deficit or stress during the crop growth period which falls outside the irrigation season. These are:

1. It is assumed that the crop is not subjected to stress during the growth period which falls outside the irrigation season.
2. The estimated stress values are given as input for this period in the form of maximum evapotranspiration (potential transpiration) and actual evapotranspiration (actual transpiration).

The first option is used as a default in the model in absence of choice of particular option.

5.3.4.2 Benefits

In a multicrop situation it is essential to transfer the crop yield into monetary return for comparing the outputs from different crops in the allocation phase, where in the gross net returns from the entire irrigation scheme are maximised. The procedure adopted to compute the net returns is described below.

Total Cost

In the CRYB submodel total costs are divided in to three : area and yield independent costs, area dependent costs and yield dependent costs.

Area and yield independent costs : These costs are assumed to be same for all the CSR-units as they do not vary appreciably in a given irrigation scheme. Therefore these are not considered in the analysis for obtaining the net returns. These include following :

(1) The expenditure on the construction of the irrigation scheme, interest on the investment on the irrigation scheme and the expense on the infrastructure required for the management of irrigation scheme - As such though these costs are considered as the area and yield independent costs and are not considered in the analysis but are reflected in the water costs which is classified under the yield dependent costs (see below). These costs do not vary with area to be irrigated but depend on the total culturable command area of the scheme.
(2) The fixed costs associated with the farm operations (agricultural equipment, storage facilities etc.) - These are not considered as it is assumed that they do not change the decision to irrigate particular crop and adopt certain irrigation strategy.
(3) The fixed costs associated with the irrigation system - As the irrigation methods adopted in the irrigation scheme is assumed as the surface irrigation method only, these costs also do not vary as per unit or irrigation strategy (except for water which is included as a yield dependant cost).

Area dependent costs : These are considered in the analysis and are different for different CSR units (but same for all irrigation strategies in a CSR unit). These include following

(1) The expenditure on the various inputs (seeds, pesticides, insecticides, weedicides and other excluding water)

(2) The expenditure on various pre-harvest operations excluding irrigation (such as land preparation, tillage, interculturing operations etc.)

Yield dependent costs : These are considered in the analysis and vary with the CSR-units and irrigation strategy within the CSR-unit. These include following.

(1) The expenses on harvesting and postharvesting operations (threshing, transportation but not storage)

(2) Water related costs which include cost of water and cost of water application.

(i) Water cost : This is computed as per two options. According to one option, it is assumed as same for a given CSR-unit that is independent of the irrigation strategy or the amount of water delivered to the unit, but different for different units. In the second option it is computed from the seasonal volume of water applied and price of water per unit volume. Water is priced according to either of these two options in the irrigation scheme, though the second option is more appropriate.

(ii) Water application cost : Water application cost is the function of the number of irrigations associated with the irrigation strategy and CSR-unit under consideration. This cost is assumed to be independent of the depth of water applied. This cost mainly involves the labour cost of applying irrigation water.

Total dependant cost is given by equation (5.59).

$$C = Ca + Cy \tag{5.59}$$

where

C = total dependant cost (unit/ha)

Ca = area dependent cost (unit/ha)

Cy = yield dependent cost (unit/ha)

Total Benefits

The total benefits are computed with the help of actual crop and fodder yield estimated for a given irrigation strategy and CSR-unit and the market value of the produce. Thus the benefits are different for different irrigation strategies and CSR-units. These are computed by equation (5.60).

$$B = Pc\,Ya + Pf\,Yfa \tag{5.60}$$

where

B = total benefits (unit/ha)

Pc = the market price of crop yield (unit/Kg)

Pf = the market price of fodder yield (unit/Kg)

Net benefits

Net benefits are computed by equation (5.61).

$$NB = B - C \tag{5.61}$$

where

NB = net benefits (unit/ha)

5.3.5 Irrigation Programmes

SWAB-CRYB model is run for all the feasible irrigation strategies for the CSR-unit under consideration and the output is obtained in the form of number of irrigations, depth of irrigation per irrigation, seasonal depth of irrigation, crop yield and net benefits for each feasible irrigation strategy. This is known as feasible irrigation programme (FEIP). Thus there is one irrigation programme corresponding to each feasible irrigation strategy. The irrigation programme for p^{th} feasible irrigation strategy ($FEIP_p$) is represented by equation (5.62)

$$FEIP_p = \{ID_{i,p}, i = 1, I, SID_P, Ya_p, NB_p\} \tag{5.62}$$

where

IP_p = p^{th} irrigation programme

$ID_{i,p}$ = irrigation depth for i^{th} irrigation of p^{th} irrigation programme (mm)

SID_p = seasonal irrigation depth for p^{th} irrigation programme (mm)

Ya_p = crop yield for p^{th} irrigation programme (Kg/ha)

NB_p = net benefits for p^{th} irrigation programme (currency unit/ha)

I = number of irrigations

If 'nfp' is the total number of feasible irrigation strategies, then all the irrigation programmes for the unit under consideration are represented by **FEIP** and is indicated by equation (5.63).

$$\mathbf{FEIP} = \{FEIP_p, p = 1, nfp\} \tag{5.63}$$

5.4 SELECTION OF IRRIGATION PROGRAMMES

This acts as the third phase of the model. Several feasible irrigation programmes are obtained at the end of the second stage. The total number of FEIP depends on the number of irrigations, the increment chosen to vary deficit ratio ($\Delta\beta$), the minimum and maximum possible irrigation depths and the permissible limit below which soil moisture in the root zone should not drop. Incorporation of all these programmes in the allocation model of the fourth phase may make the problem computationally infeasible to solve. Some of these programmes are not optimal and even if included in the allocation model will not appear in the solution. Some of the irrigation programmes which are optimal are not efficient and the chances of appearing in the solution are very low or omission of these programmes may have negligible effect on the optimal solution. Therefore the number of irrigation programmes for the given unit can be restricted by selecting only optimal irrigation programmes (OIP) or OIP's which are efficient (OEIP) so that optimality in the final solution is not lost or is closely reached and formulation of the fourth phase becomes computationally feasible. The irrigation programmes which are finally transferred in to the fourth phase are termed as selected irrigation programme (SIP). If 'nsp' is the total number of SIP's, then all the SIPs for the unit under consideration are represented by **SIP** which is indicated by the equation (5.64).

$$\mathbf{SIP} = \{SIP_p, p = 1, nsp \tag{5.64}$$

OIP and OEIP are defined as follows

(1) Optimal irrigation programme : This is the irrigation programme with output more than the output from other irrigation programme but with same or lower seasonal irrigation depth as other irrigation programmes. In the water limiting condition only optimal irrigation programmes can appear in the final solution.
(2) Optimal efficient irrigation programme : Optimal efficient irrigation programme is that optimal irrigation programme which has the tendency to give more increase in output per increase in water applied.

The output can be chosen as either crop yield or net benefits.

The selection of SIP is done in two steps. In the first step, all OIPs are selected. If the number of OIPs is less than the certain manageable number (npp, which is prescribed), then all OIPs are transferred in the fourth stage as SIPs and the second step is skipped. However if the number of OIPs is more than this manageable number, the second step is executed by selecting the prescribed number of OEIPs. The OEIPs are then transferred in the fourth phase as SIPs. There may be a small possibility of losing the optimality by entering the second step but this can be risked for computational feasibility.

5.4.1 First Step (Selection of OIPs)

Many irrigation strategies can result in one seasonal irrigation depth but different outputs. In such cases only the irrigation strategy with maximum output is relevant. Similarly there may be some irrigation strategies which result in an output less than the output obtained with the irrigation strategy with a lower seasonal depth of irrigation. These irrigation strategies also do not aid in the optimisation process. The graphical relationship between the seasonal irrigation depth and the output of all irrigation strategies for the particular unit may result in the cluster as shown in Figure 5.6. All OIPs lie on the locus of the cluster drawn from the point of maximum output at the lowest seasonal depth of irrigation in such a way that its slope is not decreased at any point. This locus is shown in Figure 5.6 by curve AB. All other irrigation programmes are not optimal. The requirement is to select the irrigation programmes which lie on the curve AB (OIPs).

The irrigation programmes are grouped at different seasonal irrigation depths and the irrigation programme with maximum output is selected for each seasonal irrigation depth. If j is the index for the seasonal irrigation depth, l is the index for the irrigation programmes at the seasonal irrigation depth j and nl_j is the number of irrigation programmes at each seasonal irrigation depth j, then the irrigation programmes associated with maximum output (computed by equation (5.65) as OCB_j) for the seasonal depth of irrigation j is obtained.

$$OCB_j = \max(OCB_{lj}, l = 1, nl_j) \qquad (5.65)$$

Optimal irrigation programmes are selected by arranging these irrigation programmes in ascending order of output and the irrigation programmes with less output than the previous one is removed. Thus irrigation programme j is removed if it satisfies the condition represented by equation (5.66). The remaining irrigation programmes are OIPs.

$$OCB_{j-1} \geq OCB_j \qquad (5.66)$$

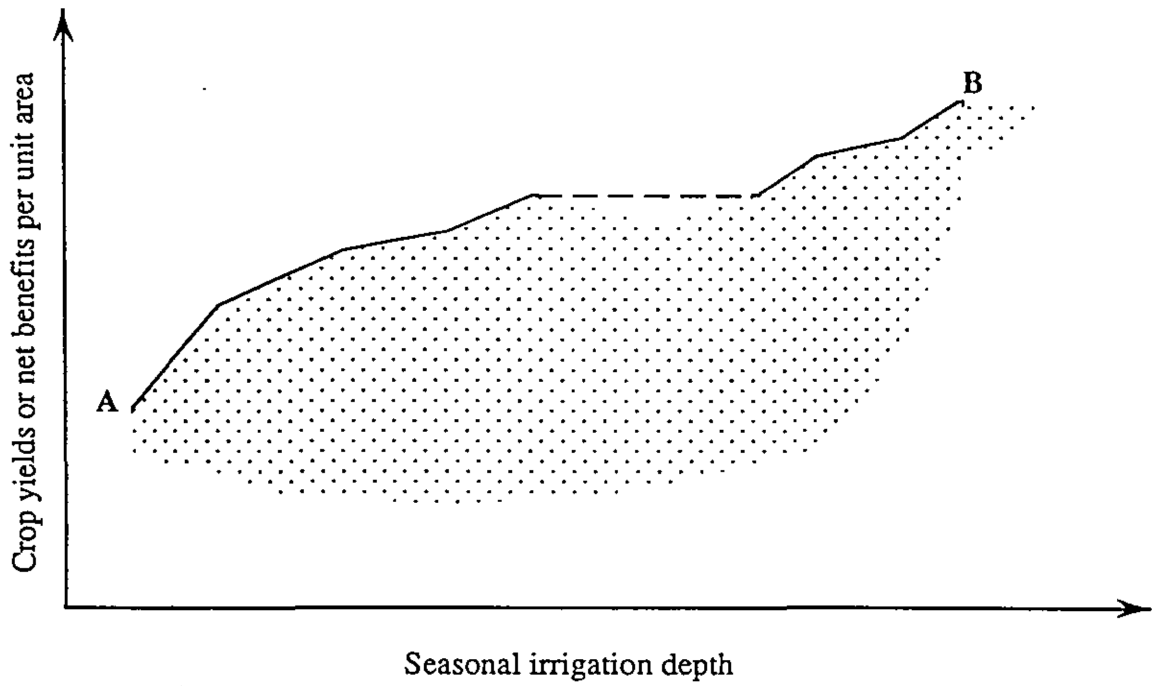


Figure 5.6 A typical relationship between seasonal irrigation depth and output (crop yield or net benefits) per unit area of all irrigation strategies for particuler CSR unit

If 'nop' is the total number of OIPs, then all the OIPs for the unit under consideration are represented by **OIP** which is indicated by equation (5.67).

$$\mathbf{OIP} = \left\{ OIP_p , p = 1, nop \right\} \tag{5.67}$$

where

SIP = a set of selected irrigation programmes (see equation 5.68)

nsp = total number of SIPs in **SIP**.

nsp and **SIP** are given by equation (5.68).

$$\begin{array}{lll} nsp = nop \quad \text{and} \quad \mathbf{SIP} = \mathbf{OIP} & \text{if } nop \le npp \\ \text{refer Section 5.4.2} & \text{if } nop > npp \end{array} \tag{5.68}$$

5.4.2 Second Step (Selection of OEIPs)

If the number of OIPs obtained in step-1 (nop) is more than the prescribed number (npp), this second step is executed. The purpose of this step is to obtain npp OEIPs. The set of OEIPs contain the OIPs with the lowest output (corresponding to the lowest seasonal irrigation depth), the highest output (corresponding to the highest irrigation depth), the highest output per unit of seasonal irrigation depth and (npp-3) most efficient OIPs form the remaining set of OIPs (nop-3 OIPs).

The land and water resources are allocated in the irrigation scheme with several types of soils, crops and with limited water. Shift of a certain amount of water from any CSR-unit may give more output either by allocating that amount to another CSR-unit or to the same CSR-unit over additional area. Therefore the basis of selecting the most efficient optimal irrigation programmes should be based on obtaining more output per unit of water or more incremental output per incremental unit of water with respect to the irrigation programmes with the lowest seasonal depth of irrigation and highest seasonal irrigation depth (this irrigation programme also produces the highest output). Thus a set of (npp-3) most efficient irrigation programmes can be obtained from following two approaches.

(1) Approach-1 : output per unit of water applied

(2) Approach-2 : ratio of rate of increase in output to rate of decrease in output.

Approach-1 : In this approach the selection is based on the maximum output per unit of water applied. The ratios of output and seasonal depth of irrigation depth are obtained as water use efficiency given by equation (5.69) for (nop-3) OIPs. The (npp-3) OIPs with higher water use efficiency are selected.

$$WUE_p = \frac{OYB_p}{SID_p} \tag{5.69}$$

where

WUE_p	=	water use efficiency of p^{th} irrigation programme (Kg/ha-mm if output is crop yield and currency unit/ha-mm if output is net returns)
OYB_p	=	output from p^{th} irrigation programme (Kg/ha if output is crop yield and currency unit/ha if output is net returns)
SID_p	=	seasonal irrigation depth of p^{th} irrigation programme (mm)

Approach-2 : This approach is based on the selection of OIPs which give a relatively higher rate of increase in output than the rate if decrease in output. The ratio (water use ratio) is computed for (nop-3) OIPs with the help of equation (5.70).

$$WUR_p = \frac{OYB_p - OYB_1}{SID_p - SID_1} \Bigg/ \frac{OYB_{nop} - OYB_p}{SID_{nop} - SID_p} \tag{5.70}$$

where

WUR_p = water use ratio for p^{th} irrigation programme (mm)

The (npp-3) OIP's with highest water use ratios are selected.

If 'noep' is the total number of OEIPs, then all the OEIPs for the unit under consideration are represented by **OEIP** which is indicated by equation (5.71).

$$\mathbf{OEIP} = \{OEIP_p, p = 1, noep\} \tag{5.71}$$

nsp and **SIP** are given by equation (5.72).

$$nsp = npp \text{ or } noep \quad \text{and} \quad \mathbf{SIP} = \mathbf{OEIP} \tag{5.72}$$

5.5 IRRIGATION PROGRAMMES FOR CSR-UNITS.

The procedure described with phases-1,2 and 3 (Section 5.2, 5.3 and 5.4) is for generating irrigation programmes for one CSR-unit. In the similar way irrigation programmes are generated for all CSR-units. The irrigation programmes for all CSR-units are represented by equation (5.73)

$$\mathbf{SIP}_{CSR},\ C = 1, NC_{SR},\ S = 1, NS_R,\ R = 1, NR \tag{5.73}$$

where

$$\mathbf{SIP}_{CSR} = \left\{ SIP_{pCSR},\ p = 1, nsp_{CSR} \right\}$$

$$SIP_{pCSR} = \left\{ D_{ipCSR},\ i = 1, Ic'_{CSR},\ SID_{pCSR},\ Ya_{pCSR},\ NB_{pCSR} \right\}$$

R = index for the region in irrigation scheme

S = index for soil group in the R^{th} region

C = index for the crop in S^{th} soil group of R^{th} region

NR = total number of regions

NS_r = total number of soil groups in R^{th} region

NC_{sr} = total number of crops in S^{th} soil group of R^{th} region

Ic'_{CSR} = total number of irrigations for C^{th} crop in S^{th} soil group of R^{th} region (including presowing irrigation)

5.6 IRRIGATION PROGRAMMES FOR GIVEN OR KNOWN IRRIGATION STRATEGIES

The procedure described from Section 5.2 to 5.5 is on the preparation of irrigation programmes by generating irrigation strategies and then preparing irrigation programmes and selecting appropriate irrigation programmes. But when it is needed to prepare the irrigation programmes for given or known irrigation strategies, the stage 'generation of irrigation strategies' is skipped. The given or known irrigation strategies may be in the following forms.

1. Irrigation strategy consisting of deficit ratio for each irrigation.
2. Irrigation strategy consisting of irrigation or application depth per irrigation.

For the first form, the irrigation programmes are prepared exactly in the same way as when they are prepared for each irrigation strategy generated from the irrigation strategy generator.

For the second form, the irrigation depth or application depth is not computed from the soil water balance (equations 5.47 to 5.52 are not performed). But if irrigation depth is given, the application depth is computed, which is needed for giving input to soil water balance equation. Similarly when application depth is given, irrigation depth is computed, which is needed in the irrigation programme (equation 5.43). This procedure is also described in the flow charts given in Figures 5.2 and 5.3.

Any number of irrigation strategies in both the forms can be given as input for preparing the irrigation programmes. Subsequently the irrigation programmes obtained from these forms can also be transferred with irrigation programmes prepared from irrigation strategies generated from irrigation strategy generator in the third phase i.e. selection of irrigation programmes. In third phase all irrigation programmes are either treated together to select the set of SIPs for given CSR unit, or irrigation programmes prepared from given irrigation strategies are transferred directly into fourth phase without considering those in the process of selection of irrigation programmes, depending on the option provided.

5.7 CONCLUSION

In AWAM, the deficit irrigation is included in the process of optimum allocation of land and water resources. The means of causing the deficit irrigation in the heterogeneous irrigation scheme with rotational water supply system are hypotheses in this study (Hypothesis 1) and these are described in Chapter III. AWAM includes all these three means for preparing the irrigation programmes by varying the deficit ratio from 0 to 1 in the process of irrigation strategy generation. It was also hypothesised that the detailed processes in the soil, plant and atmospheric subsystems can be modelled to include deficit irrigation in a computer model. The stage-2 of AWAM includes SWAB and CRYB submodels. These models are formulated to represent the relevant details of the subsystems under consideration and are used in the preparation of irrigation programmes for the generated irrigation strategies. The phases described in this chapter are subsequently used in verifying the hypotheses with the help of case study data.

CHAPTER VI

AREA AND WATER ALLOCATION MODEL
3. ALLOCATION OF RESOURCES

Summary. In this chapter, the last phase of AWAM i.e. optimum allocation of resources is described in two stages. In the first stage the irrigation programmes for each Crop-Soil (CS) unit of allocation unit (AU) are obtained from irrigation programmes of corresponding Crop-Soil-Region (CSR) unit and those irrigation programmes are then modified for distribution and conveyance losses. In the second stage, the optimisation problem (Resources Allocation model) is formulated to allocate the resources to different CS unit of AU with the help of irrigation programmes obtained in the first stage, predefined objectives and a set of constraints. In this process this chapter contributes in addressing Hypotheses 2, 3 and 4 and achieving Objective 1.

6.1 INTRODUCTION

Optimum allocation of the resources is the fourth and final phase of AWAM. In this phase resources are allocated optimally to different crops grown on different soils (CS units) of different allocation units (AUs) over the irrigation season. This is done in two stages. These are :

1. Preparation of irrigation programmes for each CS unit of AU.
2. Optimisation (Resources Allocation model)

The schematic representation of this phase is shown in Figures 6.1 and 6.2.

6. 2 PREPARATION OF IRRIGATION PROGRAMMES FOR EACH CS UNIT OF AU

In the first, second and third phases, irrigation programmes were generated for each CSR unit of the irrigation scheme and not for each CS unit of AU to save the computational efforts. As a CSR unit is not a physical division of the command area of the irrigation scheme, the conveyance and distribution efficiencies could not be considered while generating irrigation programmes of the CSR unit. Therefore in this stage the irrigation programmes for each CS unit of AU are obtained from the corresponding CSR unit, and then these are modified by considering the distribution and conveyance efficiencies.

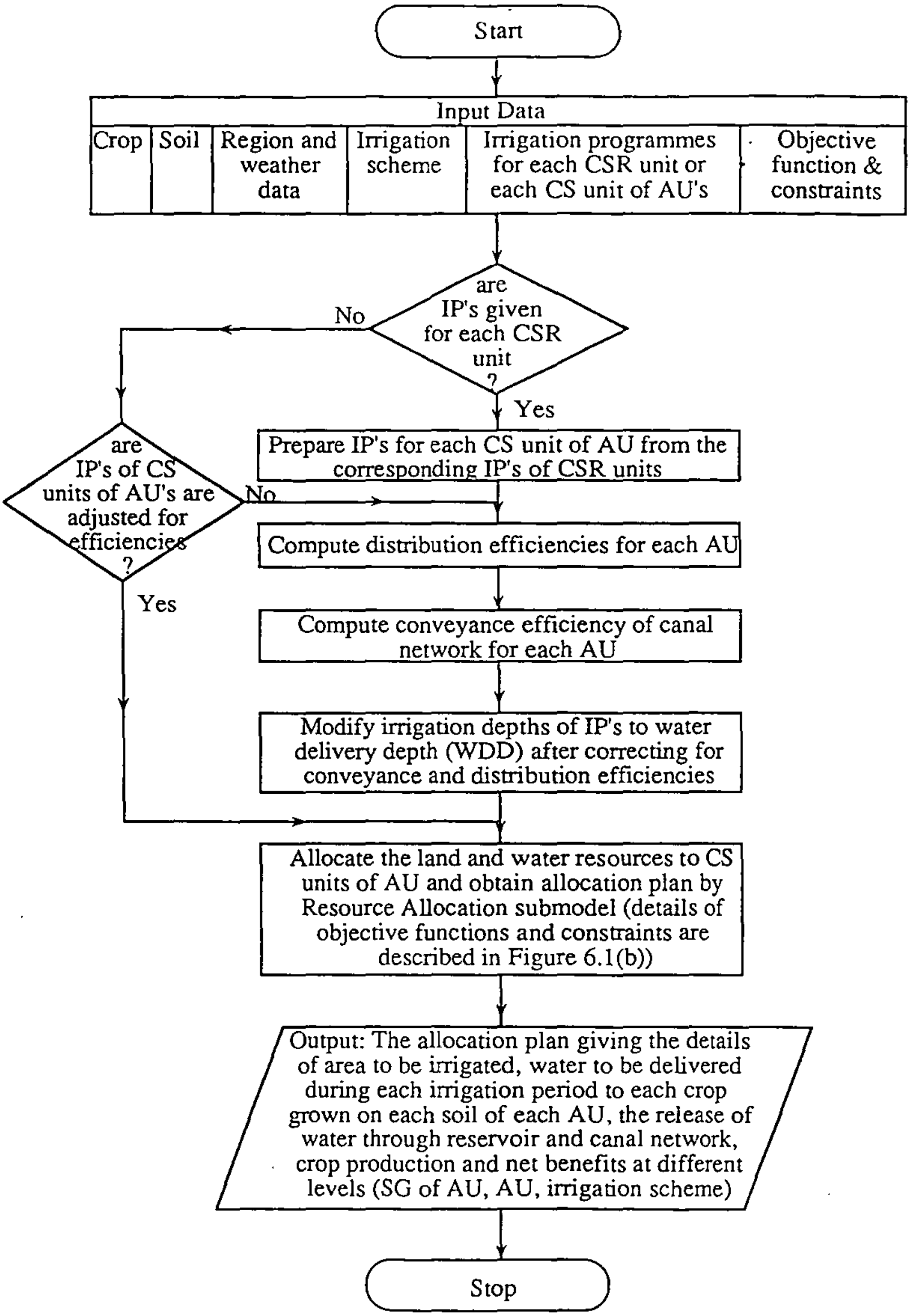


Figure 6.1 Phase-4 of Area and Water Allocation Model

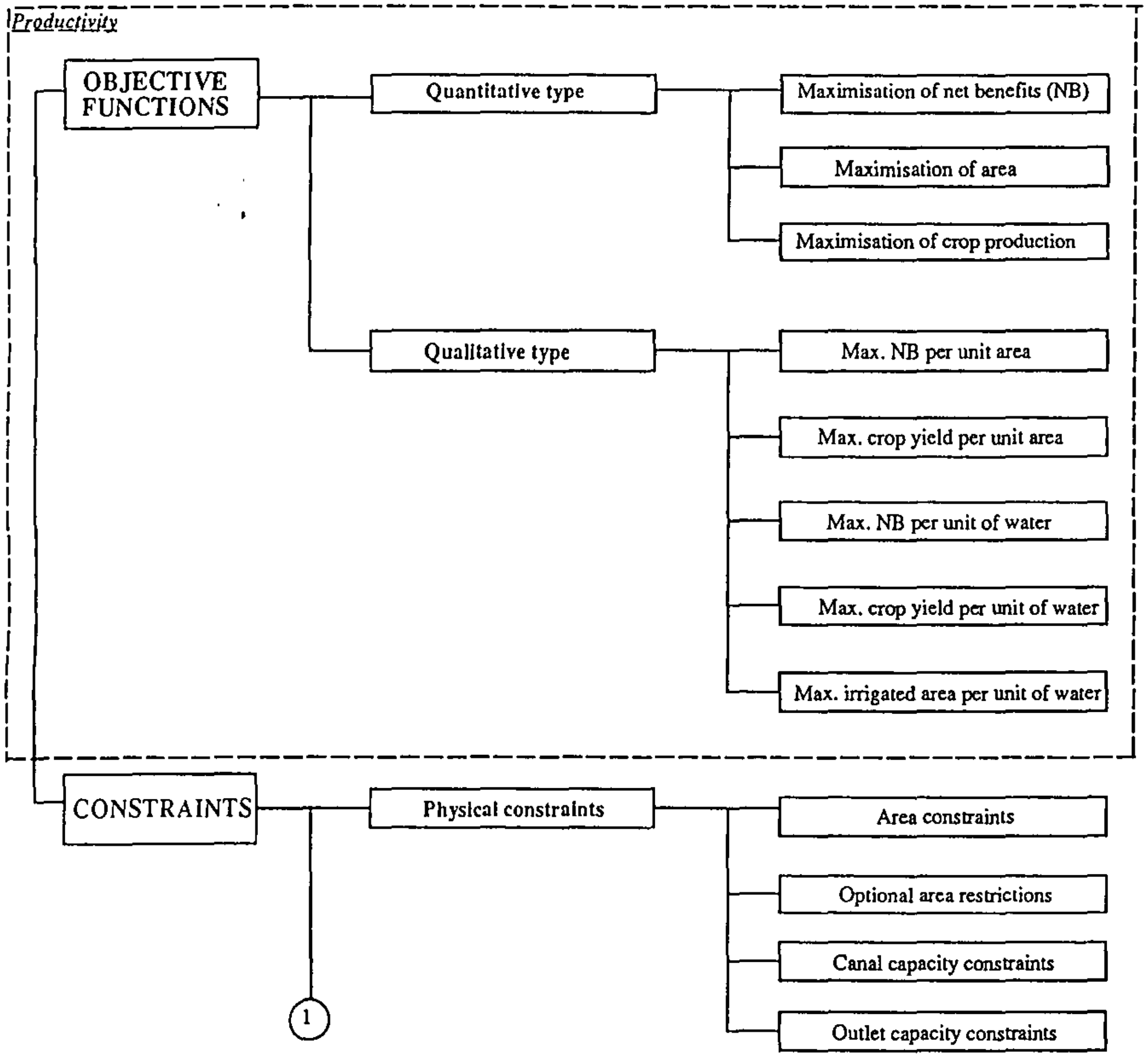
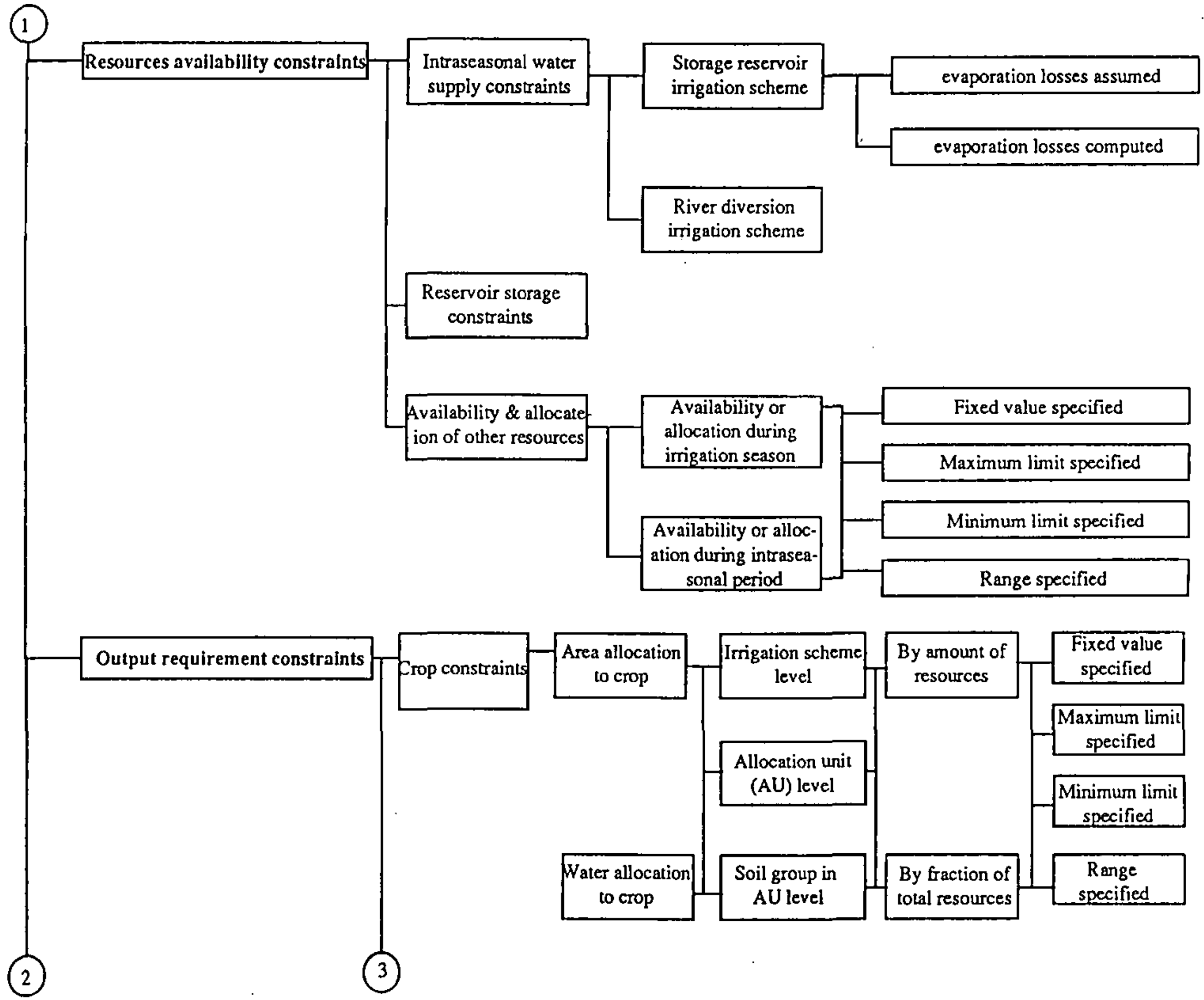
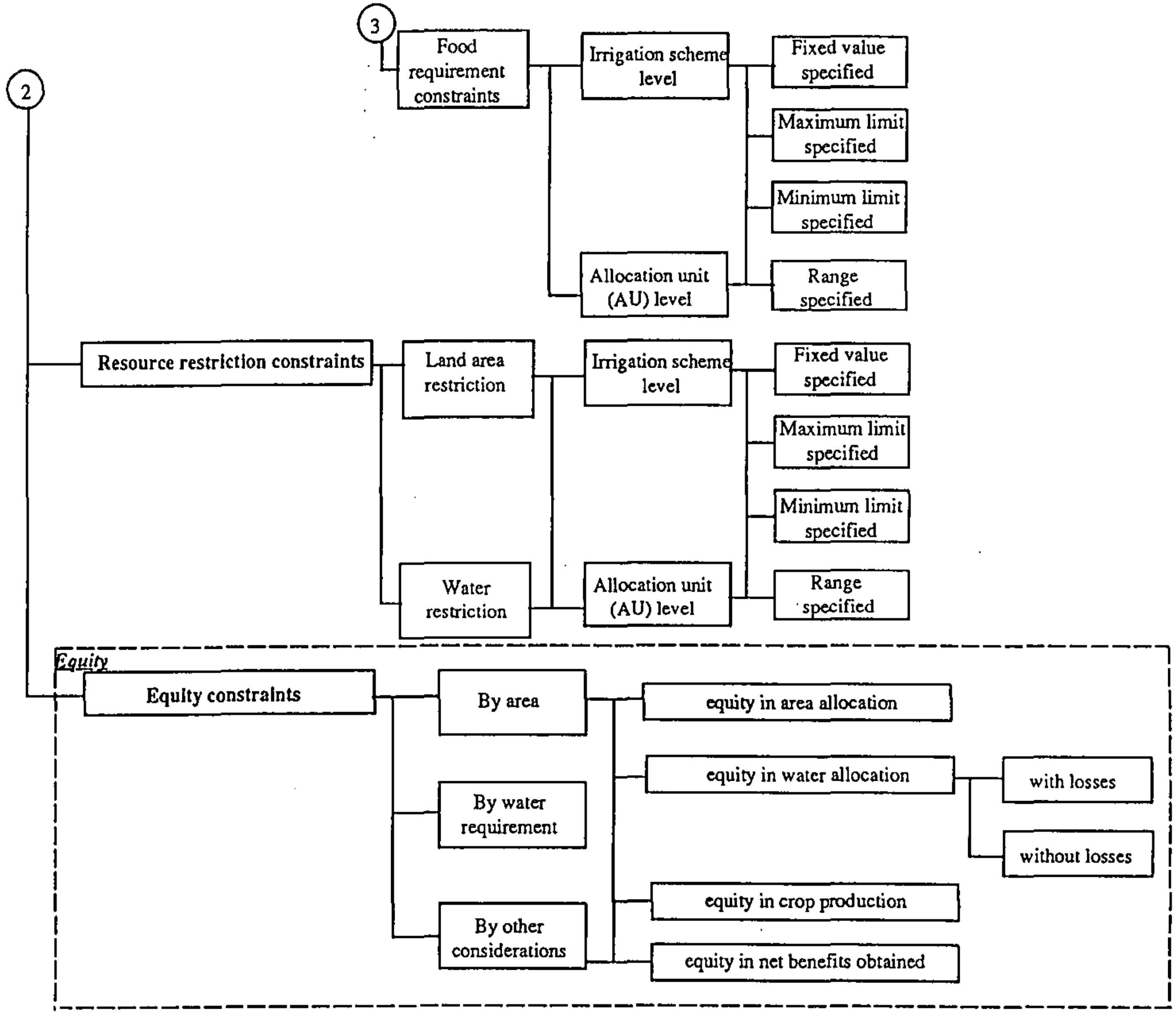


Figure 6.2 Objective functions and constraints in Resource Allocation submodel (contd..)


1
Resources availability constraints
Intraseasonal water supply constraints
Storage reservoir irrigation scheme
evaporation losses assumed
evaporation losses computed
River diversion irrigation scheme
Reservoir storage constraints
Availability & allocate-ion of other resources
Availability or allocation during irrigation season
Availability or alloc-ation during intrasea-sonal period
Fixed value specified
Maximum limit specified
Minimum limit specified
Range specified
Output requirement constraints
Crop constraints
Area allocation to crop
Water allocation to crop
Irrigation scheme level
Allocation unit (AU) level
Soil group in AU level
By amount of resources
By fraction of total resources
Fixed value specified
Maximum limit specified
Minimum limit specified
Range specified
2
3


3
2
Food requirement constraints
Irrigation scheme level
Allocation unit (AU) level
Fixed value specified
Maximum limit specified
Minimum limit specified
Range specified
Resource restriction constraints
Land area restriction
Water restriction
Irrigation scheme level
Allocation unit (AU) level
Fixed value specified
Maximum limit specified
Minimum limit specified
Range specified
Equity
Equity constraints
By area
By water requirement
By other considerations
equity in area allocation
equity in water allocation
with losses
without losses
equity in crop production
equity in net benefits obtained

6.2.1 Transfer of Irrigation Programmes

The irrigation programmes for AU are represented as

$$\mathbf{IP}_{csa}, \quad c = 1, nc_{sa}, s = 1, ns_a \;\; a = 1, na \tag{6.1}$$

where

$$\mathbf{IP}_{csa} = \{IP_{pcsa}, p = 1, nsp_{csa}$$

$$IP_{pcsa} = \{D_{ipcsa}, i = 1, Ic'_{csa} \; SID_{pcsa}, Ya_{pcsa}, NB_{pcsa}$$

a = index for AU

s = index for soil group in allocation unit

c = index for crop in soil group

(c and s together represent the index for CS unit of AU)

p = index for irrigation programme for crop (c^{th} crop in s^{th} soil group of a^{th} allocation unit)

i = index for irrigation number for an irrigation programme

na = total number of allocation units

ns_a = total number of soil groups in a^{th} allocation unit.

nc_{sa} = total number of crops in s^{th} soil group of a^{th} allocation unit

nsp_{csa} = total number of irrigation programmes of c^{th} crop in s^{th} soil group of a^{th} allocation unit

Ic'_{csa} = total number of irrigations for c^{th} crop in s^{th} soil group of a^{th} allocation unit (including presowing irrigation)

These are obtained as

$$\mathbf{IP}_{csa} = \mathbf{SIP}_{CSR} \quad \text{if} \quad \begin{aligned} region_a &= REGION_R \\ soil_{sa} &= SOIL_{SR} \\ crop_{csa} &= CROP_{CSR} \end{aligned} \tag{6.2}$$

where

region = region of a^{th} allocation unit

$REGION_R$ = R^{th} region

$soil_{sa}$ = s^{th} soil group of a^{th} allocation unit

$SOIL_{SR}$ = S^{th} soil group of R^{th} region

$crop_{csa}$ = c^{th} crop in s^{th} soil group of a^{th} allocation unit

$CROP_{CSR}$ = C^{th} crop in S^{th} soil group of R^{th} region

6.2.2 Adjustments of Irrigation Depth

The irrigation depths for each irrigation are modified for conveyance and distribution efficiencies. In previously developed allocation models (see Chapter II), the conveyance, distribution and application efficiencies were considered together as project efficiency and only one fixed value for all irrigations, crops, soils and regions was considered. However as mentioned earlier (see Chapters I, II and III), the efficiencies represent the losses in conveying water from the source to the root zone of crop and may contribute the major portion of total water consumption. These are dependant on many factors (characteristics of canal network, soil, crop and timing of irrigation during the irrigation season). Therefore arbitrary consideration of these efficiencies does not result in proper allocation of the resources and also does not give a well defined allocation plan that can be adopted for the operation of the scheme. In AWAM the application efficiency is already considered while generating the irrigation programmes in the second phase, which varied with irrigation, crop and soil. In this stage (of fourth phase) conveyance and distribution efficiencies are considered.

6.2.2.1 Distribution efficiency

This is the efficiency of the water distribution canal network in the AU supplying water up to individual field (adopted from Bos and Nugteren, 1990). This efficiency depends on the condition of the distribution network in the allocation unit and may be different for different irrigations and allocation units. This efficiency can not be considered if the setting of the model is of single field type. But this efficiency was not also considered or embodied in the conveyance or project efficiency in the allocation models of multifield type described in Chapter II. In AWAM, the provision has been made to modify the irrigation depth of each irrigation for the distribution efficiency, which itself may vary with irrigation. The values of distribution efficiencies can be given as direct input or can be determined in the model by following the procedure and data given by Bos and Nugteren.

6.2.2.2 Conveyance efficiency

Conveyance efficiency is the efficiency of canal networks from the reservoir or river diversion to the offtakes of the allocation unit (adopted from Bos and Nugteren, 1990). The water losses which occur in conveying the water to the AU from the headworks through the canal network are substantial and depend on the conveyance efficiency of the individual canal. This in turn depends on the type of canal lining, growth of vegetation, and the carrying capacity of the canal. In many allocation studies (referred to in Chapter II) the conveyance efficiency is considered uniform over the irrigation scheme, as a part of project efficiency. The reason may be that many of those studies were intended for allocation of the resources at the scheme level (single field type model) and in such cases separate consideration of the losses would not be significant as it does not include the estimate of how much water would be carried by different canals. The allocation model of multifield type also did not considered the conveyance efficiency which varied depending on the characteristics of the canal network. As water consumed in the conveyance process constitutes the major part of total water diversion from the headworks, these models thus only approximate the allocation. AWAM allocates the resources at AU level rather than at scheme level. In AWAM the conveyance efficiencies are duly considered while allocating the resources by modifying the irrigation depths in irrigation programmes for conveyance losses at each irrigation and each canal. The procedure is described in subsequent sections.

All canals in the distribution network are classified according to hierarchy in branching. These are known as levels. The canals which are directly originated from the headworks are classified as level-1 canals. The canals originating from level-1 canals are classified as level-2 canals and so on. There may be one or more than one canal at each level. All the canals at each level are numbered. Each canal at each level is specified with the canal number of all levels above its level with their length which is effective in carrying water to the canal under consideration.

The AUs can be delivered with water from canals at any level (infact different AUs may be at different levels). Each AU is specified with the level at which it exists and canal number at each level with length which is effective in carrying water to AU under consideration. The conveyance losses corresponding to the water to be delivered at each irrigation at each AU are computed for all CS units of AU with the conveyance losses of canals at the level at which it exists and canals above this level (if any). The irrigation depth for each irrigation of all CS units of AU are adjusted with the corresponding conveyance losses.

The input is in the form of information on conveyance efficiency or losses for canals at each level, and the conveyance efficiencies are required to be calculated in the following forms.

1. The conveyance efficiency of the canal network from the headworks to the allocation unit for a particular allocation unit (for adjusting the irrigation depths at AU for conveyance losses in the scheme). This is computed by equation (6.3), (6.6) and (6.11).
2. The conveyance efficiency of the canal network up to each level from the headworks for a particular allocation unit (for formulating constraints). This is computed by equation (6.4), (6.7) and (6.12).
3. The conveyance efficiency of the canal network from the headworks to the canal for a particular canal (for formulating constraints). This is computed by equation (6.5), (6.8) and (6.13).

The conveyance efficiencies in above forms are computed from any one of the three approaches. These are:

1. Conveyance efficiency of canal

In this approach the conveyance efficiency of the canal for each irrigation is given as input and the conveyance efficiency at each irrigation in different forms is computed by the equations (6.3), (6.4) and (6.5).

$$\eta ca_{ia} = \prod_{j=1}^{ncl_a} \eta c_{ikj} \qquad \text{for} \quad i=1,I \text{ and } a=1,na$$

$$k = nca_{aj} \qquad \text{for } j=1,ncl_a \tag{6.3}$$

$$\eta cc_{ija} = \prod_{m=1}^{j} \eta c_{ikm} \qquad \text{for} \quad i=1,I;\ j=1,ncl_a \text{ and } a=1,na$$

$$k = nca_{am} \qquad \text{for } m=1,j \tag{6.4}$$

$$\eta C_{ikj} = \prod_{m=1}^{j} \eta c_{ik'm} \qquad \text{for} \quad i=1,I;\ k=1,Nacn_j \text{ and } j=1,NCC$$

$$k' = ncc_{kmj} \quad \text{for } m=1,j \tag{6.5}$$

where

i = index for irrigation

ηca_{ia} = conveyance efficiency of canal network for i^{th} irrigation for a^{th} allocation unit (fraction)

ηcc_{ija} = conveyance efficiency of canal network up to j^{th} level for a^{th} allocation unit (fraction)

ηC_{ikj} = conveyance efficiency of canal network from headworks to k^{th} canal at j^{th} level (fraction)
j = index for canal levels
m = index for canal level
k = index for canal at j^{th} level
k' = index for canal number
ηcl_a = number of canal levels for a^{th} allocation unit
$Ncan_j$ = total number of canals at j^{th} level
NCL = total number of canal levels
nca_{aj} = canal number at j^{th} level of a^{th} allocation unit
ncc_{kmj} = canal number at m^{th} level of k^{th} canal at j^{th} level
ηc_{ikj} = conveyance efficiency of k^{th} canal at j^{th} level for i^{th} irrigation (fraction)

2. Conveyance losses of canal per 1000 m.

In this approach the conveyance losses in the canal in volumetric unit per 1000 m length of canal are specified for each irrigation. The conveyance efficiencies are computed by the equations (6.7), (6.8) and (6.9).

$$\eta c_{ikj} = 1 - \frac{cl_{ikj} Len_{kj}}{1000} \quad (6.6)$$

$$\eta ca_{ia} = \prod_{j=1}^{ncl_a} \left(1 - \frac{cl_{ikj}\, Len_{kj}}{1000} \right) \quad \text{for} \quad i=1,I \text{ and } a=1,na$$

$$k = nca_{aj} \quad \text{for } j=1,ncl_a \quad (6.7)$$

$$\eta cc_{ija} = \prod_{m=1}^{j} \left(1 - \frac{cl_{ikm} Len_{km}}{1000} \right) \quad \text{for} \quad i=1,I;\ j=1,ncl_a \text{ and } a=1,na$$

$$k = nca_{am} \quad \text{for } m=1,j \quad (6.8)$$

$$\eta C_{ikj} = \prod_{m=1}^{j} \left(1 - \frac{cl_{ik'm} Len_{k'm}}{1000} \right) \quad \text{for} \quad i=1,I;\ k=1,Ncan_j \text{ and } j=1,NCL$$

$$k' = ncc_{kmj} \quad \text{for } m=1,j \quad (6.9)$$

where

cl_{ikj} = conveyance losses in m^3/s per m^3/s flow rate per 1000 m length of canal for k^{th} canal at j^{th} level for i^{th} irrigation.

Len_{kj} = length in m for k^{th} canal at j^{th} level for i^{th} irrigation. (lengths of canals at each level are those lengths which are active in carrying water to the AU or to canal for which efficiencies are computed)

3. Conveyance efficiency per 1000 m length of canal.

In this approach conveyance efficiency per 1000m length of canal is specified per irrigation instead of conveyance losses. The conveyance efficiency of the distribution network for the allocation unit for each irrigation is computed by the equations (6.11), (6.12) and (6.13).

$$\eta c_{ikj} = \frac{\eta cl_{ikj} Len_{kj}}{1000} \tag{6.10}$$

$$\eta ca_{ia} = \prod_{j=1}^{ncl_a} \left(\frac{\eta cl_{ikj} \, Len_{kj}}{1000} \right) \quad \text{for} \quad i=1,I \text{ and } a=1,na$$
$$k = nca_{aj} \quad \text{for } j=1,ncl_a \tag{6.11}$$

$$\eta cc_{ija} = \prod_{m=1}^{j} \left(\frac{\eta cl_{ikm} Len_{km}}{1000} \right) \quad \text{for } i=1,I;\ j=1,ncl_a \text{ and } a=1,na$$
$$k = nca_{am} \quad \text{for } m=1,j \tag{6.12}$$

$$\eta C_{ikj} = \prod_{m=1}^{j} \left(\frac{\eta cl_{ik'm} Len_{k'm}}{1000} \right) \quad \text{for } i=1,I;\ k=1,Ncan_j \text{ and } j=1,NCL$$
$$k' = ncc_{kmj} \quad \text{for } m=1,j \tag{6.13}$$

where

ηcl_{ikj} = conveyance efficiency of k^{th} canal at j^{th} level for i^{th} irrigation allocation unit per 1000 m length of canal (lengths of canals at each level are those lengths which are active in carrying water to the AU or to canal for which efficiencies are computed)

With the knowledge of distribution and conveyance efficiencies, it is possible to know water to be delivered from the headworks for the given irrigation depth at each irrigation for the given CS unit of AU. The depth of water to be delivered from the headworks to the CS unit of AU for applying the required irrigation depth at CS unit of AU is termed as water delivery depth (WD') and is computed from equation (6.14).

$$WD'_{ipcsa} = \frac{ID_{ipcsa}}{\eta ca_{ia} \, \eta da_{ia}} \tag{6.14}$$

where

ηda_{ia} = distribution efficiency for i^{th} irrigation of a^{th} allocation unit.

The seasonal water delivery depth (SWD) is computed by the equation (6.15)

$$SWD_{pcsa} = \sum_{i=1}^{Ic'_{csa}} WD'_{ipcsa} \tag{6.15}$$

WD' is the water delivery depth from presowing irrigation to last crop irrigation. It is adjusted from the first irrigation of the irrigation season (WD) as follows:

$$\begin{aligned} WD_{ipcsa} &= 0 && \text{if} \quad (if_{csa} - ifp_{csa}) < i < il_{csa} \\ WD_{ipcsa} &= WD'_{(i-if_{csa}-ifp_{csa}+1),pcsa} && \text{if} \quad (if_{csa} - ifp_{csa}) \le i \le il_{csa} \end{aligned} \tag{6.16}$$

where

if = number of first crop irrigation

il = number of last crop irrigation

ifp = the difference in number of irrigations between presowing irrigation and first crop irrigation

The modified irrigation programme for each CS unit of AU can be represented by the equation (6.17).

$$IP_{pcsa} = \{WD_{ipcsa}, i = 1, I, SWD_{pcsa}, Ya_{pcsa}, NB_{pcsa} \tag{6.17}$$

6.3 RESOURCE ALLOCATION (RA) MODEL

This is the second stage of the final phase. Phases-1,2 and 3 and Stage-1 of Phase-4 model the physical aspects of the system, for knowing the water delivery from the reservoir at various instances of time to irrigate various crops scientifically. The Stage-2 of Phase-4 models the system as well as allocates the resources in the system to the users (farmers) in the system with the knowledge of water delivery.

The water in the irrigation scheme is managed by the irrigation authority or administrator or manager through several other supporting staff appointed by the government. The recipients of water are the farmers. All users are interested in getting the water to irrigate maximum land area, as the benefits from the irrigation are higher than the cost of water. However the water in the irrigation scheme is not adequate for meeting all the demands for water from the users. Therefore the job of irrigation manager becomes complex. He has to achieve maximum productivity within the irrigation scheme by following the guidelines from the government and with the water in the scheme. The guidelines may include the preferences or restrictions on irrigating certain crops or irrigating certain land area to achieving fairness in distribution of water. The farmers, on the other hand, are interested to satisfy their food needs and obtain maximum net benefits to meet other demands. Thus the allocation of resources to different users is a multiobjective and multivariable process and needs certain optimisation technique to obtain the solution. Therefore a Resource Allocation model using optimisation technique is formulated to ensure the government's goals and farmers needs. This model is described in this section.

This stage allocates the resources optimally to different crops grown on different soils (CS units) in different allocation units (AUs) with the knowledge of net benefits (crop yield) for different amount of water delivery at each irrigation turn. The allocation is subjected to constraints such as limitations to different resources at different levels of allocation, capacity of system and different requirements.

The optimum allocation of land and water resources would have been simple had it been only for one CS unit in one AU, as all the water is allocated with the IP giving maximum net returns or crop yield per unit of water and deciding the area to be irrigated by simple division rule. But when several units are involved the allocation process becomes complex due to the following reasons.

1. The IPs giving maximum net returns per unit of water for each unit can be treated as the final IP for the corresponding units when the water supplies for each of the units are independent. But when the water supplies are common for all the units, the alteration to water delivery of one unit affects the water availability of another unit, thereby influencing the net benefits. Therefore all the IPs need to be considered for all the units together.

2. The number of units and their IPs results in many activities and hence any simple rule can not be applied for the allocation of finite resources.

The linear programming (LP) is the approach which can be adopted when resources are to be allocated optimally to several activities (irrigation programmes of all CS units in all AUs). It can also handle the restrictions put to any one or group of activities and constraints to the resources. Therefore this approach is used in this stage for optimum allocation of the resources to different units under specified objective, different constraints and limitations. The LP optimisation technique contains the activities, objective function and the constraints. These are discussed in subsequent sections. The two performance goals to be achieved while allocating the resources i.e. the productivity and equity make the problem multiobjective in nature. As the LP formulation contains a single objective, productivity is included in the objective function and equity is incorporated through several constraints.

6.3.1 Activities

The area to be allocated to a CS unit of AU by a certain IP is one activity. The total number of activities are given by equation (6.18).

$$nt = \sum_{a=1}^{na} \sum_{s=1}^{ns_a} \sum_{c=1}^{nc_{sa}} np_{csa} \qquad (6.18)$$

where

nt = total number of activities.

The aim is to find out the area to be allocated to each activity (A_{pcsl}) from which area and water to be allocated to each CS unit of AU can be obtained.

6.3.2 Objective Function

The resources are allocated with certain objectives. These objectives are of two types. The one type of objectives deal with the total output from the system and are termed as "Quantitative Type". The another type of objectives deal with the output per unit of the resources utilised along with the total output from the system and are termed as "Qualitative Type". The quantitative type of objective is the primary objective and is essential for optimisation. However qualitative type of objective is secondary and optional. This objective, if used, is always coupled with quantitative type.

6.3.2.1 Quantitative type

The resources can be allocated with any one of the following objectives.

1. Maximisation of net benefits

To generate maximum net benefits is the common objective for many irrigation schemes. This is the objective in many land allocation and land and water allocation models described in Chapter II. This is given by the equation (6.19).

$$\text{Max} \quad OBJ = \sum_{a=1}^{na} \sum_{s=1}^{ns_a} \sum_{c=1}^{nc_{sa}} \sum_{p=1}^{np_{csa}} NB_{pcsa} A_{pcsa} \qquad (6.19)$$

where

Max = symbol used for maximisation

OBJ = the value of objective function (currency unit)

A = Area to be allocated to each activity (ha)

NB = net benefits obtained from each activity (currency unit/ha)

2. Maximisation of area

Sometimes the objective of the irrigation scheme is to spread the benefits of irrigation to maximum area (many users) rather than to obtain the maximum net benefits for the irrigation scheme. In such cases the objective function should be to maximise the total area and is represented by equation (6.20).

$$\text{Max} \quad OBJ = \sum_{a=1}^{na} \sum_{s=1}^{ns_a} \sum_{c=1}^{nc_{sa}} \sum_{p=1}^{np_{csa}} A_{pcsa} \qquad (6.20)$$

3. Maximisation of production

When it becomes necessary to maximise the food production instead of spreading the benefits over large area or to obtain maximum net benefits, the objective function shall be to maximise total production. However this can be adopted only when a single crop is grown in the irrigation scheme (though in some studies involving multicrop, minimisation of total crop production is used as the objective function). This is the objective used in many water allocation models described in Section 2.4.1 of Chapter II. This objective function is represented by the equation (6.21).

$$\text{Max} \quad OBJ = \sum_{a=1}^{na} \sum_{s=1}^{ns_a} \sum_{c=1}^{nc_{sa}} \sum_{p=1}^{np_{csa}} Ya_{pcsa} A_{pcsa}$$

$$nc_{sa} = 1, \text{ for all s and a} \tag{6.21}$$

6.3.2.2 Qualitative type

The following secondary objectives are included in the model. The resources can be allocated with any one of these secondary objectives along with the primary objective. However its inclusion is optional.

1. Obtaining maximum net benefits per unit area
2. Obtaining maximum crop yield per unit area
3. Obtaining maximum net benefits per unit of water
4. Obtaining maximum crop yield per unit of water
5. Obtaining maximum irrigated area per unit of water or supplying minimum possible water for irrigating unit area.

The secondary objective can be selected with or without considering conveyance and distribution efficiencies. However the allocation process always considers these efficiencies. In the model secondary objectives are included by selecting the irrigation programme which satisfies its underlying statement from the set of IPs for each CS unit of AU according to following.

1. Selecting the IP with maximum net benefits
2. Selecting the IP with maximum crop yield
3. Computing B = NB/SWD or B = NB/SID for all IPs and selecting the one with maximum B.
4. Computing B = Ya/SWD or B = Ya/SID for all IPs and selecting the one with maximum B.
5. Selecting the IP with minimum SWD or SID.

With the selection of any one secondary objective, the number of activities are reduced to

$$nt = \sum_{a=1}^{na} \sum_{s=1}^{ns_a} nc_{sa} \tag{6.22}$$

Selection of the quantitative type of objective function or quantitative and qualitative objective functions together and the choice of a particular quantitative or qualitative type of objective function depend on the productivity criteria selected for achieving the performance of the irrigation scheme. The quantitative type of objective function should be used for the productivity criteria based on achieving total output from the scheme, and the quantitative and qualitative type of objective functions should be used together for the productivity criteria based on achieving output per unit of resource utilised. Incorporation of the qualitative objective function optimises the total output from the scheme while obtaining maximum output per unit of the resources utilised.

6.3.3 Constraints

The allocation of the resources can be restricted by the following constraints. These are
1. Physical constraints
2. Resource availability constraints
3. Output requirement constraints

Land and water resources available in the irrigation scheme are utilised for other purposes along with irrigation. The land which is available and suitable for irrigation (irrigable command area) is used in the constraints involving any restrictions to land area. The other resource, water has also many uses However the amount of water available for irrigation can not be isolated like land as water for other purposes is used concurrently with water for irrigation and sometime is carried through the same canal network. The following section describes the total water use in the irrigation scheme.

6.3.3.1 Total water use

There are two types of irrigation scheme depending on the supply of water. These are:

1. Storage water irrigation scheme: In this type of irrigation scheme river runoff is stored in the reservoir which is used for different purposes when needed.
2. River diversion irrigation scheme: The river runoff is diverted directly for the different uses.

The water available in the irrigation scheme is utilised for several purposes and irrigation is the prime user of water. AWAM is developed to optimise the use of water which is available for irrigation, for allocating during different irrigations and to different crops grown on different soils in different allocation units. The use of water for other purposes during different periods is computed separately and is the direct input to the model. The different purposes for which water is needed are:

1. Domestic and industrial use of water : Water for this purpose is directly delivered from the reservoir or headworks or carried through the canal network.
2. Agreed demand of water for irrigation: In the command area of an irrigation scheme, several irrigation societies exist, which manage water themselves. Similarly the irrigation ponds are constructed in the scheme for supplying water to the irrigation users which are out of command area of the irrigation scheme. The certain amount of water is agreed to be delivered to those societies and in the irrigation ponds. The water is delivered to them either from the reservoir or through canal networks. There are certain crops grown in the allocation units which are not considered in the allocation plan but should be supplied with water for irrigation. These include perennial plantation such as horticultural crops and trees and crops following from the previous seasons. The water requirement for such crop during different periods for each AU is computed separately. Water for this purpose is carried through the canal network. If QOI_{ia} is the quantity of water required for irrigating these crops for the i^{th} irrigation at a^{th} allocation unit, then water to be diverted from the headworks for irrigating these crops during the i^{th} irrigation for a^{th} allocation unit($QOHI_{ia}$) is equal to $QOI_{ia} / \eta ca_{ia} \eta da_{ia}$.
3. Other: This includes the water to be diverted for other unspecified uses depending on the requirement of the irrigation scheme and water lost from the canal by theft etc.

if QOO_{ia} is the amount of water required for other purposes during the i^{th} irrigation for a^{th} allocation unit, the water to be delivered from the headworks is $QOHO_{ia}$ and is equal to $QOO_{ia} / \eta ca_{ia}$.

As discussed above some uses draw water directly from the reservoir, some through canal networks and some from both. Therefore these are considered in the model at appropriate places. Though the input of water required for these uses during different irrigation periods is directly given to the model, its inclusion in the model is required for restrictions on reservoir capacity and capacity of the canal network.

6.3.3.2 Physical constraints

These are the constraints which limit the use of resources available in the scheme according to the ability of the system to use those resources.

1. Area constraints

The total area to be irrigated at any instance in any soil group of an allocation unit in the irrigation scheme should not exceed the maximum irrigable area of the soil group of AU. The total area to be irrigated constitutes the area which is being irrigated under different crops, and the area which is not yet irrigated but is planned for irrigating a certain crop and is under land preparation for irrigation. This constraint is represented by the equation (6.23).

$$\sum_{c=1}^{nc_{sa}} \sum_{p=1}^{np_{csa}} A_{pcsa} \leq TAAS_{sa} \qquad \text{for} \quad s=1,ns_a$$

a=1,na and
i=1,I

$$A_{pcsa} = 0 \qquad \text{if} \quad pld_{csa}-lnp_{csa} > Ei_i \quad \text{or} \quad hrd_{csa} < SI_i \qquad (6.23)$$

where

$TAAS_{sa}$	=	total area that can be irrigated in s^{th} soil group of a^{th} allocation unit (ha)
pld_{csa}	=	planting date of c^{th} crop grown in s^{th} soil group of a^{th} allocation unit
lnp_{csa}	=	land preparation required for c^{th} crop grown in s^{th} soil group of a^{th} allocation unit(days)
hrd_{csa}	=	harvesting day of c^{th} crop grown in s^{th} soil group of a^{th} allocation unit
SI_i	=	starting day of i^{th} irrigation
EI_i	=	Ending day of i^{th} irrigation

2. Optional area restrictions

These are the optional constraints restrict the total area to be irrigated of the entire irrigation scheme in a certain prescribed range. It states that the total area to be irrigated within an irrigation scheme should lie in between minimum and maximum prescribed limits of area to be irrigated. This is represented by equation (6.24).

$$TA\ nos\ ftn \leq \sum_{a=1}^{na} \sum_{s=1}^{ns_a} \sum_{c=1}^{nc_{sa}} \sum_{p=1}^{np_{csa}} A_{pcsa} \leq TA\ nos\ ftx \qquad (6.24)$$

$ftn \leq ftx$

$ftn = 0$ if no limits for minimum area

$ftx = \infty$ if no limits for maximum area (equation (6.23) restricts the maximum area that can be irrigated)

where

TA	=	total irrigable area of irrigation scheme (ha)
nos	=	number of crop seasons
ftn	=	fraction for minimum limit on area to be irrigated for irrigation scheme
ftx	=	fraction for maximum limit on area to be irrigated for irrigation scheme

3. Canal Capacity Constraint

Water to be carried through the canals in the water distribution network for delivering it to different AUs should not exceed the carrying capacity of respective canals. In the allocation process during a particular irrigation interval, water can be allocated to the group of allocation units with the same canal for delivering water to those AUs, so that this canal may not carry the allocated amount of water. In the similar way allocation of water may be such that the canal may have to carry the amount of water which is less than its prescribed minimum limit (the prescribed minimum limit may be zero). Therefore it is necessary to consider the limitations of carrying capacities of canals in the allocation process, so that in actual operation canal capacity should not restrict the specified allocation plan.

In the previous allocation studies, the constraints on capacity of canals were either neglected or put on only main canals. In those studies it might have been assumed that the canal distribution network is capable of carrying the allocated amount of water (when the canal capacity constraint was not considered). The constraint on capacity of only the main canal is sufficient for those studies which allocate the water at scheme level rather than at allocation unit level or assume that the other canals are designed to carry the water diverted from the main canal. The latter may be true when a fixed depth of water is applied to all AUs. In the AWAM as the water is allocated at AU level (with varying depths for each CS of AU), it was thought necessary to consider the carrying capacities of all canals in the distribution network.

As described earlier there are different levels in the water distribution network at which different canals offtake. At each level there may be one or more canals. At level-1, there may be only one canal (main canal) or two canals (left bank canal and right bank canal). In considering the limitations on canal capacities, the conveyance efficiency of the water distribution network up to each level for a particular allocation unit needs to be known for computing the amount of water to be carried by different canals at different levels. These are computed by equations (6.4), (6.8) and (6.12) for three different approaches described in Section 6.2.2.2.

The canal capacity constraint states that the water to be carried through the canal should lie within the minimum and maximum limits of canal carrying capacities. The water to be carried through the canal includes water to be delivered to different AUs for irrigating crops in the allocation plan and irrigating crops not in the allocation plan, water needs for other purposes, water to be diverted for non irrigation purpose and theft of water, from the canal under consideration and all canals for which the canal under consideration carries the water. Water to be diverted for non irrigation purpose and theft of water from the canal under consideration and all canals for which the canal under consideration carries the water are computed by equation (6.25).

$$QCCO_{ikj} = \sum_{j'=j}^{NCL} \sum_{k'=1}^{Ncan_{j'}} \frac{QCO_{ik'j'}}{\sum_{j''=j'}^{j} \eta cc_{ik''j''}} \qquad (6.25)$$

$$\text{for } i = 1, I, \quad K = 1, Ncan_j \text{ and } j = 1, NCL$$

$$\text{and } ncc_{k'jj} = k' ; \quad k'' = ncc_{k'j''j'}$$

where

$QCO_{ik'j'}$ = quantity of water to be diverted from k'^{th} canal at j'^{th} level during i^{th} irrigation period for non irrigation purposes and estimated theft of water from this canal(ha-m)

$QCCO_{ikj}$ = quantity of water to be carried by k^{th} canal at j^{th} level during i^{th} irrigation period for non irrigation purposes and estimated theft of water (ha-m).

This is formulated for all the canals in the water distribution network and is represented by equation (6.26).

$$CC\min_{ikj} II_i \varepsilon_{ikj} KN \le \left(\sum_{a=1}^{na} \sum_{s=1}^{ns_a} \sum_{c=1}^{ns_{sa}} \sum_{p=1}^{np_{csa}} WD_{ipcsa} A_{pcsa} \eta cc_{ija} \right) +$$

$$\left(\sum_{a=1}^{na} QOHI_{ia} \eta cc_{ija} \right) + \sum_{a=1}^{na} QOHO_{ia} \eta cc_{ija} + QCCO_{ikj} \qquad (6.26)$$

$$\le CC\max_{ikj} II_i \varepsilon_{ikj} KN$$

for $i = 1, I$

$k = 1, Ncan_j$

$j = 1, NCL$

and for all a for which $J_a < j$ and $K_{aj} = k$

where

j	=	index for canal level
k	=	index for canal number at any canal level
J_a	=	the canal level at which j^{th} AU exists
K_{aj}	=	the canal number for j^{th} level of a^{th} allocation unit
$CCmin_{ikj}$	=	the minimum prescribed limit of carrying capacity of k^{th} canal at j^{th} level during i^{th} irrigation interval (m^3/s)
$CCmax_{ikj}$	=	the maximum prescribed limit of carrying capacity of k^{th} canal at j^{th} level during i^{th} irrigation interval (m^3/s)
II_i	=	the irrigation period of i^{th} irrigation interval (days)
ε_{ikj}	=	supply factor for k^{th} canal at j^{th} level for i^{th} irrigation period
KN	=	3600*24/10000

In the present study the consideration is given to different capacities of canal during different irrigation periods. This was considered because of the possibility of improving or deteriorating canal capacity due to cleaning or to vegetation growth and/or silting of canal, respectively. The supply factor determines the length of period for which the particular canal runs during a particular irrigation period. This depends on various factors related to management such as grouping of different canals for operation purpose, not to put extra stress on capacities of canal at upper levels, maintenance time for the canal etc.

4. Outlet Capacity Constraints

If the allocation unit is served by an outlet, the consideration of this constraint restricts the delivery of the water and thus influences the allocation of area to different crops within the allocation unit according to the discharge capacity of the outlet. However if the outlets exist within the allocation unit, this constraint is not necessary as allocation to the allocation unit is not affected by outlet capacities. If several allocation units are served by one outlet, then the outlet can be considered as the 'canal' at an appropriate level for the sake of limiting the water delivery according to its capacity, and constraint to its capacity can be included in the canal capacity constraints. The outlet capacity constraint states that the water delivery through the outlet for irrigating different crops in allocation plans and crops not in allocation plans and utilised for other purposes in AU during any irrigation period should not exceed the maximum carrying capacity and should be above the minimum carrying capacity of the outlet during this irrigation period. These constraints are represented by equation (6.27)

$$OC\min_{ia} II_i \varepsilon o_{ia} KN \le \left(\sum_{s=1}^{ns_a} \sum_{c=1}^{nc_{sa}} \sum_{p=1}^{np_{csa}} WD_{ipcsa} A_{pcsa} \eta ca_{ia} \right) + \frac{QOI_{ia}}{\eta da_{ia}} + QOO_{ia}$$

$$\le OC\max_{ia} II_i \varepsilon o_{ia} KN$$

for a=1,na and i=1,I (6.27)

where

$OCmin_{ikj}$	=	the minimum prescribed limit of carrying capacity of outlet of a^{th} allocation unit during i^{th} irrigation interval (m^3/s)
$OCmax_{ikj}$	=	the maximum prescribed limit of carrying capacity of outlet of a^{th} allocation unit during i^{th} irrigation interval (m^3/s)
εo_{ia}	=	supply factor for outlet of a^{th} allocation unit for i^{th} irrigation
QOO_{ia}	=	quantity of water required for other purposes in a^{th} allocation unit for i^{th} irrigation (ha-m)

6.3.3.3 Resource availability constraints

These constraints set the limits on availability of different resources in the scheme, depending on which land area is allocated to different activities.

1. Intraseasonal water supply constraints

The total quantity of water to be delivered for irrigation during any intraseasonal period (irrigation period) should not exceed the total quantity of water that can be made available in that irrigation period. This varies according to the type of irrigation scheme. Therefore the intraseasonal water supply constraints are formulated differently for storage reservoir and river diversion irrigation schemes.

I) Storage reservoir irrigation scheme

The total quantity that can be available for irrigation in any intraseasonal period is computed from the storage of water in the reservoir at the beginning of the period, inflows (river runoff and direct rainfall) received during the period, evaporation, seepage and other losses during the period, water transported for other purposes (both irrigation and nonirrigation and to be diverted directly from the headworks or carried through canal network). The quantity of water lost from the reservoir due to seepage and used for other purposes during each intraseasonal period are estimated at the beginning of the irrigation season.

The evaporation losses during each intraseasonal period are either assumed to be known at the beginning of the irrigation season or computed within the season from the water available in the reservoir at the beginning and the end of each intraseasonal period and from evaporation data. As the AWAM is developed for the irrigation in the semi-arid region, where evaporation losses are predominant and vary considerably during the irrigation season, these need proper estimation. The assumption that the evaporation losses are known prior to the start of the irrigation season may prove incorrect as evaporation losses from the reservoir during any intraseasonal period is a function of the reservoir water surface area and weather variation during that period. The reservoir water surface area depends on the amount of water available in the reservoir which in turn depends on the amounts of water delivered to different CS units of AU in the previous periods. However the amounts of water to be delivered to different CS units in AU are decision variables and are determined in the optimisation process. Thus evaporation losses from the reservoir depend on the water to be delivered to different activities (unless the effect of deliveries on reservoir surface area are negligible) and therefore need to be incorporated in the optimisation model.

As stated earlier, the seepage losses are assumed to be known at the start of the irrigation season. This may add to inaccuracy but its influence is less because seepage losses are influenced by several other factors such as permeability and, position of water table. Moreover the seepage losses are a non linear function of water content in the reservoir, which is difficult to linearise. Consideration of computation of both evaporation and seepage losses in the optimisation process adds to complexity in solving the problem. Therefore as evaporation losses are considered important, seepage losses are estimated in the beginning of irrigation season rather than computing within the season.

The intraseasonal water supply constraints are represented in the following way.

a) Evaporation losses assumed at the start of the irrigation season

$$\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} WD_{ipcsa}A_{pcsa} \le ST_{i-1} - S\min + Inf_i - el_i - ol_i - sp_i$$

for i=1,I (6.28)

Continuity

$$ST_{i-1} = ST_{i-2} + Inf_{i-1} - el_{i-1} - ol_{i-1} - sp_{i-1} - \sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} WD_{i-1,pcsa}A_{pcsa}$$

for i=2,I

$= So$ for i=1

(6.29)

From equations (6.28) and (6.29), the constraints are represented by equation (6.30).

$$\sum_{i1=1}^{i}\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} WD_{i1,pcsa}A_{pcsa} \le So - S\min + \sum_{i1=1}^{i} Inf_{i1} - \sum_{i1=1}^{i} el_{i1} - \sum_{i1=1}^{i} ol_{i1} - \sum_{i1=1}^{i} sp_{i1}$$

for i=1,I

(6.30)

where

So	=	initial reservoir storage (at the beginning of irrigation season) (ha-m)
Smin	=	dead storage capacity of the reservoir or the minimum storage of water that should always be maintained in the reservoir (ha-m)
Inf_i	=	the inflow of water into the reservoir which constitutes the river runoff into the reservoir and rainfall over the reservoir (ha-m) during i^{th} irrigation period
el_i	=	evaporation losses from the reservoir during i^{th} irrigation period (ha-m)
sp_i	=	seepage losses form the reservoir during i^{th} irrigation period (ha-m)
ol_i	=	water to be diverted for other purposes (ha-m) during i^{th} irrigation period. This is computed as

$$ol_i = \left(\sum_{j=1}^{NCL} \sum_{k=1}^{Ncan_j} \frac{QCO_{kj}}{\eta C_{kj}} \right) + \left(\sum_{a=1}^{na} QOHO_{ia} \right) + \left(\sum_{a=1}^{na} QOHI_a \right) + olr_i$$

olr_i = water to be diverted from the headworks for other purposes during i^{th} irrigation period

The inflow into the reservoir by direct rainfall is computed by knowing the maximum reservoir surface area and depth of rainfall.

b) Evaporation losses computed during the irrigation season in optimisation process
Evaporation losses are computed from volume vs. depth and area vs. depth relationships of the reservoir. These relationships are converted into volume vs. area relationship (equation (6.31)) of linear type to incorporate into the model.

$$SA = \gamma_1 ST + \gamma_2 \tag{6.31}$$

where

ST = reservoir storage (ha-m)

SA = reservoir surface area (ha)

γ and γ_2 = the constants of the relationship (slope and intercept, respectively)

Evaporation losses are computed at the mid point of the irrigation period, by computing reservoir surface area at the beginning of the irrigation period (or at the end of previous irrigation period) and at the end of the current irrigation period, with the help of equation (6.32).

$$el_i = \frac{SA_{i-1} + SA_i}{2} ep_i \tag{6.32}$$

where

ep_i = evaporation losses (depth) over the irrigation period (m)

Evaporation losses (depth) are computed by Penman method (Penman, 1948) or pan evaporation method (Doorenbos and Pruit, 1984) by using appropriate factor. As el is the function of ST which itself depends on water diversion from the reservoir (and thus allocation of water to different CS units of AU), el can not be incorporated directly (like equation (6.30)) but has to be included in constraints. From equations (6.30), (6.31)and (6.32) and solving further

$$\sum_{i1=1}^{i}\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} WD_{i1,pcsa}A_{pcsa}\lambda 1_{i1} \leq$$

$$\lambda 2_i So - S\min + \sum_{i1=1}^{i}\lambda 1_{i1} Inf_{i1} - \sum_{i1=1}^{i}\lambda 1_{i1} sp_{i1} + \sum_{i1=1}^{i}\lambda 1_{i1} ol_{i1} + \lambda 3_i \quad \text{for} \quad i=1,I \tag{6.33}$$

where

$$\lambda 1_{i1} = 1 - 0.5\gamma 1 + ep_i \qquad \text{if} \quad i1 = i$$
$$\gamma 1_{i-i1} - \gamma 1_{i-1} ep_i \qquad \text{else}$$
$$\lambda 2_i = 1 - \gamma 1 ep_i \qquad \text{if} \quad i = 1$$
$$= \lambda 2_{i-1} - \lambda 2_{i-1}\gamma 1 el_i \qquad \text{else}$$
$$\lambda 3_i = -\gamma 2 ep_i \qquad \text{if} \quad i = 1$$
$$= \lambda 3_{i-1}\left\{-\gamma 2 ep_i + \lambda 3_{i-1}\left(-\gamma 1 ep_i\right)\right\} \quad \text{else}$$

II) River diversion irrigation scheme

The formulation of intraseasonal water supply constraints in this type of scheme is straightforward as the continuity equation is not needed due to absence of a reservoir and thus carryover water storage from one period to another. Similarly evaporation and seepage losses from the reservoir can be omitted. The constraint is simplified to equation (6.34).

$$\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} WD_{ipcsa}A_{pcsa} \leq Inf_i - ol_i \qquad \text{for} \quad i=1,I \tag{6.34}$$

2. Reservoir Storage Constraint

The intraseasonal water constraints consider that the inflows received in a particular irrigation period can be utilised towards water delivery during the same irrigation period. The water delivery during any irrigation period can be equal to the difference between storage capacities at the beginning and end of the irrigation period and inflows received during that period. But it is assumed that the water delivery during that irrigation period should not exceed the maximum available storage in that period and inflows received in the irrigation period above maximum storage capacity of the reservoir acts as spillage (infact this constraint assumes that the inflows are lumped at the beginning of irrigation period). The constraint is represented by the equation (6.35)

$$\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} WD_{ipcsa}A_{pcsa} + ol_i \leq S\max - S\min \qquad \text{for} \quad i=1,I \tag{6.35}$$

where

Smax = maximum storage capacity of the reservoir (ha-m)

3. Availability and allocation of other resources

In AWAM, the allocation of land and water resources are considered in detail. While allocating water to land for irrigating a certain crop, the influence of allocation of different quantities of water application to the output (crop yield/net benefits) is considered along with the total quantity of water available for irrigation in the scheme. The optimisation formulation also considers the possibilities of allocating different hectarage (restricted to total hectarage available for irrigation) to different crops with different amount of water to arrive at a final optimum solution. However there are other resources (inputs) which influence the output of the irrigation scheme. These are for example fertilisers, seeds, machine hours, human labourers, pesticides, capital available etc. In AWAM, the influence of availability of these resources on allocation of land and water to different crops can be considered. But the effect of applying different quantities of resources per unit area of crop under irrigation is not considered. Thus only one level of application of these resources per unit area (unlike water, wherein many levels of application are considered) is considered. It is assumed that when certain amount of land is irrigated under certain crop, the availability of these resources, does not restrict the output from the land under irrigation. However the availability of these resources can restrict the amount of land to be brought under irrigation and thus total output from the irrigation scheme.

The availability or use of these resources are considered at scheme and AU level. These constraints state that the total use of the resource under consideration in AU or scheme should not exceed the total availability of this resource in the AU or the scheme, should not be less than minimum level of use of these resources, should be in the range of use of these constraints or be equivalent to the specified level of use of these resources in the AU or the scheme. These constraints are described by equation (6.36).

I) Scheme level

$$\Omega T\min_r \leq \sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} \Omega_{csa}A_{pcsa} \leq \Omega T\max_r \qquad \text{for} \quad r=1,NRS \tag{6.36}$$

where

r	=	index for the resource
$\Omega T\min_r$	=	minimum level of availability or use of r^{th} resource during irrigation season (total resource)
$\Omega T\max_r$	=	maximum level of availability or use of r^{th} resource during irrigation season (total resource)
Ω_{csa}	=	the use or need of r^{th} resource for c^{th} crop in s^{th} soil group in a^{th} allocation unit during per unit area during irrigation season (resource/hectare)
NRS	=	total number of resources to be considered at scheme level and during irrigation season

II) AU level

$$\Omega aT\min_{ar} \leq \sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}\Omega_{csa}A_{pcsa} \leq \Omega aT\max_{ar} \qquad \text{for} \quad r=1,NRSa \qquad (6.37)$$

where

$\Omega aT\min_r$	=	minimum level of availability or use of r^{th} resource at a^{th} AU during irrigation season (total resource)
$\Omega aT\max_r$	=	maximum level of availability or use of r^{th} resource at a^{th} AU during irrigation season (total resource)
NRS_a	=	total number of resources to be considered at AU level and during irrigation season

The constraints formulated by equations (6.36) and (6.37) represent the availability or the use of resources during the entire irrigation season. However for some of the resources (e.g. labour), their availability and requirement need to be considered during the smaller period. In AWAM, there is provision to consider the availability or use of the resources at scheme or AU level during each intraseasonal period. The related constraints are presented by equations (6.38) and (6.39)

I) Scheme level

$$\Omega Ti\min_{ir} \leq \sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}\Omega i_{icsa}A_{pcsa} \leq \Omega Ti\max_{ir} \qquad \text{for} \quad i=1,I \text{ and } r=1,NRSI \qquad (6.38)$$

where

$\Omega Ti\min_{ir}$ = minimum level of availability or use of r^{th} resource during i^{th} irrigation period (total resource)

$\Omega Ti\max_{ir}$ = maximum level of availability or use of r^{th} resource during i^{th} irrigation period (total resource)

Ωi_{icsa} = the use or need of r^{th} resource for c^{th} crop in s^{th} soil group in a^{th} allocation unit resource during i^{th} irrigation period per unit area (resource/hectare)

NRSI = total number of resources to be considered at scheme level and during intraseasonal period

II) AU level

$$\Omega aTi\min_{iar} \le \sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} \Omega i_{icsa} A_{pcsa} \le \Omega aTi\max_{iar} \qquad \text{for} \qquad r=1,\text{NRSIa} \qquad (6.39)$$

where

$\Omega aTi\min_{ir}$ = minimum level of availability or use of r^{th} resource at a^{th} AU during i^{th} intraseasonal period (total resource)

$\Omega aTi\max_{ir}$ = maximum level of availability or use of r^{th} resource at a^{th} AU during i^{th} intraseasonal period (total resource)

NRSIa = total number of resources to be considered at AU level and during intraseasonal period

Type of limitations

for using the resource equivalent to specified value:

RHS = LHS = specified value

for not exceeding the use of resource beyond specified value:

RHS = specified value and LHS= 0

for not lowering the use of resource than specified value:

RHS= ∞ and LHS = specified value

for using the resources within specified range:

RHS= specified value and LHS = specified value

where

RHS = the variable at right hand side of the equations (6.36) to (6.39)

LHS = the variable at left hand side of the equations (6.36) to (6.39)

6.3.3.4 Output requirement constraints

These constraints specify the need to generate output at a certain prescribed level and/or by a certain prescribed law.

1. Crop Constraints

These are the constraints required to put certain restrictions on the resources to be allocated to different crops grown in the irrigation scheme according to certain predetermined criteria. The most optimum solution may contain the resources allocated to only one crop or a few crops giving maximum output as per the chosen objective. Frequently however this is not the only objective. It is also necessary to allocate the resources to all the crops or some crops according to required value or in a certain prescribed range. The inclusion of such constraints satisfies this requirement.

The limitations on the resources to be allocated to different crops can be incorporated at scheme level, AU level or soil group of AU, depending on the need for restriction. The resources on which this limitation can be put are land and water. The limits can be based on the amount of resources or the fraction of the total resources available. The limitations can be specified according to a fixed quantity to be allocated to different crops or a fixed fraction of the total quantity of resources to be allocated to different crops, by specifying a minimum amount or fraction (the total resources to be allocated to certain crops should be above this minimum limit), by specifying a maximum the amount or fraction (the total resources to be allocated to a certain crop should be below this maximum limit) or by specifying the range (the total resources to be allocated to a certain crop should be within the prescribed range). The various options available in the AWAM are summarised below.

I) Resources to be limited for allocation
- a. Land
- b. Water

II) Levels for limitation
- a. Scheme
- b. Allocation unit
- c. Soil group (SG) in allocation unit

III) Criteria of limitation
- a. Amount of resources
- b. Fraction of total resources

IV) The form of limitation

a. Fixed

b. Minimum limit specified

c. Maximum limit specified

d. Range specified (both maximum and minimum limits specified)

The formulations of constraints for above options are described below

I) With land as resource

a) Scheme-Area-Amount

$$AC\min_c \le \sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{p=1}^{np_{csa}} A_{pcsa} \le AC\max_c \qquad \text{for} \quad c=1,NC \tag{6.40}$$

where

$ACmax_c$ = maximum limit on the area to be irrigated for c^{th} crop (ha)

$ACmin_c$ = minimum limit on the area to be irrigated for c^{th} crop (ha)

b) Scheme-Area-Fraction

$$\Gamma n_c\left(\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} A_{pcsa}\right) \le \sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{p=1}^{np_{csa}} A_{pcsa} \le \Gamma x_c\left(\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} A_{pcsa}\right) \qquad \text{for} \quad n=1,NC \tag{6.41}$$

where

Γx_c = maximum limit on the fraction of total area of scheme that can be irrigated, for c^{th} crop

Γn_c = minimum limit on the fraction of total area of scheme that can be irrigated for c^{th} crop

c) AU-Area-Amount

$$ACa\min_{ca} \le \sum_{s=1}^{ns_a}\sum_{p=1}^{np_{csa}} A_{pcsa} \le ACa\max_{ca} \qquad \text{for} \quad a=1,na \text{ and } c=1,NC \tag{6.42}$$

where

$ACamax_{ca}$ = maximum limit on the area to be irrigated for c^{th} crop (ha)) in a^{th} allocation unit (ha)

$ACamin_{ca}$ = minimum limit on the area to be irrigated for c^{th} crop (ha) in a^{th} allocation unit (ha)

d) AU-Area-Fraction

$$\Gamma an_{ca}\left(\sum_{s=1}^{ns}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} A_{pcsa}\right) \leq \sum_{s=1}^{ns_a}\sum_{p=1}^{np_{csa}} A_{pcsa} \leq \Gamma ax_{ca}\left(\sum_{s=1}^{ns}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} A_{pcsa}\right)$$

for a=1,na and n=1,NC

(6.43)

where

Γax_{ca} = maximum limit on the fraction of total area of a^{th} allocation unit that can be irrigated, for c^{th} crop

Γan_{ca} = minimum limit on the fraction of total area of a^{th} allocation unit that can be irrigated for c^{th} crop

e) Soil group of AU-area-amount

$$ACsa\min_{csa} \leq \sum_{p=1}^{np_{csa}} A_{pcsa} \leq ACsa\max_{csa}$$

for a=1,na;

s=1,ns_a and c=1,nc_{sa}

(6.44)

where

$ACsamax_{ca}$ = maximum limit on the area to be irrigated for c^{th} crop (ha) in s^{th} soil group of a^{th} allocation unit (ha)

$ACsamin_{csa}$ = minimum limit on the area to be irrigated for c^{th} crop (ha) in s^{th} soil group of a^{th} allocation unit (ha)

f) SG of AU-area-fraction

$$\Gamma san_{csa}\left(\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} A_{pcsa}\right) \leq \sum_{p=1}^{np_{csa}} A_{pcsa} \leq \Gamma sax_{csa}\left(\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} A_{pcsa}\right)$$

for a=1,na; s=1,ns_a and n=1,nc_{sa}

(6.45)

where

Γsax_c = maximum limit on the fraction of total area of s^{th} soil group of a^{th} allocation unit that can be irrigated, for c^{th} crop

Γsan_c = minimum limit on the fraction of total area of s^{th} soil group of a^{th} allocation unit that can be irrigated for c^{th} crop

Form of limitations

i) Fixed
RHS = LHS = specified value
ii) Minimum limit specified
RHS = TA (amount-scheme level)
RHS = TAA_a (amount-AU level)
RHS = $TAAS_a$ (amount-SG of AU level)
RHS = 1 (fraction)
LHS = specified value
iii) Maximum limit specified
RHS = specified value
LHS = 0
iv) Range specified
RHS = specified value
LHS = specified value

II) With water as resource

a) Scheme-Water -Amount

$$WC\min_c \leq \sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{p=1}^{np_{csa}} SWD_{pcsa}A_{pcsa} \leq WC\max_c \qquad \text{for } c=1,NC \tag{6.46}$$

where

$WCmin_c$ = maximum limit on the water to be delivered for c^{th} crop (ha)

$WCmax_c$ = minimum limit on the water to be delivered for c^{th} crop (ha)

b) Scheme-Water -Fraction

$$\Gamma wn_c\left(\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} SWD_{pcsa}A_{pcsa}\right) \le \sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{p=1}^{np_{csa}} SWD_{pcsa}A_{pcsa} \le$$

$$\Gamma wx_c\left(\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} SWD_{pcsa}A_{pcsa}\right)$$

for n=1,NC

(6.47)

where

Γwx_c = maximum limit on the fraction of total water that is available for irrigation in the scheme, for c^{th} crop

Γwn_c = minimum limit on the fraction of total water that is available for irrigation in the scheme, for c^{th} crop

c) AU-Water -Amount

$$WCa\min_{ca} \le \sum_{s=1}^{ns_a}\sum_{p=1}^{np_{csa}} SWD_{pcsa}A_{pcsa} \le WCa\max_{ca}$$

for a=1,na and

c=1,NC

(6.48)

where

$WCamin_{ca}$ = maximum limit on water to be delivered for c^{th} crop in a^{th} allocation unit (ha)

$WCamax_{ca}$ = minimum limit on the water to be delivered for c^{th} crop in a^{th} allocation unit (ha)

d) AU-Water Fraction

$$\Gamma wan_{ca}\left(\sum_{s=1}^{ns}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} SWD_{pcsa}A_{pcsa}\right) \le \sum_{s=1}^{ns_a}\sum_{p=1}^{np_{csa}} SWD_{pcsa}A_{pcsa}$$

$$\le \Gamma wax_{ca}\left(\sum_{s=1}^{ns}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} SWD_{pcsa}A_{pcsa}\right)$$

for a=1,na and n=1,NC

(6.49)

where

Γwax_{ca} = maximum limit on the fraction of total water that is available for a^{th} allocation unit, for c^{th} crop

Γwan_{ca} = minimum limit on the fraction of total water that is available for a^{th} allocation unit that can be irrigated for c^{th} crop

e) SG of AU-Water -Amount

$$WCsa\min_{csa} \leq \sum_{p=1}^{np_{csa}} SWD_{pcsa}A_{pcsa} \leq WCsa\max_{csa} \qquad \text{for} \quad a=1,na;$$

$$s=1,ns_a \text{ and } c=1,nc_{sa} \qquad (6.50)$$

where

$WCsamin_{csa}$ = maximum limit on the water to be delivered for c^{th} crop in s^{th} soil group of a^{th} allocation unit (ha)

$WCsamax_{csa}$ = minimum limit on the water to be delivered for c^{th} crop in s^{th} soil group of a^{th} allocation unit (ha)

f) SG of AU-Water-Fraction

$$\Gamma wsan_{csa}\left(\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} SWD_{pcsa}A_{pcsa}\right) \leq \sum_{p=1}^{np_{csa}} SWD_{pcsa}A_{pcsa} \leq$$

$$\Gamma wsax_{csa}\left(\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} SWD_{pcsa}A_{pcsa}\right)$$

$$\text{for} \quad a=1,na;\ s=1,ns_a \text{ and } c=1,nc_{sa} \qquad (6.51)$$

where

$\Gamma wsax_{ca}$ = maximum limit on the fraction of total area of s^{th} soil group of a^{th} allocation unit that can be irrigated, for c^{th} crop

$\Gamma wsan_{ca}$ = minimum limit on the fraction of total area of s^{th} soil group of a^{th} allocation unit that can be irrigated for c^{th} crop

Form of limitations

These are similar to those as described with area as restriction (TA, TAA_a and $TAAS_{sa}$ being replaced by Wmax, maximum water available in the scheme in ha-m)

Restrictions on the crop area to be irrigated at a certain level and in certain forms resulted in several sets of constraints. Many of these sets need the fixed values, minimum values or certain fractions. The sum of fixed values of resources may exceed the total available resources or if care is taken to match it to total available resource (e.g. land area), the availability of another resource (e.g. water) can act as a restriction to irrigate the specified land area under different crops. The minimum value needs to be set properly otherwise there is a possibility of getting an infeasible solution, especially when the sum of minimum limits of the resources set for different crops in different units exceeds the total availability of the resources. Similarly when the set of constraints needs the fraction, care should be taken to match the sum of all the fractions of total resources for all the units to one.

Some sets of constraints can be used together while some sets are to be used individually. For example, the set of constraints setting the minimum limit on the water to be diverted for certain crops at scheme level (scheme-water-amount-minimum limit specified) and keeping the area to be irrigated for certain crops in the allocation units in a certain range of fraction of total area that can be irrigated in allocation unit (AU-area-fraction-range specified) can be used together (the feasible solution depending on minimum limit and fractions). But the set of constraints stating to deliver fixed fraction of total water available to different crops at scheme level (scheme-water-fraction-specified value) and fixed amount of area to be irrigated under different crops at scheme level (scheme-area-amount-specified value) may not be used together. As such the set containing the fixed value (amount or fraction) of resources to be allocated to crops may not be used with other set of constraints, as the fixed values is deciding factor rather than range, minimum or maximum limits.

Constraints setting areas to be irrigated under different crops in different soil groups of different AUs to certain values (SG of AU-area-amount-specified value) is specifically useful for evaluating a certain irrigation strategy or obtaining a water delivery plan (amount of water delivered to different crops grown in different soil groups of different AUs) for a certain area allocation plan (land area allocated to different crops on different soil groups of different AUs) for the irrigation scheme. Similarly the constraints setting water to be allocated to different crops in different soil groups of different AUs (SG of AU-water-amount-specified value) are used for evaluating certain water delivery plans for the irrigation scheme. The RA submodel with these constraints evaluates the allocation plans, by taking into consideration the physical constraints of the scheme (such as water availability in different intraseasonal periods, capacity of the canal distribution network etc.)

2. Food Requirements Constraints

The area and water restriction constraints for different crops (described above under crop restrictions) do not specify the food production to be obtained in land and water allocation models. The criterion used in earlier allocation studies, mainly land allocation models (refer Section 2.4.1) was to irrigate a certain minimum area for a certain crop. This was predominantly to satisfy the food requirements of the inhabitants in the irrigation scheme. As these models considered the predetermined water allocation policy for which estimated crop yield was known, the minimum restriction on area to be irrigated on a certain crop was equivalent to the food requirement constraints.

As in AWAM, the water allocation policy along with the area allocation policy is decided from the optimum solution, the level of crop yield obtained per unit area for a certain crop is not known before the planning starts and thus minimum limits on the area to be irrigated under different crops or water to be delivered is not sufficient to satisfy the food needs. These constraints are therefore formulated separately. These constraints state that the production obtained from the irrigation of different crops should be in accordance with defined policy. The policy can be that the production from a certain crop should be in a prescribed range, below a prescribed value, above a prescribed value or equivalent to a prescribed value. These constraints are also formulated at scheme level and AU level. The AU level constraints are useful when the extent of irrigation scheme is large and needs for food are to be satisfied at lower level (allocation unit level). These are described below.

I) Scheme level

$$P\min_c \leq \sum_{a=1}^{na} \sum_{s=1}^{ns_a} \sum_{p=1}^{nc_{pcsa}} Ya_{pcsa} A_{pcsa} \leq P\max_c \qquad \text{for} \quad c=1,NC$$

$$P\max_c \geq P\min_c \qquad (6.52)$$

where

$Pmin_c$ = minimum limit of crop production to be obtained from the scheme, for c^{th} crop (Kg)

$Pmax_c$ = maximum limit of crop production to be obtained from the scheme, for c^{th} crop (Kg)

II) AU level

$$\text{Pa}\min_c \le \sum_{s=1}^{ns_a} \sum_{p=1}^{np_{csa}} Ya_{pcsa} A_{pcsa} \le \text{Pa}\max_c \quad \text{for} \quad a=1,na \text{ and } c=1,NC$$

$$\text{Pa}\max_c \ge \text{Pa}\min_c \tag{6.53}$$

where

$Pamin_c$	=	minimum limit of crop production to be obtained from the AU, for c^{th} crop (Kg)
$Pamax_c$	=	maximum limit of crop production to be obtained from the AU, for c^{th} crop (Kg)

Form of limitations

for obtaining crop production equivalent to specified value:
RHS = LHS = specified value
for not exceeding crop production beyond specified value:
RHS = specified value and LHS = 0
for not lowering crop production than specified value:
RHS = ∞ and LHS = specified value
for obtaining crop production within specified range:
RHS = specified value and LHS = specified value

Food requirement constraints and constraints for area and water limitation to different crops are to be used carefully. The food requirement constraints decide finally the area to be irrigated under a certain crop and the water to be delivered to those crops. If the constraints to set the limits of area to be allocated and/or water to be delivered to certain crops is set separately, it may clash with the food requirement constraints.

3. Resource restriction constraints

If it is necessary to restrict the use of a certain resource to different AUs or SGs in AUs to certain values, these constraints are used. This situation particularly exists when a certain amount of area is to be irrigated or a certain amount of water is to be diverted to selected AUs (or SGs in AUs), depending on the rights of farmers in a certain area to use fixed or minimum resources, or supplying fixed or minimum water to farmers in certain AUs. The latter situation especially exists in the irrigation schemes which are severely short of water for irrigation. In such schemes the rotation in allocation among different seasons is followed (for example, in India). Some farmers are assured water in one irrigation season and remaining farmer or assured water in next season.

These constraints state that the resource (land or water) to be allocated to a certain unit (AU or SG in AU) should be equal to, more than, or less than the specified value or within the range of specified values.

Thus the constraints are formulated for the following situations.

I) Resources for restriction
   a) Area
   b) Water

II) Levels for restriction
   a) Allocation unit
   b) Soil group

III) Form of restrictions
   a) fixed amount
   b) maximum amount
   c) minimum amount
   d) within range

I) AU-area

$$Ara\min_a \le \sum_{s=1}^{ns_a} \sum_{c=1}^{nc_{sa}} \sum_{p=1}^{np_{csa}} A_{pcsa} \le Ara\max_a \qquad \text{for} \quad a=1,na \tag{6.54}$$

II) SG in AU

$$Aras\min_{sa} \le \sum_{c=1}^{nc_{sa}} \sum_{p=1}^{np_{csa}} A_{pcsa} \le Aras\max_{sa} \qquad \text{for} \quad s=1,ns_a \text{ and } a=1,na \tag{6.55}$$

III) AU-water

$$Wra\min_a \le \sum_{s=1}^{ns_a} \sum_{c=1}^{nc_{sa}} \sum_{p=1}^{np_{csa}} SWD_{pcsa} A_{pcsa} \le Wra\max_a \qquad \text{for} \quad a=1,na \tag{6.56}$$

IV) SG in AU-water

$$Wras\min_{sa} \leq \sum_{c=1}^{nc_{sa}} \sum_{p=1}^{np_{csa}} SWD_{pcsa} A_{pcsa} \leq Wras\max_{sa} \qquad \text{for} \quad s=1,ns_a$$

a=1,na

(6.57)

where

$Aramax_a$	=	the maximum limit of area to be irrigated for a^{th} allocation unit (ha)
$Aramin_a$	=	the minimum limit of area to be irrigated for a^{th} allocation unit (ha)
$Arasmax_{sa}$	=	the maximum limit of area to be irrigated for s^{th} soil group of a^{th} allocation unit (ha)
$Arasmin_{sa}$	=	the minimum limit of area to be irrigated for s^{th} soil group of a^{th} allocation unit (ha)
$Wramax_a$	=	the maximum limit of water to be allocated to a^{th} allocation unit (ha-m)
$Wramin_a$	=	the minimum limit of water to be allocated to a^{th} allocation unit (ha-m)
$Wrasmax_{sa}$	=	the maximum limit of water to be allocated s^{th} soil group of to a^{th} allocation unit (ha-m)
$Wrasmin_a$	=	the minimum limit of water to be allocated s^{th} soil group of to a^{th} allocation unit (ha-m)

The forms of limitation

a) Fixed

RHS = LHS = specified value

b) Minimum limit specified

RHS = nos TAA_a (AU level-area)

RHS = nos $TAAS^{sa}$ (SG of AU level-area)

RHS = Wmax (AU level-water and SG of AU level-water)

LHS = specified value

c) Maximum limit specified

RHS = specified value

LHS = 0

d) Range specified

RHS = specified value

LHS = specified value

4. Equity Constraints

The importance and dependability of productivity and equity on each other and factors affecting equity are described in Chapter II. The productivity criteria for allocation of resources is included in the objective function. The equity in allocation of resources is incorporated through constraints in the model. Several constraints are formulated to include different aspects of equity. These are categorised in to:

I. Base of equity
II. Means of equity

I) Basis of equity

By equity criteria the resources are allocated fairly to the users. The main decision is on the choice for selection of the bas which decides the fair distribution. There are several options and these are described below.

a) Area: The resources are allocated on the basis of land area possessed by the users. These are allocated in proportion to the land area owned by the users. The advantage of selecting area as the base of equity is that it is the simplest means of deciding the equity in allocation of the resources without needing much data collection and there is less possibility of arguments among the users and irrigation authority. But there are two distinct disadvantages. If the resources are allocated on the basis of area, the users with more land area will be allocated more resources (though it is in proportion to area possessed by the user) and the one with little area will get less resources. In this way small farmers may get less area for irrigation or less water which may not be sufficient for their livelihood. Another disadvantage is that it does not consider the productivity of the land possessed by the farmers. For example, the area proportionate water allocation to the land with shallow or sandy soil will be unfavourable to the land owner.

b) Water requirement

By this option, the resources are allocated in proportion to the total water requirement of the total land area possessed by the farmers. Computation of total water requirement also contains the aspect of area based equity. So the allocation will be biased towards the larger farmers (in view of satisfying the minimum requirement of the small farmers in the scheme). This is a more tedious aspect to compute. It involves the computation of total water requirement of the land area, and hence the crops to be grown with their area distribution for each user should be known prior to the allocation. But allocation precisely decides these parameters. However there are some simplifications such as considering the water requirement by assuming a certain crop mix. It removes the disadvantage of allocating water without considering the soil type observed in allocation on the basis of area but it adds another, as described below.

As the computation of water requirement for the total land area considers the soil type, allocation is influenced by the soil type of the land area. This tends to allocate more water to the land with inferior soil. The farmers with the inferior soils, thus, will be compensated. But for overall scheme, it reduces the productivity and water use efficiency as the allocation of more water to the inferior soil results in increased water loss.

c) Other

The area and water requirement of the land area are irrigation related bases for considering equity and relatively simple to compute. But these consider only the land possessed by the farmers and not consider the social aspects involved in the irrigation scheme. For example, the farmer with more land area may have a large family and solely depend on farming for his livelihood, and a small farmer may have a small family and be supported by side business. Thus other types of base of equity are required to be considered. For example, the number of members in family of farmer, dependency of farmer on the agriculture, capacity of the farmer for efficient farming etc. However all these are complex issues and much depends on the objective of the irrigation scheme.

In the RA model the value of the proportion of resource to be located to the allocation unit can be calculated on the basis of area and water requirement of the area. The value of this proportion can be given as direct input. This facility can be used to allocate the resources by other bases, by computing the value of proportion separately out of model. The selection of base of equity depends on the objective of irrigation scheme.

The allocation of the resources based on equity is included in the model at allocation unit level. But allocation unit may be formed with several farmers. In such cases the resources are either allocated on the basis of area within the allocation unit or RA submodel is again run by considering AU as the irrigation scheme and farming unit as the AU. Alternatively each farming unit can be considered as the AU directly. But this is possible only for small irrigation scheme with less number of farms. There will be computational problems for irrigation schemes with large number of farmers.

The values of proportion on the basis of area and total water requirement are calculated as follows:

a) Area

$$\lambda d_a = \frac{Aa\,max_a}{\sum_{a=1}^{na} Aa\,max_a} \tag{6.58}$$

where

λd_a = proportion for allocating the resources for a[th] allocation unit (fraction) or desired allocation proportion for a[th] allocation unit

b) Water

Two options are provided

i) If the crop mix (the proportion of area to be irrigated under different crops) is known for the allocation unit, the total water requirement of the allocation unit for irrigating the crops as per proportion and for producing maximum crop yield/net benefits is computed. The total water requirement is also computed for the entire scheme by summing up the total water requirement of all the allocation unit. The proportion for equity is computed as the ratio of total water requirement of allocation unit and the irrigation scheme by the equation (6.59)

$$\lambda d_a = \frac{\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\left(\Gamma a_{ca} TAAS_{sa} SWD_{np_{csa}csa}\right)}{\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\left(\Gamma a_{ca} TAAS_{sa} SWD_{np_{csa}csa}\right)} \tag{6.59}$$

where

Γa_{ca} = the proportion of area to be irrigated under c[th] crop in a[th] allocation unit

ii.) If the crop mix is not given the total water requirement is computed for the crop which needs maximum water. This is computed by equation (6.60)

$$\lambda d_a = \frac{\max\left[\left(\sum_{s=1}^{ns_a} SWD_{np_{1sa}1sa} TAAS_{sa}\right) \ldots\ldots \left(\sum_{s=1}^{ns_a} SWD_{np_{nc_{sa}}nc_{sa}sa} TAAS_{sa}\right)\right]}{\max\left[\left(\sum_{a=1}^{na}\sum_{s=1}^{ns_a} SWD_{np_{1sa}1sa} TAAS_{sa}\right) \ldots\ldots \left(\sum_{a=1}^{na}\sum_{s=1}^{ns_a} SWD_{np_{nc_{sa}}nc_{sa}sa} TAAS_{sa}\right)\right]} \quad (6.60)$$

c) Other

λd_a for a=1,na are calculated separately for the chosen base and given as input to the model

II) Means of equity

Equity can be achieved in area allocation for irrigation or water allocation among different users. In previous studies (Shyam et al., 1994 and Onta et al., 1995) the equity in water allocation is attempted. The final objective of the allocation may be to achieve equity in distribution of output from the irrigation scheme. In the model which considers only land allocation and assumes the soil in the scheme is homogenous, climate is uniform and various losses are not location specific, the particular depth of water diverted from the headworks for irrigating certain crop results in the same output. In this case equity in area allocation and water distribution are same and results in fair distribution of output. But as AWAM captures heterogeneity in soil, climate and losses, the equity in area allocation and water distribution produce the differing results and output distribution among various users may not be fair. Therefore in this model the equity in distribution of output (crop production and net benefits) are also included. Thus following four means of achieving equity are incorporated in the model.

a) Area
b) Water
c) Crop production and
d) Net benefits

a) Area

By this means, the area is allocated for irrigation to the different allocation units as per given value of proportion for equity.

$$\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}A_{pcsa} = \lambda a\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}A_{pcsa} \qquad \text{for} \quad a=1,na \tag{6.61}$$

This aspect may not result in proportionate distribution of output as the soil, climate and losses influence the output.

B) Water

By this means the water is distributed to different allocation units as per the value of proportion for equity.

Water can be distributed by considering conveyance and distribution losses, considering conveyance losses or without considering any of these losses. If the conveyance losses are considered, the allocation units at far ends or towards tail of the system will be compensated for the losses and will receive the comparable share of water to those received by the allocation units at the head of the system. However by giving equal importance to the allocation units at the tail of the system (by not considering the conveyance losses), the productivity of the irrigation scheme may be hampered because of excessive loss of water in the conveyance process. Similarly if distribution losses are considered, the allocation unit with poor distribution network will be compensated for the losses in distribution of water within allocation unit. But again by giving the equal importance to the allocation units with poor and efficient distribution network, the productivity of the irrigation scheme may be reduced because of excessive loss of water in the distribution network in the allocation unit.

i) With considering conveyance and distribution losses

$$\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}SWD_{pcsa}A_{pcsa} = \lambda a\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}SWD_{pcsa}A_{pcsa} \qquad \text{for} \quad a=1,na \tag{6.62}$$

ii) With considering conveyance losses only

$$\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}\sum_{i=1}^{I}\frac{WD_{ipcsa}}{\eta ca_{ia}\eta da_{ia}}A_{pcsa} = \lambda a\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}\sum_{i=1}^{I}\frac{WD_{ipcsa}}{\eta da_{ia}}A_{pcsa} \qquad \text{for} \quad a=1,na \tag{6.63}$$

iii). Without considering the losses

$$\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}\sum_{i=1}^{I}\frac{WD_{ipcsa}}{\eta ca_{ia}\eta da_{ia}}A_{pcsa}=\lambda a\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}\sum_{i=1}^{I}\frac{WD_{ipcsa}}{\eta ca_{ia}\eta da_{ia}}A_{pcsa}$$

for a=1,na (6.64)

This aspect does not consider the varying soil and climate in the scheme.

c) Crop production

By this means the resources are allocated in a way to obtain the crop production to different users as per the proportion. However in multicrop situation this can not be used as production obtained from different crops are not comparable.

$$\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}Ya_{pcsa}A_{pcsa}=\lambda a\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}Ya_{pcsa}A_{pcsa}$$

for a=1,na

(6.65)

d) Net benefits

This states that the expected net benefits obtained from irrigating the land should be distributed as per the proportion for equity

$$\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}NB_{pcsa}A_{pcsa}=\lambda a\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}NB_{pcsa}A_{pcsa}$$

for a=1,na

(6.66)

(c) and (d) consider the proportionate distribution of output by considering varying soils, climate and losses in the scheme.

6.4 CONCLUSION

This chapter presented the last phase of the AWAM i.e. the optimum allocation of the resources. The allocation of the resources in the irrigation scheme differs depending on the objective of the scheme. The several options are included in the RA submodel (second stage of final phase). These make it applicable for the irrigation schemes with differing objectives.

The method to prepare the irrigation programmes based on deficit irrigation was developed in Chapter V. These irrigation programmes are used in the last phase of AWAM to allocate the land and water resources in the heterogeneous irrigation scheme with rotational water supply, which is described in this chapter. The AWAM is subsequently used to compare deficit and adequate irrigation (Chapter VIII), obtain allocation plans for different conditions (Chapter IX) and obtain allocation plans with consideration of productivity and equity (Chapter X). This chapter thus contributed in addressing the Hypotheses 2, 3, 4 and 5, while formulating the last phase of AWAM (i.e. allocation of the resources) and achieving the Objective 1.

CHAPTER VII

CALIBRATION AND DATA REQUIREMENT OF AWAM

Summary. The Area and Water Allocation Model (AWAM) developed in Chapters IV to VI is based on deficit irrigation and is able to operate in planning and operation modes for the situations described in Chapter IV (Section 4.9). This chapter and Chapters VIII to X verify the hypotheses which prompted the development of the AWAM and demonstrate the utility of the model in improving the management of the irrigation scheme. In the present chapter the data generated or used for testing the hypotheses and utility of the model are presented. The process of generating some of the data with AWAM in calibration mode also verifies the Hypothesis 1 by showing the detailed processes in the soil, plant and atmospheric subsystems can be modelled accurately. The data collected for these purposes (testing the hypotheses and utility of the model) are mainly focused on describing the utility of the model for the kind of irrigation schemes described in Section 4.9 of Chapter IV instead of studying a particular irrigation scheme.

7.1 INTRODUCTION

The AWAM needs various types of data. Some data related to crop and soil subsystems may not be available directly for all the crops in each soil group. These data can be estimated by calibrating the related submodel in AWAM (SWAB) while the remaining data can be made available or collected in the irrigation scheme. The first part of this chapter elaborates the AWAM in calibration and simulation modes, which are useful to estimate some data. In this process, the part of Hypothesis 1 is verified (Hypothesis 1 is also discussed in Chapter VIII). The AWAM in calibration mode is described by giving the details of calibration parameters, test parameters and test criteria and with one case study. AWAM in simulation mode is explained by simulating the parameters of certain processes for a selected irrigation schedule. The next part of this chapter gives the details of the data needed, collected and used for running the AWAM in different modes. The data was collected for the Nazare Medium Irrigation Project in Maharashtra State of India. This irrigation scheme lies in semi-arid region.

7.2 CALIBRATION STUDY

The SWAB submodel of AWAM can be calibrated for several parameters involved in different processes considered while formulating the submodel. The validity of a particular value of the calibration parameter can be tested with different parameters (test parameters) by adopting different tests (test criteria). These are described in subsequent sections. The procedure of calibration is described by formulating one case study in the last part of this section.

7.2.1 Calibration Parameter

The calibration parameters used for calibrating the models for given crop-soil-climate condition are of the following two types.

1) Crop related calibration parameters
2) Soil related calibration parameters

7.2.1.1 Crop related calibration parameter

These are incorporated through the following processes.

1) Crop root growth
2) Soil water depletion
3) Root water extraction

(1) Crop root growth: The root growth may vary according to the following options in the model.

- Linear root growth model
- Sigmoidal root growth model
- Other models

The linear and sigmoidal root growth models are directly incorporated in the model and can be used by giving the inputs of the depth of sowing (Zo), maximum depth of root (Zm) and the number of days required to reach from Zo to Zm (tm). The other models can be used by giving the inputs of daily root growth over the crop period.

(2) Soil water depletion: The values of soil water depletion factors over the crop period can vary according to following options.

- Values proposed by Doorenbos and Kassam (1986): The values are specified for different crops and are a function of maximum crop evapotranspiration (ETm) for particular crop.
- Equation (5.18): The inputs of ETm1, ETm2, p1 and p2 are needed. Several options can be incorporated by varying the values of ETm1, ETm2, p1 and p2.

3) Root water extraction: This process can be included through percentage of root water extraction through different extraction layers and transpiration deficit occurring for a particular soil layer.

The root water extraction may vary according to the following options.

- Root water extraction model: This needs the input of a number of extraction layers (nel) and extraction exponent (ce). Several options can be obtained by varying the values of nel and ce.
- Given root water extraction pattern: Instead of using ce for computing percentage root water extraction through different layers, it can be given as direct input for each layer.

The deficit in transpiration load can be considered in the following two ways.

- The deficit in transpiration for a particular soil layer to be reduced from the transpiration requirement corresponding to the same layer.
- The deficit in transpiration to be transferred to the transpiration requirement of the next soil layer.

7.2.1.2 Soil related calibration parameter

The soil related calibration parameters are

1. The soil depth contributing to the soil evaporation (esd)
2. Number of days since last wetting during which soil evaporation takes place at potential rate (tp)
3. Exponent representing the decay of soil evaporation rate since the wetting (cs)
4. The limit of minimum rainfall which can be considered as the wetting (RFm)

7.2.2 Test Parameters

The following parameters are selected as the test parameters in the model for testing the performance of calibration parameters.

1) Soil moisture content in the soil root zone on particular days
2) Soil moisture content in each soil layer in the soil root zone on any particular day
3) Actual evapotranspiration on each day (ETa) or cumulative ETa on particular days.

7.2.3 Test Criteria

The observed and simulated values (by the model) can be compared with several criteria. Jacovides and Kontoyiannis (1995) reviwed various criteria to evaluate a model's performance with the advantages and disadvantages of using each criterion. All these criteria generally take the following form.

$$\text{Min} \quad Z = f(Sm_i, Ob_i, n) \tag{7.1}$$

where

n	=	number of observations over which observed value of test parameter is recorded
i	=	index for the observation number
Sm_i	=	simulated value of the test parameter for i^{th} observation
Ob_i	=	observed value of the simulated parameter for i^{th} observation

The following test criteria are incorporated in the model.

(1) Root mean square (rmse)

$$rmse = \left(\sum_{i=1}^{n} (Sm_i - Ob_i)^2 / n \right)^{1/2} \tag{7.2}$$

(2) Relative mean error (rme)

$$rme = 100 \frac{1}{n} \sum_{i=1}^{n} \frac{\sqrt{(Sm_i - Ob_i)^2}}{Ob_i} \tag{7.3}$$

(3) Mean absolute error (mae)

$$\text{mae} = \sum_{i=1}^{n} \frac{\left|(Sm_i - Ob_i)\right|}{n} \tag{7.4}$$

(4) Regression coefficient (Rc)

$$Rc = \frac{\sum_{i=1}^{n} Sm_i Ob_i - \left(\sum_{i=1}^{n} Sm_i\right)\left(\sum_{i=1}^{n} Ob_i\right)/n}{\sqrt{\left[\sum_{i=1}^{n} Sm_i^2 - \left(\sum_{i=1}^{n} Sm_i\right)^2 / n\right]\left[\sum_{i=1}^{n} Ob_i^2 - \left(\sum_{i=1}^{n} Sm_i^2\right)^2 / n\right]}} \tag{7.5}$$

(5) Index of agreement (ia)

$$ia = 1 - \left(\frac{\sum_{i=1}^{n} (Sm_i - Ob_i)^2}{\left(\left|Sm_i - \overline{Sm}\right| + \left|Ob_i - \overline{Ob}\right|\right)^2} \right) \tag{7.6}$$

The values of rmse, rme and mae approaching towards 0 and values of ia approaching towards 1 indicate more agreement between simulated and observed calibration parameters.

7.2.4 Calibration Test

7.2.4.1 Details of the experiments

The data and the results of the experiment entitled "Study of Evapotranspiration of Wheat Crop in Varying Soil Moisture Conditions" (Jadhav, 1991) conducted at the College of Agriculture, Pune, Maharashtra State, India were used for explaining the calibration test. The experiment was conducted during 1989-90 on clayey soil for wheat crop. Seven different irrigation schedules (treatments) based on IW/CPE (irrigation water applied to cumulative pan evaporation) were adopted for obtaining varying soil moisture conditions. The treatments were replicated twice. The crop was sown in mid-November and physiological maturity was attained in 99 to 108 days, depending on the irrigation schedule. One presowing irrigation six days before the sowing was given for all irrigation schedules. The depth of irrigation at each irrigation was 80 mm. The irrigation water was measured by V-notch. Irrigation schedules, the corresponding number of irrigations and the day of irrigation since sowing are presented in Table 7.1. The soil depth extended beyond 1000 mm. The physical soil properties which influence moisture storage capacity of soil (field capacity, wilting point and bulk density) were measured for each soil layer of 150 mm thickness up to 900 mm. The moisture content in each soil layer was measured only before each irrigation. The soil moisture measurements for the uppermost layer were taken by gravimetric method and a neutron probe was used for measuring soil moisture in other layers. The soil moisture measurements were recorded for all the treatments of one replication. The daily climatological data were collected from Central Agricultural Meteorological Observatory located 400 m away from the experimental site. The grain yields were recorded for all the irrigation schedules of both the replications.

Table 7.1 Irrigation schedules and corresponding number of irrigations (excluding presowing irrigation)

Sr. No.	Irrigation schedule	IW/CPE ratio	No. of irrigations	Day of irrigation for each irrigation				
				1	2	3	4	5
1	IS-1	1.0	5	19	39	61	78	94
2	IS-2	0.9	4	21	46	69	87	
3	IS-3	0.8	4	24	52	73	93	
4	IS-4	0.7	3	26	56	81		
5	IS-5	0.6	3	31	66	93		
6	IS-6	0.5	2	39	78			
7	IS-7	0.4	2	52	94			

7.2.4.2 Selection of calibration parameter, test parameter and test criteria

(1) The calibration parameters and their values selected for the calibration are described below.

a) Crop root growth: Linear root growth and sigmoidal root growth models
b) Soil water depletion: Values proposed by Doorenbos and Kassam (1986)
c) Root water extraction:
Root water extraction model: The selected values of ce are 1.00, 1.25, 1.50, 1.75, 2.00, 2.50 and 3.00 and selected values of nel are 2, 3, 4, 5, and 6.

Given extraction pattern: The number of layers and extraction from each layer selected for calibration test are

6 layers - 0.30, 0.25, 0.20, 0.15, 0.10, and 0.00
5 layers - 0.35, 0.25, 0.20, 0.15, and 0.05
4 layers - 0.40, 0.30, 0.20, and 0.10
3 layers- 0.50, 0.30, and 0.20
2 layers - 0.70 and 0.30

Transpiration deficit: Transpiration deficit is reduced from the transpiration of same layer and transpiration deficit is transferred to the next layer.

d) esd: 100, 200 and 300 mm.
e) tp: 1, 2 and 3 days
f) ds: 0.2, 0.3, 0.4, 0.5, and 0.6

(2) The observed values of soil moisture in each soil layer before the irrigation were available. Therefore this was selected as the test parameter.

(3) The rmse was selected as the test criteria.

7.2.4.3 Test runs

The climate, soil and crop data of the experiments discussed above were used as input data. No rainfall was recorded during the crop growth period. The ETr values were computed by modified Penman method. The crop factors were determined by equation (7.10).

IS-1, IS-2, IS-4 and IS-6 were selected for calibration and IS-3, IS-5 and IS-7 were used for testing. The pairs of IS-2 and IS-3, IS-4 and IS-5 and IS-6 and IS-7 were applied with same numbers of irrigations with same amount of water application but with different timings of water application (Table 7.1). The total number of calibration sets resulting from the combinations of the selected values of the calibration parameters are 7200. The model was run for each set of calibration parameters and for each irrigation treatment selected for the calibration. The value of rme was computed for the observed and estimated values of the test parameter over all the four irrigation treatments. The values ranged from 6.3 to 12.7. The set of calibration parameters giving the minimum value of rme was selected for testing the validity of the model for the remaining irrigation treatments. The values of the parameters in the chosen set are as follows.

1) Crop root growth model: Linear

2) Soil water depletion:	Values proposed by Doorenbos and Kassam (as assumed)
3) Root water extraction	
i) Root water extraction model:	nel=3 and ce=3.0
ii) Transpiration deficit:	to be reduced from the transpiration requirement of the same layer
4) esd:	300 mm
5) tp:	1 day
6) cs:	0.6

The layerwise soil moisture values were obtained with the selected set of calibration parameters for the treatments, IS-2, IS-4 and IS-6 for testing the validity of the selected set of calibration parameters. The average value of rme was found to be 7.3 (8.7, 7.0 and 5.4 for IS-2, IS-4 and IS-6, respectively). The value of rme for testing is little higher than that obtained for calibration.

The rme values obtained during the calibration and testing processes are less than 10 (the predecided limit). The observed versus estimated values of layerwise moisture contents for all the irrigation schedules, the actual regression line fitted between observed and simulated values, the regression line of perfect agreement and the range of 1 SD (standard deviation) of observed values around the regression line of perfect agreement are shown in Figure 7.1. The value of the regression coefficient is 0.85 and most of the estimated values lie in the range of 1 SD of the observed values. Hence the model can be considered as valid for the above described set of data. The divergence of the actual regression line from the perfect regression line (within range of 1 SD) may be due to some possible errors in the measurements and some assumptions made in the model while considering different processes (for example, the distribution of moisture in the entire soil root zone is instantaneous). The daily layerwise variation of simulated moisture content and the observed moisture contents on the day of recording are shown in Figure 7.2.

The crop yields are estimated by the multiplicative type of crop production function using the yield response factors documented by Doorenbos and Kassam (1986). The observed and estimated values of crop yield are presented in Figure 7.3. The rme value for the crop yield is 11.9.

7.2.5 Transpiration Deficit

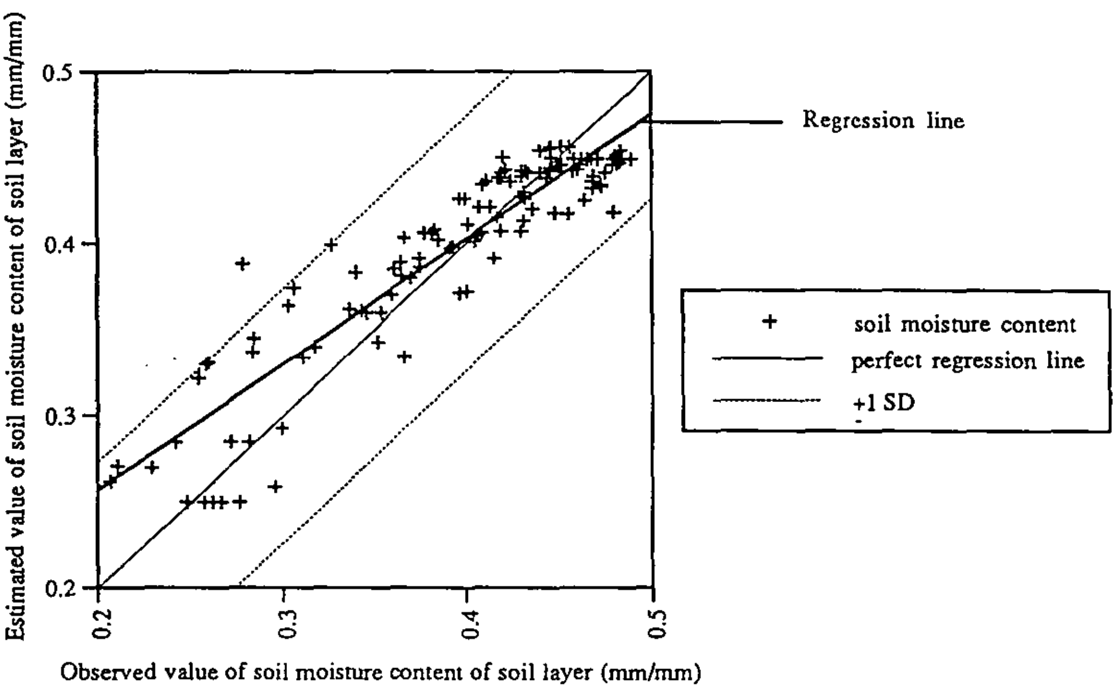


Figure 7.1 Layerwise observed and estimated values of soil moisture content

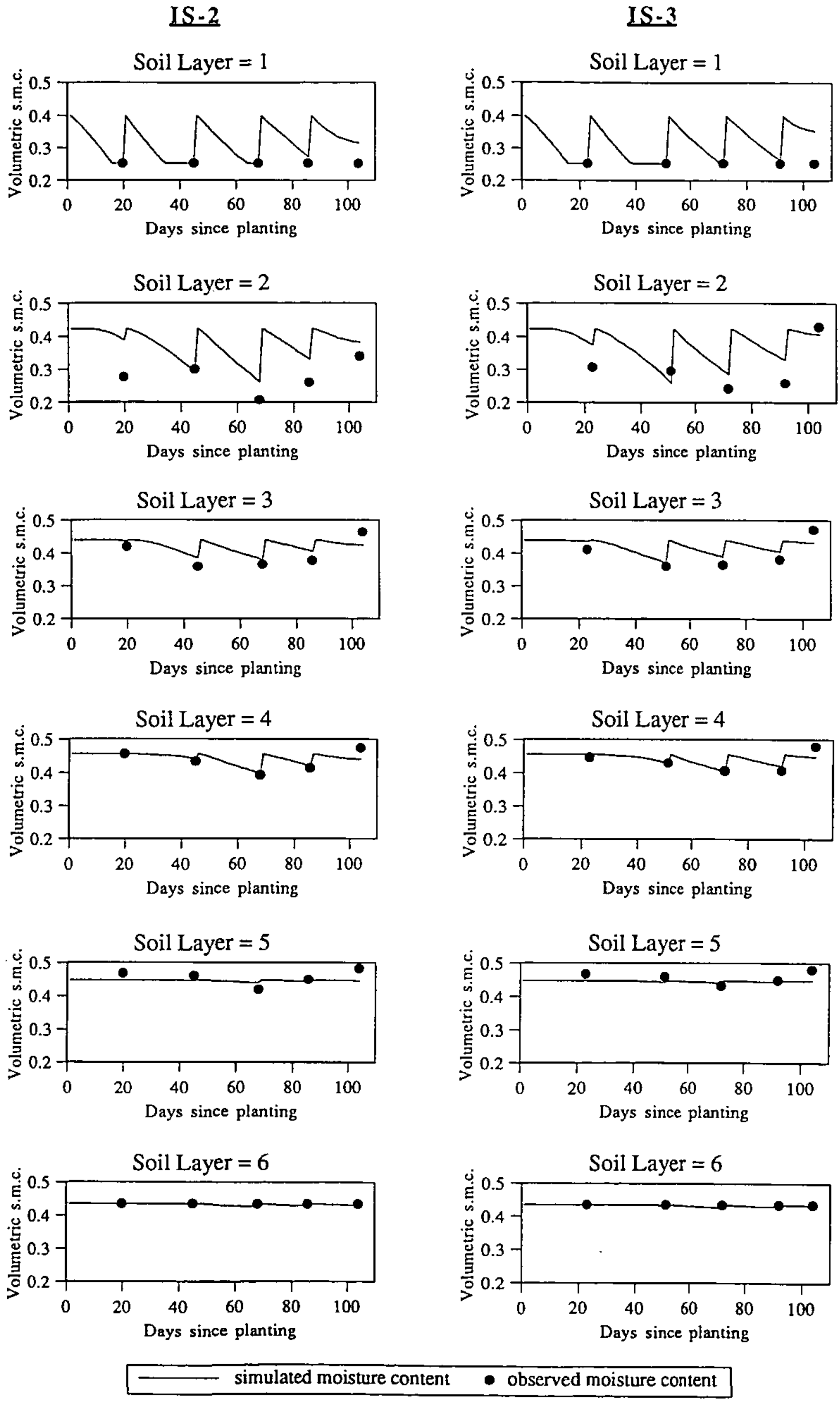
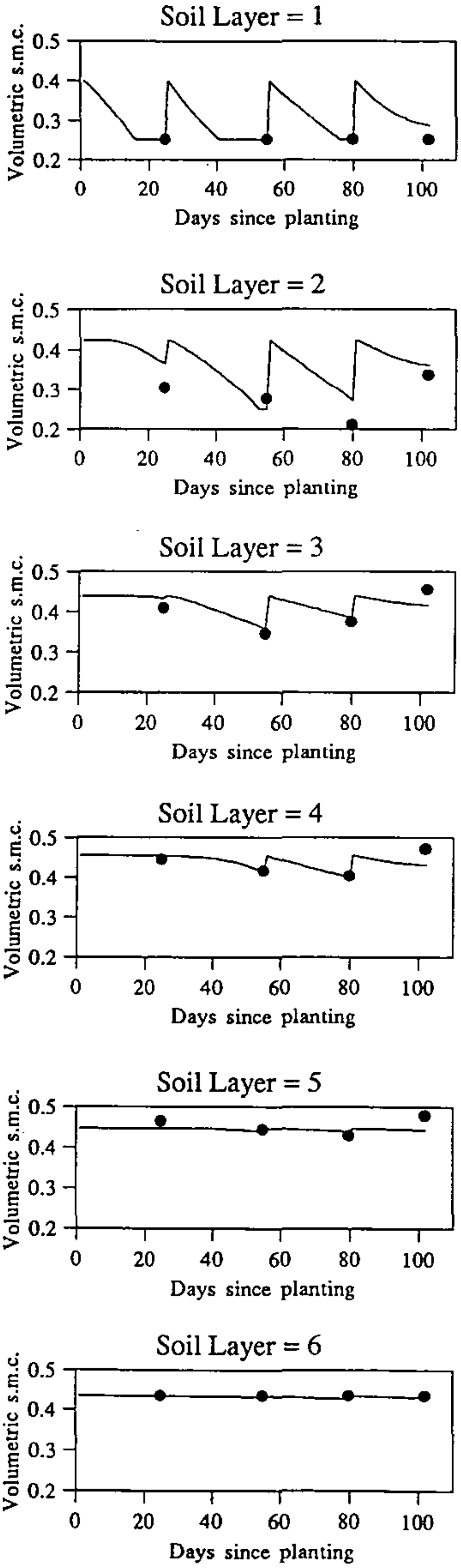
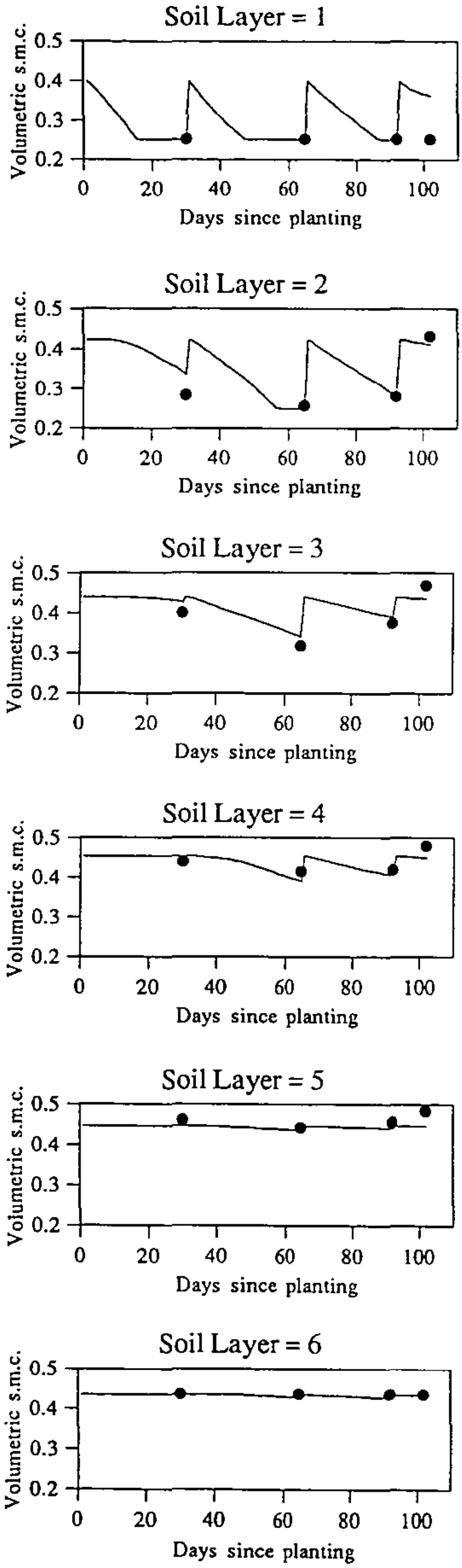


Figure 7.2 The layerwise variation of simulated moisture content and observed moisture content on the day of recording (contd..)

IS-4


Soil Layer = 1
Soil Layer = 2
Soil Layer = 3
Soil Layer = 4
Soil Layer = 5
Soil Layer = 6
Volumetric s.m.c.
0.2
0.3
0.4
0.5
Days since planting
0
20
40
60
80
100

IS-5


Soil Layer = 1
Soil Layer = 2
Soil Layer = 3
Soil Layer = 4
Soil Layer = 5
Soil Layer = 6
Volumetric s.m.c.
0.2
0.3
0.4
0.5
Days since planting
0
20
40
60
80
100

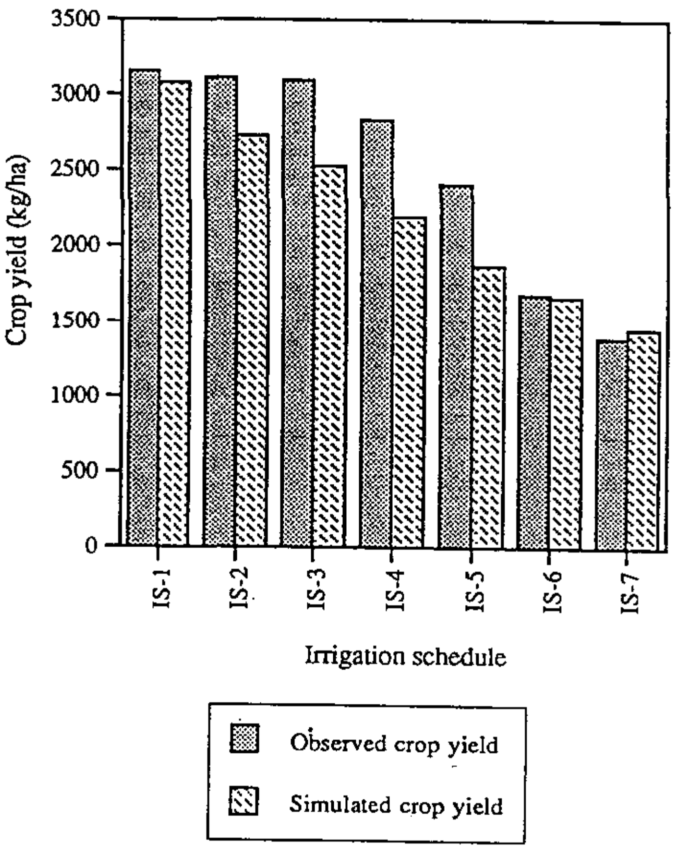


Figure 7.3 The observed and estimated crop yields (with the selected set of calibration parameters)

If the transpiration requirement of the crop from a particular soil layer is more than the soil moisture available in that soil layer, then the difference between transpiration requirement and the available soil moisture is referred to as the transpiration deficit. In the soil moisture balance models referred to in Chapter V, if transpiration deficit occurs in a particular soil layer then it is transferred to the next layer. This is valid as the crop roots have a tendency to grow in the direction of moisture availability. But at the same time the crop growth may be hampered due to the unavailability of moisture and limited capacity of roots to extend beyond a particular limit at a particular crop growth stage or period. This aspect is considered in the SWAB submodel by deducting the transpiration requirement of the crop from a particular soil layer by a transpiration deficit, instead of transferring it to the next soil layer. This results in actual transpiration reduced by the transpiration deficit. Actual transpiration already considers the characteristic of the crop of not drawing moisture equivalent to the potential transpiration rate if the soil moisture falls below the allowable depletion level.

The influence of the transpiration deficit to be deducted from the same soil layer is demonstrated by separating the sets of calibration parameters according to the transpiration deficit to be deducted or transferred to the next layer. The values of rme for IS-1, IS-2, IS-4 and IS-6 varied in the range from 6.3 to 11.8 and 9.5 to 12.6 when the transpiration deficit was deducted from the transpiration requirement of the same layer (Case 1), and transferred to the transpiration requirement of the next layer (Case 2), respectively. In Case 2, however, the transpiration deficit of the last layer is deducted from the total transpiration requirement, meaning that the transpiration deficit over the entire root zone is considered (rather than the individual soil layer as in Case 1. Thus there is no marked difference among the soil moisture values. However the rme values of crop yield were found to be 12 and 33.6, respectively for the two cases. Thus even though the soil moisture values matched closely in both the cases, the error in estimation of crop yield in Case-2 is more than two and a half times the error in Case-1. This shows that the input parameter of CRYB submodel (in this case actual transpiration) was not estimated correctly in Case-2. The measured values of actual evapotranspiration were not available for this study. Therefore ET deficit in relation to maximum crop ET (which is measure of crop yield) was computed for all the irrigation schedules used for the calibration tests and for both the cases and are compared in Figure 7.4. The daily soil moisture content in the root zone as a whole and moisture content at the allowable depletion level are shown in Figure 7.5.

Figure 7.5 shows that the moisture content in the root zone as a whole in most of the irrigation schedules in both the cases is above depletion level, and thus there should not

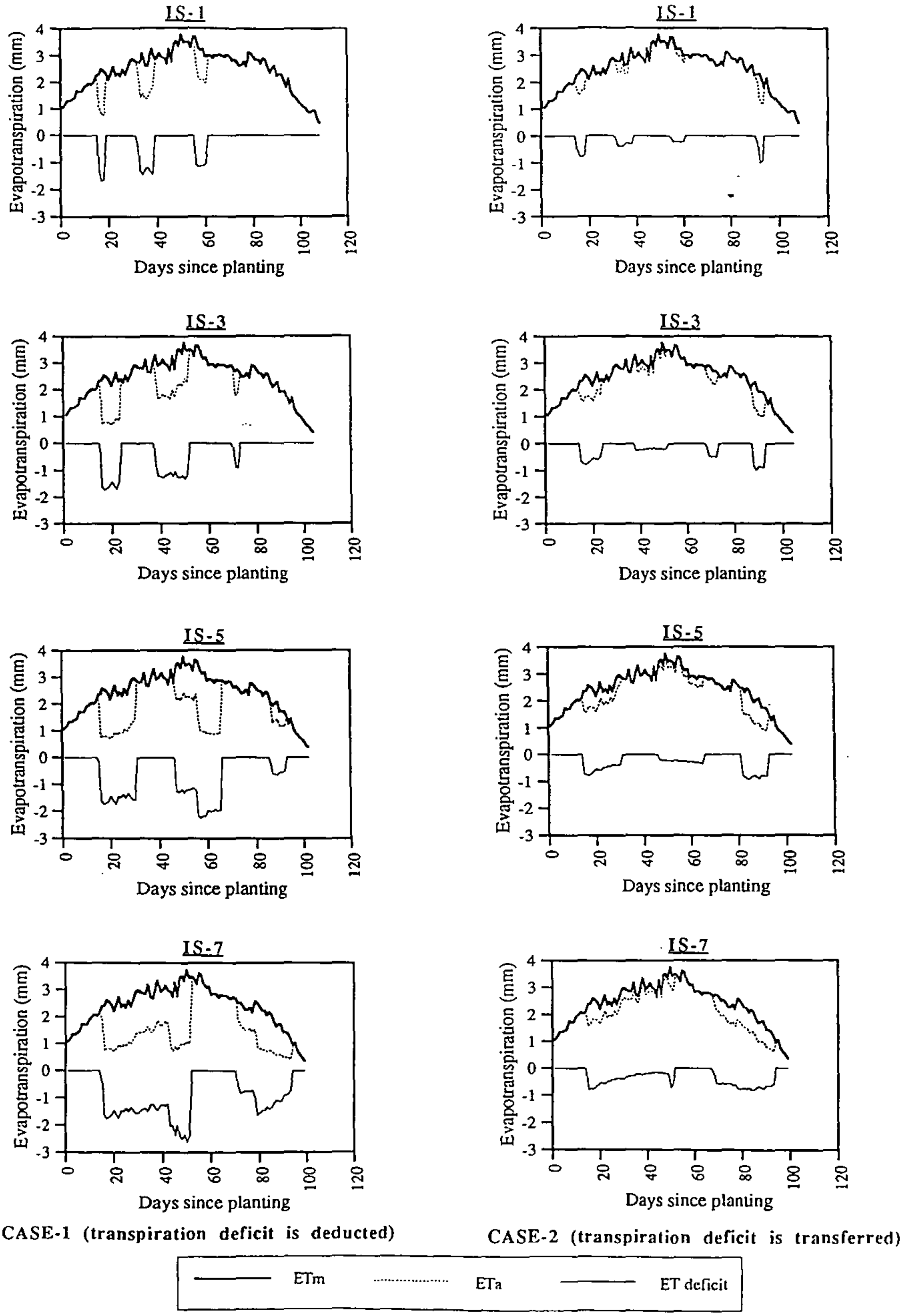


Figure 7.4 Daily maximum crop ET (ETm), actual crop ET (ETa) and ET deficit for Case-1 and Case-2

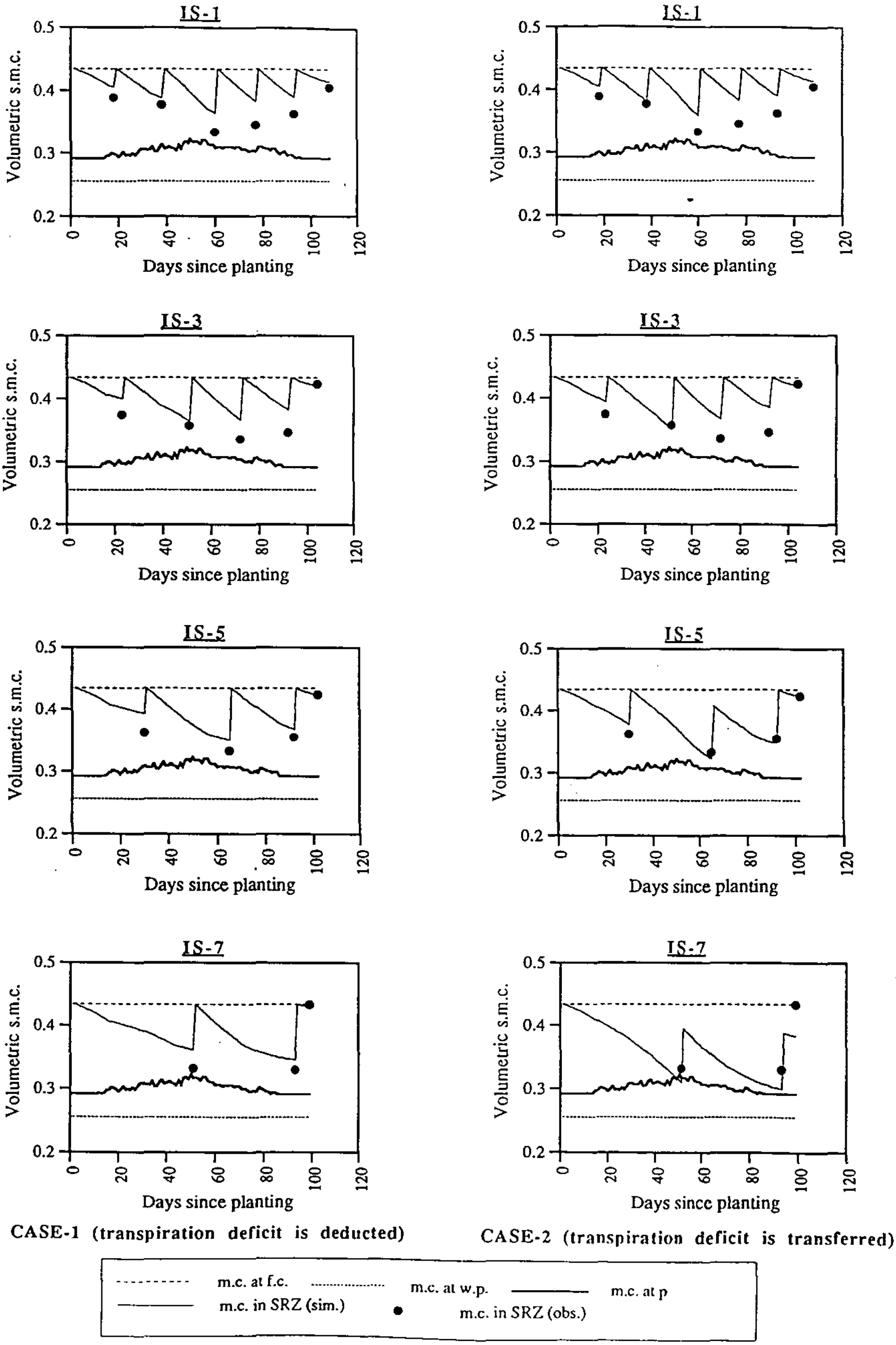


Figure 7.5 Daily soil moisture (in the soil root zone) profile for Case-1 and Case-2

be ET deficit in both the cases. But in Case-1, an ET deficit is found in all irrigation schedules. This ET deficit was the result of deficit in transpiration of a certain layer and instead of transferring that deficit to the next layer, it was deducted from the transpiration requirement of the same layer. Thus reducing the actual transpiration by the transpiration deficit (and thus actual ET), even though moisture content in the root zone as a whole was above allowable depletion level. However in case-2, the transpiration deficit is transferred to the transpiration requirement of the next layer. But as the transpiration deficit of the last layer is deducted from the total transpiration requirement, a lower ET deficit is observed, and thus the actual transpiration was closer to the potential transpiration than in Case-1. The closer estimation of crop yield in case-1, therefore, justifies the need for considering the transpiration deficit of each individual soil layer.

7.3 SIMULATION STUDY

In this section the estimation of simulated values of the parameters involved in the different processes of soil water balance is described, with the case study used in the calibration section and the selected set of calibration parameters, but with two different irrigation schedules. One irrigation schedule represents the adequate irrigation (IS-A). In this schedule an irrigation depth of 80 mm is applied every 14 days. Another irrigation schedule relates to deficit irrigation (IS-D). In this schedule an irrigation depth of 80 mm was applied every 28 days. The constant application efficiency of 75% was assumed for both the cases.

The simulated parameters such as soil moisture in the root zone, actual transpiration, soil evaporation, evapotranspiration and deep percolation are estimated daily with the model. These parameters along with daily values of reference crop ET, crop factor, maximum crop ET, soil water depletion factor and root zone depth and crop yield are presented in Tables A.1(a) and (b) and Tables A.2 (a) and (b) of Appendix A for IS-A and IS-D, respectively. The soil moisture profile obtained for both the schedules are shown in Figure 7.6. There is marked deviation between soil moisture profiles obtained with both the schedules in terms of soil moisture deficit along the root zone depth and with respect to time in crop period. The details of parameters given in tables of Appendix A and Figure 7.6 show the ability of the model to simulate the different processes in the soil, plant and atmospheric subsytems.

7.4 THE COMMENTS ON HYPOTHESIS 1

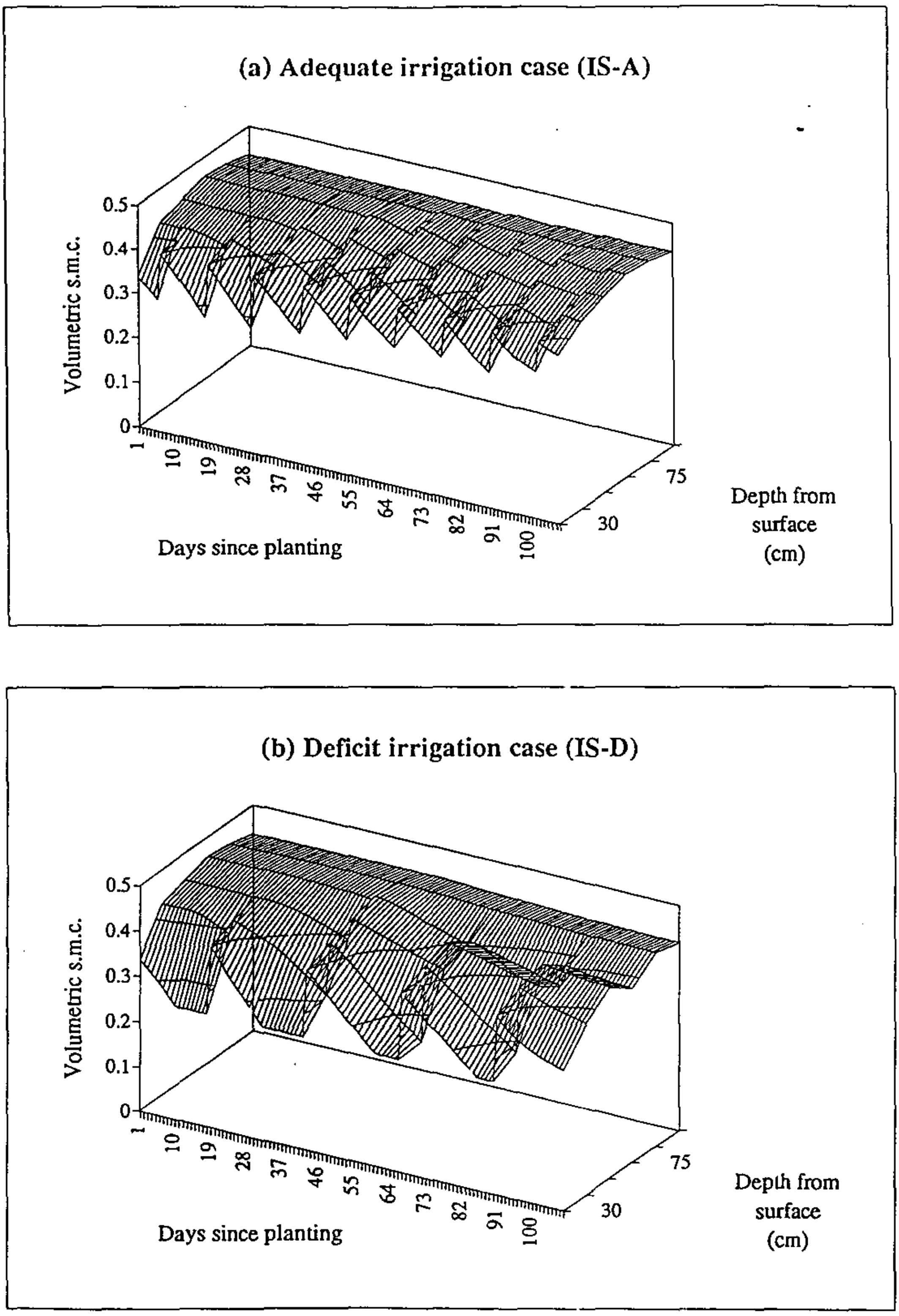


Figure 7.6 Simulated soil mositure profiles for the cases of adequate and deficit irrigation

The Sections 7.2 and 7.3 describe the ability of the model to represent and simulate different processes in the soil, plant and atmospheric subsystems. As seen from Table 7.1, the irrigation schedules used in the experiment also consisted of deficit irrigation (irrigation schedules with IW/CPE ratio less than one). These irrigation schedules were used for the calibration of the processes using the model. The accuracy of all the processes could not be judged in absence of data available, but the closeness of observed and estimated values of important parameters (i.e. layerwise soil moisture content and crop yield in the calibration process) should confirm the reliability of estimation in other parameters also as these are interdependant. The SWAB and CRYB submodels of AWAM described in Chapter V and the results of calibration (with IS-1, IS-2, IS-4 and IS-6) and test (with IS-2, IS-5 and IS-7) runs indicate the accuracy of the model to represent the detailed processes in the soil-plant-atmospheric subsystems accurately and thus verifies the part of Hypothesis 1.

7.5 DATA COLLECTION

The "Nazare Medium Irrigation Project" in Maharashtra State of India was selected for the purpose of testing the hypotheses and investigating the applicability of the AWAM in line with the objectives described in Chapter I. Irrigation schemes in India are managed by the central authority (the government), need to supply water to several users and are of heterogeneous type (refer Section 1.5 and Section 4.5). Therefore the irrigation planning involves the preparation of allocation plans to accommodate different crops grown on different soils and climate, shortage of water, and fair distribution of water to the land owned by different users. In most of the irrigation schemes the water available for irrigation is known at the time of preparation of allocation plan. The AWAM is particularly suitable for such schemes. The Nazare Medium Irrigation (NMI) project or scheme lies in semi-arid region of the State and is representative of other schemes in the region as it lies in the water scarce area of the state and the climate, soils, water distribution system and cropping patterns are similar to the other medium and major irrigation schemes in the region.

In this section the data collected and used for this study are described. The source of these data is "A Report on Action Research Programme in Nazare Medium Irrigation Project, Maharashtra State" (Stofkoper and Tilak, 1992), "Report of Pre-Irrigation Soil Survey of the Command of Nazare Medium Irrigation Project, Dist: Pune" (IRD, 1992), several other internal reports and discussion with the persons working in the irrigation scheme.

7.5.1 Location

The irrigation scheme is situated on Karha river in Purandar taluka of Pune district in Maharashtra State of India. The latitude and longitude are 19° 17' 30" (N) and 74° 12' 50" (E), respectively.

7.5.2 Irrigation Season

The irrigation season starts from the 15th October and ends on 14th October of next year. There are three distinct crop seasons within the irrigation season. These are Kharif, Rabi and Summer. The details of these seasons are given in Table 7.2. As seen from the Figure 7.9 (referred later), most of the rainfall is received in Kharif (monsoon) season. Therefore crops grown in this season need one or two irrigations (protective irrigations) only. As little rainfall is received in Rabi season, the crops grown in this season are supplied with irrigation water for their growth. In summer season no rainfall is received but it is characterised with high evapotranspiration (Figure 7.9). Therefore in this particular irrigation scheme, in past the irrigations were not given in summer season to keep the water consumption per unit area minimum. But recent data show that the irrigations are given to a limited extent in the summer season also. Thus in the scheme, the main irrigation season is the Rabi with irrigations to a restricted area in summer and limited numbers (one or two) of irrigations in Kharif. The irrigations during Kharif season are of little interest in this study as the reservoir fills during the Kharif season. Therefore for this scheme in this study, the irrigation season is considered to spread over Rabi and Summer crop seasons. The irrigation season thus starts from the beginning of the Rabi season i.e. 15th October (1st day of irrigation year) and ends at the end of Summer season i.e. 30th June (259th day of irrigation).

Table 7.2 Details of crop seasons in the irrigation scheme (NMI Project)

Sr. No.	Crop season	Duration	Characteristics
1	Kharif (rainy)	1 July - 14 October	more rainfall and humidity and therefore less number of irrigations (generally no irrigation or one or two irrigations)
2	Rabi (winter)	15 October - 28/29 February	less temperature and slight rainfall and therefore more number of irrigations are required
3	Summer	1 March - 30 June	high temperature, wind and no rainfall and therefore many irrigations are required

7.5.3 Irrigation System

7.5.3.1 Reservoir

The catchment area above the dam site is 397.82 Km^2. The elevation of the catchment area varies from RL 1118.90 m to RL 658.53 m and the river at the dam site is 658.24 m. The entire catchment falls under low rainfall zone with average annual rainfall of 635 mm. The percentage annual runoff is 54.2. The river has no perennial flows and the flows are due to the monsoon rains. The values of the daily inflow in to the reservoir collected from the reservoir site indicates that the flows are received from June to October. No flows are received in the remaining months.

The gross reservoir capacity and dead storage capacity of the reservoir are 22.313 and 5.684 Mm^3, respectively. The information on seepage losses could not be made available. Therefore uniform seepage losses of 10% of half the storage capacity of the reservoir are assumed over the entire irrigation season. The water surface-area-storage capacity relationship used for computing the reservoir evaporation losses is obtained from the depth-water surface area and depth-storage capacity relationships available for the reservoir and is presented in the Figure 7.7. The linear relationship is developed between capacity and water surface area of the reservoir. This is indicated by the equation (7.7) The regression coefficient is 0.97.

$$SA = 0.121ST + 58.7 \tag{7.7}$$

7.5.3.2 Water distribution network

One main canal originates from the headworks. The full supply discharge and length of the main canal are 1.528 m^3/s and 3.05 Km, respectively. One distributory canal emerges from the main canal, the length of which is 11.75 Km. The carrying capacity of the distributory canal is 1.528 m^3/s. The measuring devices are provided on the main and distributory canals. Main and distributory canals are lined and the average conveyance losses based on the actual study conducted by the Irrigation Research and Development (IRD), Department of Irrigation, Maharashtra State are 9%. The conveyance losses in both the canals are assumed as 2% per 1000 m for this study and same for all the irrigations.

7.5.3.3 Command area and allocation units

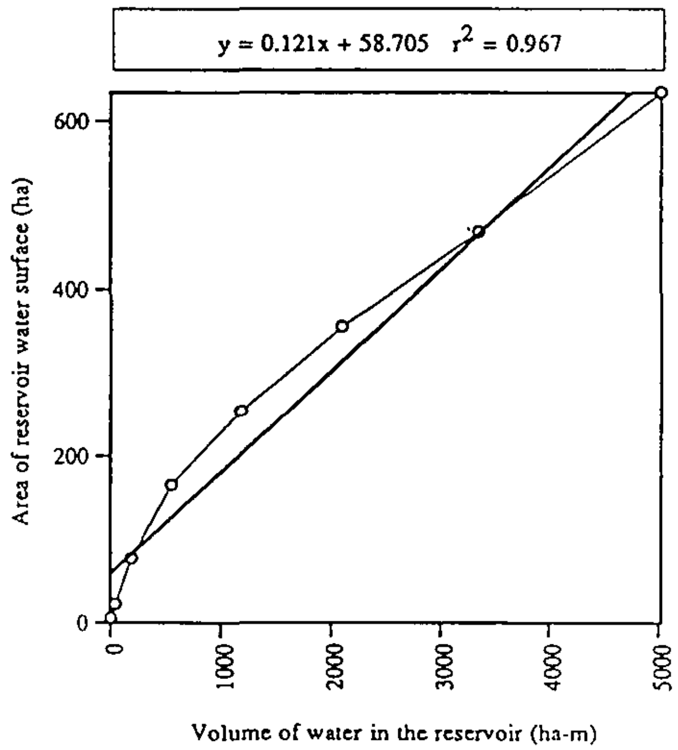


Figure 7.7 Relationship between reservoir water surface (ha) and volume (ha-m)

The cultural command area (CCA) of the irrigation scheme is 4304 ha. But the CCA of 765 ha lies under the branch canal (Chorwadi branch canal) which is yet to be completed. Therefore the CCA of the irrigation scheme is effectively 3539 ha. There are 28 direct outlets (4 on main canal and 24 on distributory canal) and four minors (all on distributory canal). There are 9 outlets on the minor. Some of the outlets are provided with screw type gates however, some are without gates. However, the screw type of gates are being considered for all the outlets. No permanent measuring devices are installed at outlet but the installation of Cut Throat Flumes are being considered for all the outlets. Measuring devices are not provided on the minors but are being considered.

The details of the outlets on the minors could not be obtained. Therefore CCA of all 28 outlets and 4 minors are considered as allocation units, resulting in 32 AUs. The AU numbers 5, 9, 12, and 20 are related to minors and others to direct outlets. The index map showing the canal distributory network and location, soil type, and capacity of outlet or minor for each AU is shown in Figure 7.8.

The conveyance efficiency of field channels below the outlet is 86%. Hence the distribution efficiency of each AU related to outlet is considered as 86%. The conveyance efficiency of minor is 80%. Therefore the distribution efficiency of AUs, which are CCA of minor is considered as 68.8%. The distribution efficiencies are assumed the same for all the irrigations for particular allocation units.

7.5.3.4 Water use for other purposes

The reservoir supplies water for non-irrigation purposes and for irrigating land other than considered in the allocation units. The requirement of water to be delivered in each crop season for these purposes is given in Table 7.3.

Table 7.3 Crop seasonwise water requirement (Mm^3) for other purposes

Use of Water		Crop Season		
		Kharif	Rabi	Summer
Industrial	MIDC	0.212	0.274	0.244
	Indian Seamless Pipe Co.	0.412	0.533	0.475
Domestic	Regional water supply	0.093	0.124	0.093
	Municipal water supply	0.081	0.105	0.093
Other area	Lift irrigation	0.412	0.533	0.475
	Chorwadi branch canal	2.13	-	-

(Source: Stofkoper and Tilak, 1992)

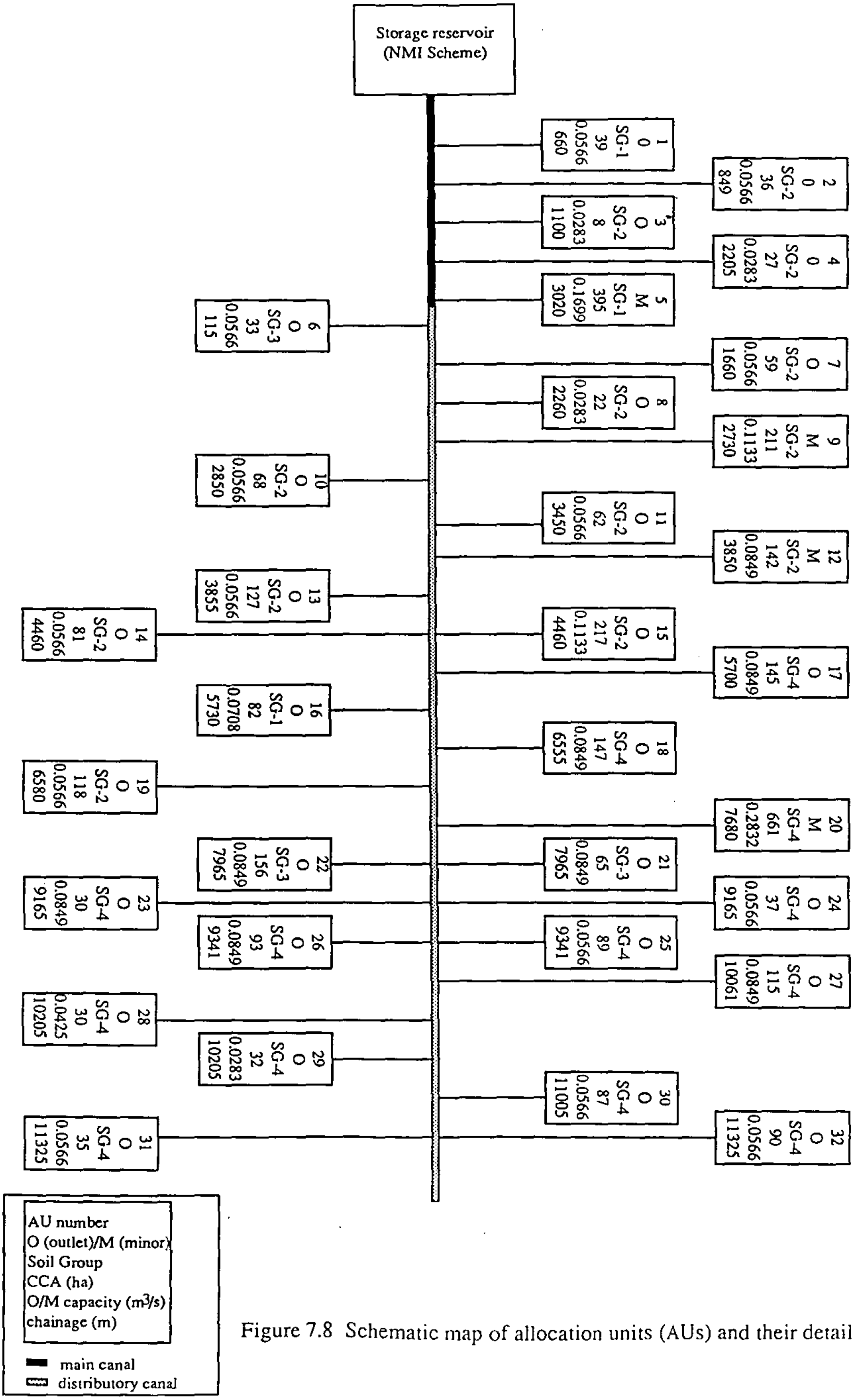


Figure 7.8 Schematic map of allocation units (AUs) and their details

As the daily requirement for the water supply for these uses could not be known, the demand of water over the crop season was divided equally over the days in the crop season to obtain the daily release of water from the reservoir for these uses. The unauthorised use of water or theft of water by lifting it from upstream of the reservoir (backwater) and through canals and using it out of turn is common in the irrigation schemes of the region. But the information on this could not be collected. It is assumed that these losses could be minimised or avoided in efficient management practice and therefore they are not considered in the present study.

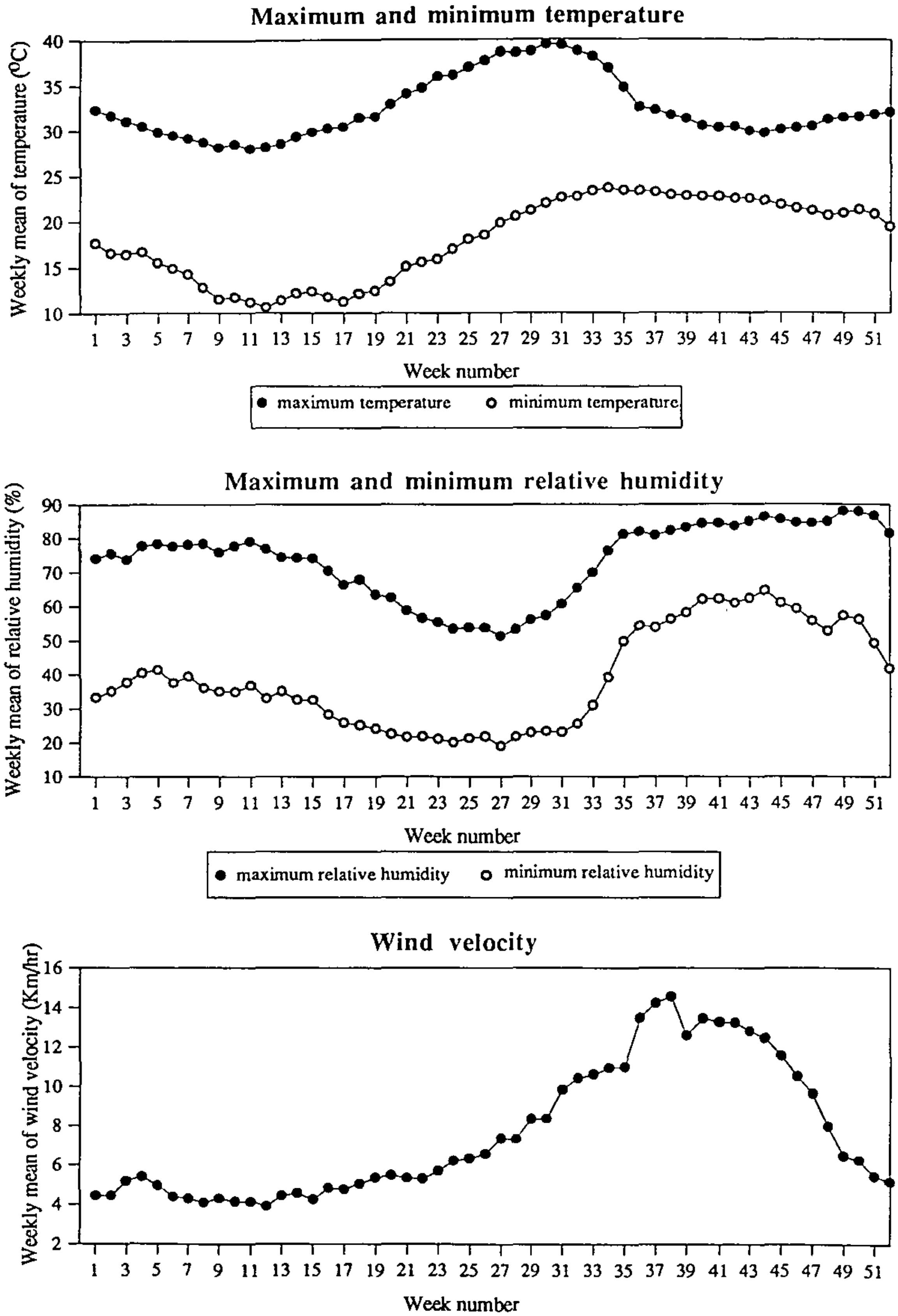
7.5.4 Climate

No systematic climatological data are available at the reservoir site or in the command area of the scheme. Therefore the climatological data was collected from the daily records of the Meteorological Observatory of the nearest agricultural university (Mahatma Phule Agricultural University, Rahuri), which is about 100 km away from the scheme site. The various weather parameters at the observatory are measured by the trained person within the guidelines issued by the Indian Meteorological Department. The daily values of maximum and minimum temperature (^{o}C), maximum and minimum relative humidity (%), wind velocity (Km/hr), actual sunshine hours (hr), pan evaporation (mm) and rainfall (mm) for 18 years (from 1976-77 to 1993-94) were collected. The same data series is used for the reservoir (for estimating the water evaporation) and command area (for estimating the reference crop evapotranspiration and bare soil evaporation). It is assumed that the climate over the entire command area is uniform. Thus there is only one 'Region'. The weekly average values of the different climatological parameters over the period of record are presented in Figure 7.9 and daily values of these parameters for the year 1991-92, which were used for the analysis (Chapters VIII to X) are given Table B.1 of Appendix B.

The modified Penman method (Doorenbos and Pruitt, 1984) is used for computing reference crop evapotranspiration and Penman method (1948) for computing water surface evaporation and bare soil evaporation. The reflection coefficients considered are 0.25, 0.10 and 0.05 for reference crop, bare soil and water surface, respectively.

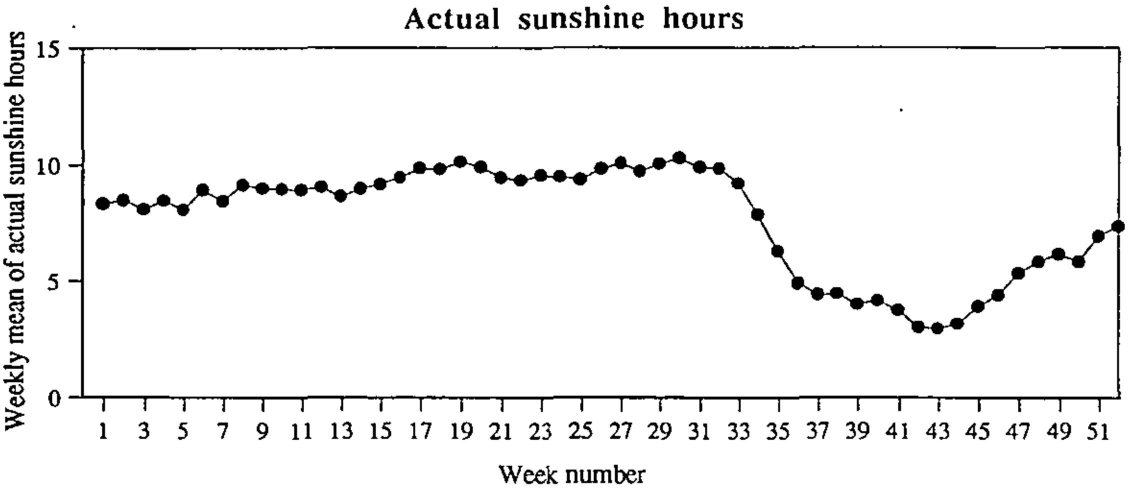
7.5.5 Soils

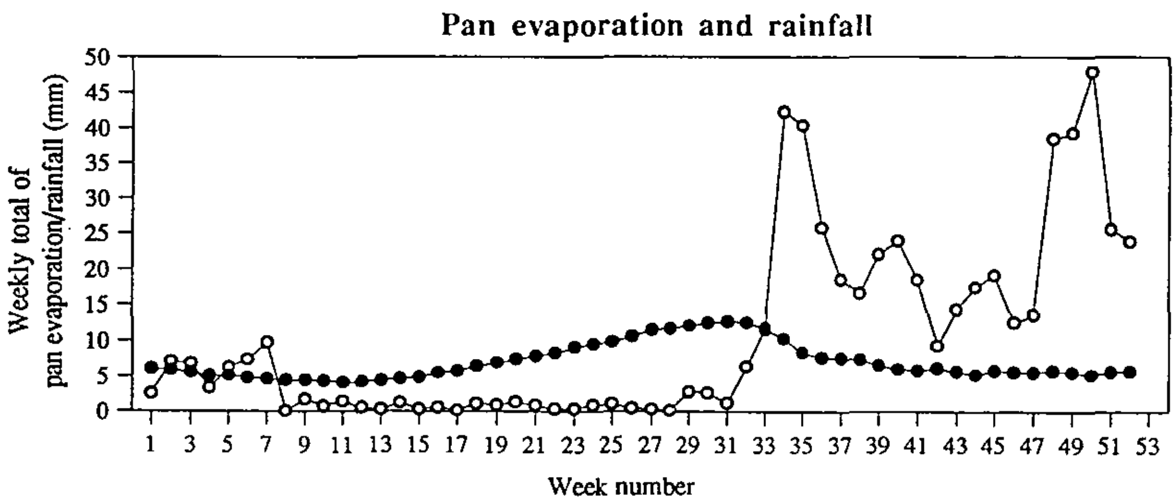
The detail soil survey has been carried out for the scheme by the IRD and the results are reported in the "Report of Pre-Irrigation Soil Survey of the Command of Nazare



(Note: The week-1 starts from 15th October)

Figure 7.9 The weekly average values of different climatological parameters from 1978 to 1993 (contd...)


Actual sunshine hours
Weekly mean of actual sunshine hours
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51
Week number


Pan evaporation and rainfall
Weekly total of pan evaporation/rainfall (mm)
50
45
40
35
30
25
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53
Week number

Medium Irrigation Project, Dist: Pune" (IRD, 1992). At the field soil samples were taken in each grid of 200 x 200 m up to 2500 m (or up to the hard strata if first met) by taking auger holes. The intensity of soil samples was adjusted to suit the topography and special features. At the laboratory level, samples were tested from every 4th auger hole and the properties were measured by the standard procedures. Open profiles were studied as required. The following five soil series were identified in the irrigation scheme.

1) Lakhangaon soil series (SG-0) 2) Chandoli soil series (SG-1)
3) Shirwal soil series (SG-2) 4) Angar soil series (SG-3) and
5) Ghodegaon soil series (SG-4)

The codes in bracket are the name of soil groups used for the present study. The soil type and water holding capacity (WHC) of each soil group up to 1300 mm soil depth are presented in Table 7.4. The volumetric soil moisture content at field capacity and wilting point are fixed from the soil type and WHC for the use in model. The soil group of each AU is shown in Figure 7.8.

Table 7.4 Soil type and WHC of each soil group

Soil Group		Soil Layers				
		1	2	3	4	5
SG-0	thickness (mm) Soil type WHC (mm/mm)	200 clay loam 220				
SG-1	thickness (mm) soil type WHC (mm/mm)	200 loam 200	150 sandy loam 185			
SG-2	thickness (mm) soil type WHC (mm/mm)	250 silty clay 210	250 silty clay 210	200 silty clay 210	300 clay 190	
SG-3	thickness (mm) soil type WHC (mm/mm)	250 clay 190	250 silty clay 210	300 silty clay 210	300 silty clay 210	200 clay loam 220
SG-4	thickness (mm) soil type WHC (mm/mm)	250 clay 190	250 clay 190	50 clay 190	250 clay 190	300 clay 190

(Source: IRD, 1992)

The SG-0 was not recommended for irrigation and falls mostly under the command area of Chorwadi branch canal. The other soil parameters such as esd, tp, cs, and RFm are assumed as 300 mm (except for SG-1, for which it is assumed as 200 mm), 1, 0.3 and 25, respectively.

7.5.6 Crops

The farmers in the region adjust their cropping pattern according to their food requirement and demand in the local market. The lighter cropping pattern (crops without high water consumption) is recommended for this scheme due to shortage of water. According to the project reports, the recommended important crops in the scheme are millet, maize and vegetables in Kharif season and gram, sorghum, vegetables (mainly onion) and wheat in Rabi season. No crops are recommended in Summer season due to high water requirement but recent information shows that groundnut on some area is being irrigated in Summer season. Millet, sorghum, wheat, gram, and vegetables are cultivated as food crops and production above domestic needs is sold in the local market. Maize and the straw from millet, sorghum and groundnut act as fodder. Groundnut is raised as a cash crop and sold to the local oil industries. In the present study as two crop seasons form the irrigation season, gram, sorghum, onion, wheat (Rabi crops), groundnut and sunflower (summer crops) are considered in the analysis. Sunflower is included as the farmers in the adjoining schemes are cultivating this crop (mainly due to the increased demand from oil industries) and the farmers in this scheme may also show interest for this crop. Another important cash crop of the region is sugarcane, but it is not recommended in the cropping pattern of this scheme.

The data related to all these crops are obtained from the reports of Nazare Medium Irrigation Project, the information from the nearest agricultural university (Mahatma Phule Agricultural University), the Journal of Maharashtra Agricultural University (where in the results of the research experiments conducted in the agricultural universities in Maharashtra State are mainly found), Handbook of Agriculture (ICAR, 1992) and FAO Irrigation and Drainage Paper No. 24 and No. 33 (Doorenbos and Pruitt, 1984 and Doorenbos and Kassam, 1986).

Table 7.5 gives the details of planting and harvesting days. The linear root growth model was used for all crops and other details of the model are given in Table 7.5. The extraction model with nel=4 and ce=1.5 (parabolic extraction pattern) was assumed for all the crops. The transpiration deficit was deducted from the transpiration requirement of the same layer. The crop coefficients as a function of the ratio of days since planting to the crop period of gram, sorghum, wheat and groundnut were included through the relationships presented by equations (7.8) through (7.11). These relationships are obtained by modifying the relationships between crop coefficient and days since planting developed by Suryawanshi et al., (1990). The crop growth stagewise values of crop coefficient documented by Doorenbos and Pruitt (1984) are adopted for onion and sunflower.

Gram

$$Kc_i = 0.43 + 0.37\left(\frac{i}{T}\right) + 7.29\left(\frac{i}{T}\right)^2 - 14.52\left(\frac{i}{T}\right)^3 + \left(\frac{i}{T}\right)^4 \tag{7.8}$$

Sorghum

$$Kc_i = 0.34 + 0.67\left(\frac{i}{T}\right) + 2.15\left(\frac{i}{T}\right)^2 - 3.15\left(\frac{i}{T}\right)^3 + 0.08\left(\frac{i}{T}\right)^4 \tag{7.9}$$

Wheat

$$Kc_i = 0.28 + 3.43\left(\frac{i}{T}\right) - 1.44\left(\frac{i}{T}\right)^2 - 4.84\left(\frac{i}{T}\right)^3 + 2.67\left(\frac{i}{T}\right)^4 \tag{7.10}$$

Groundnut

$$Kc_i = 0.37 + 0.42\left(\frac{i}{T}\right) + 4.56\left(\frac{i}{T}\right)^2 - 7.92\left(\frac{i}{T}\right)^3 + 3.17\left(\frac{i}{T}\right)^4 \tag{7.11}$$

(refer Section 5.3.3.4 for the definitions of terms used in equations 7.8 to 7.11)

The additive type of crop growth model based on ET (equation 5.57) is adopted to estimate crop yields for all the crops. The values of stagewise yield response factor for all the crops are adopted from Doorenbos and Kassam (1986). The maximum crop yield is presented in Table 7.5. The irrigation strategies producing crop yield less than certain prescribed limit (minimum crop yield) were not considered in the analysis. This limit was set at 10% of maximum crop yield. The relationship between crop yield and fodder yield were not available. Therefore these were developed from the related data published in the Journals of Maharashtra Agricultural Universities (Lomte et al., 1988; Bapat and Gujar, 1990; Ramu et al., 1991; Bhalerao et al., 1993 and Naphade et al., 1993)and are given in Table 7.5.

Table 7.5 Planning and harvesting days, parameters of root growth model and crop and fodder yields for different crops.

Crop	Planting day	Harvesting day	Root growth model			Crop yield (Kg/ha)	Fodder yield	
			Zo	Zm	tm		fa	fb
gram	23 Oct.	9 Feb.	150	800	55	2500	-	-
sorghum	15 Sep	28 June	100	1200	50	4000	0	4
onion	18 Oct.	14 Feb.	150	400	30	30000	-	-
wheat	13 Nov.	12 Mar.	150	900	50	3500	-	-
sunflower	1 Mar.	28 June	150	1200	60	1500	-	-
groundnut	15 Mar.	28 July	150	1200	40	2500	0	2

7.5.7 Crop-Soil Data

The presowing irrigation was assumed for wheat, sunflower and groundnut on all soils. The presowing irrigation for all these crops is given just before planting. The depth of presowing irrigation was computed in the model (to bring the soil moisture in the soil root zone to field capacity). The initial soil moisture contents (the soil moisture content at the start of irrigation just before planting) for gram, sorghum, onion and wheat were assumed at half the water holding capacity above wilting point, for sunflower at quarter the water holding capacity above wilting point and for groundnut at wilting point, for all soils.

The field application efficiency of 75% was assumed for all the crops on all soils and for all irrigations (including presowing irrigation). The value of runoff coefficient for computing effective rainfall was assumed as 0.70 for all crop-soil combinations. The maximum and minimum possible values of irrigation depth were assumed as 150 and 50 mm, respectively for all crops grown on all soils, though a scheduled irrigation could be missed, giving an application of 0 mm.

The economics related data were assumed the same for all the soils for particular crop. For the present study area dependant cost, yield dependant cost and cost of applying water were considered together. All these costs were computed for the year 1991-92 (Salve, 1992 and reports and discussion with the members of Department of Agricultural Economics, Mahatma Phule Agricultural University, Rahuri, India). These are 3375, 5790, 10000, 6985, 4060, and 7750 Rs/ha for gram, sorghum, onion, wheat, sunflower, and groundnut, respectively. The cost of irrigation water is uniform for all the irrigation schemes in the region and depends on the crop and season in which it is irrigated. The costs are specified per unit area irrigated and not on the volume of water consumed. This system of pricing water may be justified for the present practice of water distribution in which fixed depth of water (depending on crop) is applied at fixed time interval (depending on the season). In the present study the deficit irrigation approach, where in different quantities of water may be applied for the same crop in different AUs, is used and therefore water charges based on volume basis is more appropriate. But at present the prices of water are low. These are 85 Rs/ha for gram, sorghum, onion, wheat and sunflower and 170 Rs/ha for groundnut. The fixing of low prices of water is the part of government's policy of giving the benefits of irrigation to the farmers in the scheme for development of the region rather than generating the benefits for the scheme. The low prices of water makes the generation of irrigation programmes more dependant on the yield reduction or increase due to variation in application of water and less on charges of water. Similarly the price of water on a unit volume basis were not available (though it can be approximately estimated). Therefore in the present study the prices of water based on area basis were considered. However, for the schemes in the region the pricing of water per unit volume basis for avoiding the excessive use of water is now being discussed.

The observation of the market prices of the produce over the past five years showed that these vary considerably over the years and within the year. Therefore these were decided from the market prices over previous two years. These are 6, 1.7, 1, 4, 7.5, and 5 Rs/kg for gram, sorghum, onion, wheat, sunflower and groundnut, respectively. Fodder prices are 0.2 and 0.5 Rs/kg for sorghum and groundnut, respectively.

7.5.8 Water Distribution to the Farmers

In this irrigation scheme, like other irrigation schemes in the region, the distribution of water to different farm areas follows a rotational water supply system known as "Shejpali". Shejpali is based on applying water to various crops grown on different farms by a "fixed interval-fixed depth" approach. The frequency of irrigation (which is fixed over a particular crop season) may vary from 14 to 21 days in the Rabi crop season and 7 days to 14 days in the summer season. An irrigation interval of 21 days for Rabi season is proposed for this irrigation scheme (Stofkoper and Tilak, 1992). This was computed by considering the soil types and maximum crop water requirement. Irrigation intervals are not specified for Summer and Kharif seasons as the irrigation is not common in summer season and protective irrigation is followed in Kharif season.

The fixed irrigation depth for each crop is either determined from the duty which is different for different crops, or by specifying a uniform irrigation depth for all the crops for all irrigations over the crop season. Duty of the crop is the area that can be irrigated by one unit of flow of water over the entire crop period. The duty is either determined from the empirical observations, or by computing the irrigation depth over the entire crop period (delta), which is based on the maximum crop water requirement. Reference crop ET is generally computed by the modified Penman method. The duty and delta are specified for each crop at the farm head and adjusted for different losses as the computations proceed towards headworks. For this irrigation scheme a uniform irrigation depth of 70 mm is proposed (Stofkoper and Tilak, 1992) for all crops at an interval of 21 days in the Rabi season. The application efficiency of 75% is assumed while computing this irrigation depth.

The crops to be grown and the percentage area under different crops are already stipulated for the scheme. These may undergo changes later on but generally the cropping pattern is kept in mind while allocating water to different farms for different crops. The cropping pattern proposed for this irrigation scheme from the reports of the irrigation scheme is

Kharif season: millet (15%), maize (5%), vegetables (3%)

Rabi season: sorghum (50%), wheat (7%), gram (3%), vegetables and others (7%)

For deciding water and area allocations to different crops and farms, the Preliminary Irrigation Programme (PIP) is prepared by the irrigation authority approximately one month before the start of the crop season. The PIP is based on the estimated availability of water for irrigation at the start of the crop season and the average area of major crops irrigated in the previous three years. The target of different crops fixed by the government is also taken into consideration. The amount of water required for irrigation is worked out by considering the losses in the canal network and the capacity of the network. Changes in the area under different crops are made, if found necessary. The irrigation authority issues a notice to all farmers in the command area indicating the water available, crops permissible etc. The areas to be allocated to different farms for different crops are computed from the demand received from the farmers, and by taking into consideration the underlying government policy (such as distribution based on area owned by each farmer or giving preferences to small farmers). Each farmer is supposed to grow crops for canal irrigation according to the allocation assigned to him. The rotation schedule for different canals in the network is prepared. Within in the outlet the sequence of irrigation for each farmer along with the date, time and duration of irrigation for each farmers is fixed. This system of water supply is known as "rigid

Shejpali". In original Shejpali the duration of irrigation is not specified and the farmer can apply water to the field to his satisfaction. In this system the farmer is supposed to apply water at most to bring the soil to field capacity (as considered in the computation of duty or deciding the fixed depth of irrigation) but due to lack of knowledge he tends to overirrigate the field, many times resulting in disturbance of the schedule. In most of the schemes in the region the rigid Shejpali is followed.

In the present study the proposed deficit irrigation approach and fixed depth approach are compared. Both the aspects of fixed depth i.e. applying uniform fixed depth to all the crops grown in the season and applying different fixed depth to different crops are considered while comparing both the approaches. Rigid Shejpali suits both the approaches.

7.6 CONCLUSION

The SWAB and CRYB submodels of AWAM which represent the climate, soil, and crop subsystems were formulated such that minimum data are required and the various processes in the soil-plant-atmospheric subsystems are represented, by incorporating the calibration component. The calibration procedure was described in this chapter. The irrigation schedules used for the calibration and testing the calibration parameters also consisted of deficit irrigation. The results indicated that the calibration could improve the estimates and thus the detailed processes in the soil-plant-atmospheric subsystems could be modelled accurately, verifying the Hypothesis 1. The calibration for each CSR unit would make the irrigation programmes more appropriate. The ability of the model to simulate several parameters which was described by the model in simulation mode is helpful to understand the different processes involved in the subsystems. The last part of this chapter elaborated the various data needs of the model and those collected for the study. Thus this chapter verified the part of Hypothesis 1 (Hypothesis 1 is also discussed in Chapter VIII), described the data requirement of AWAM and data used for testing the hypotheses and describing the utility of the model.

CHAPTER VIII

INVESTIGATING THE METHOD AND EFFECT OF DEFICIT IRRIGATION

Summary. In this chapter the validity of the concepts outlined under Hypotheses 1 and 2 is discussed. Hypothesis 1 highlights the means of practising deficit irrigation. The three approaches described in Chapter III correspond to the means of developing the deficit. These are discussed in this chapter in the context of full, partial, fixed and variable irrigation depths. The Hypothesis 2 states that the effect of deficit irrigation is beneficial, if practised over the entire irrigation scheme under water scarcity. This is discussed in this chapter with six different crops. The results justified the outlined concepts and thus verified the Hypotheses 1 and 2.

8.1 INTRODUCTION

In Chapter III deficit irrigation was defined as deliberately stressing the crop to reduce irrigation water use which may result in reduced crop yield and net benefits. It was hypothesised in this study that deficit irrigation may be beneficial in the times of water scarcity over the entire irrigation scheme (Hypothesis 2). This leaves the task of developing the ways to cause deficit irrigation. Hypothesis 1 states the means of causing deficit. These are to prolong the interval between irrigations, apply less water every irrigation than required for full irrigation or both. To test these hypotheses, the Nazare Medium Irrigation Project case study was used with the AWAM and constant irrigation intervals of 14, 21, 28 and 35 days were chosen. The irrigation depth was varied in the range of minimum and maximum possible irrigation depths. The three approaches described in Chapter III correspond to the different ways of causing deficit outlined under Hypothesis 1. These are discussed in the context of full, partial, fixed and variable irrigation depths.

Having developed the causes of deficit irrigation, these are tested to evaluate their effect on the output (the net benefits or crop yield when the results are obtained per unit area and net benefits when the results are for the entire irrigation scheme). The crops considered in the discussion are gram, sorghum, onion, wheat, sunflower and groundnut. The detailed results are presented only for wheat. At many places only one soil group (SG-2) is considered for brevity. The climatological data are used for the year 1991-92.

8.2 MEANS OF DEFICIT IRRIGATION

The different means of causing deficit irrigation are described for full, partial, fixed and variable depth irrigation in this section. This is the subject of Hypothesis 1.

8.2.1 Full Irrigation

The crop yields and net benefits are obtained for irrigation intervals of 14, 21, 28 and 35 days when full irrigation is applied at every irrigation. The results for all the crops are presented in Tables 8.1 to 8.6 with dr (deficit ratio) =1. It is seen that the maximum yields are obtained for sorghum for all irrigation intervals. For gram and wheat, the maximum yields are obtained for I=14 and 21 days. Other crops (onion, sunflower and groundnut) did not produce maximum crop yield for any of the irrigation intervals tried but the maximum crop yields are found with I = 7 days for these crops. However with I=14 days, the yields are not maximum but very close to maximum. Thus I=7 days, I=21 days and I=35 days for onion, sunflower and groundnut; for gram and wheat and for sorghum, respectively are the maximum irrigation intervals which do not cause reduction in crop yield and thus deficit, when the moisture content in the root zone is brought to field capacity at every irrigation. This irrigation interval is termed as the "adequate irrigation interval".

The general trend is that the crop yields and net benefits decrease with irrigation interval when this is increased beyond the adequate irrigation interval. The seasonal irrigation depth is either decreased or increased with increasing irrigation interval, depending on the combination of decreasing number of irrigations and increasing full irrigation depth with increasing irrigation interval. In this particular case the seasonal irrigation depth decreases with increasing irrigation interval except for gram (when I = 35 days) and wheat (when I = 28 and 35 days).

The soil moisture profile in the root zone and the ET deficit for wheat are presented in Figure 8.1 for all the irrigation intervals. It is seen that the soil moisture content is always above the allowable depletion level and the ET deficit is zero over the crop period, when I=14 and 21 days. The number of irrigations is higher but the depth of irrigation per irrigation is small. When the irrigation interval is increased to 28 days, little deficit is caused at the end of the third crop irrigation, which is reflected in a slight decrease of crop yield. For I =35 days, the deficit occurred at the end of every irrigation interval, resulting in more decrease in crop yield. Thus when the irrigation interval is

Table 8.1 Seasonal irrigation depth, crop yield and net benefits for full and partial irrigation depths for gram.

dr	I											
	14			21			28			35		
	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB
1.0	465	2500	11125	440	2500	11125	385	2464	10908	410	2338	10155
0.95	455	2500	11125	435	2500	11125	375	2464	10908	405	2315	10014
0.90	450	2500	11125	430	2500	11125	370	2464	10908	395	2286	9839
0.85	445	2500	11125	425	2500	11125	365	2461	10893	390	2251	9628
0.80	440	2500	11125	420	2500	11125	360	2433	10725	380	2210	9385
0.75	435	2500	11125	415	2500	11125	350	2393	10485	370	2158	9073
0.70	425	2500	11125	410	2500	11125	340	2332	10118	355	2030	8306
0.65	420	2500	11125	400	2479	11000	325	2221	9450	345	1891	7468
0.60	415	2500	11125	390	2433	10723	310	2095	8695	325	1777	6785
0.55	410	2500	11125	380	2362	10298	295	1955	7858	310	1584	5631
0.50	405	2500	11125	360	2247	9604	275	1763	6705	290	1371	4351
0.45	400	2500	11125	345	2095	8697	255	1552	5437	270	1143	2982
0.40	400	2500	11125	325	1961	7888	235	1356	4261	240	841	1172
0.35	400	2500	11125	310	1800	6922	215	1073	2565	25	655	52
0.30	400	2500	11125	300	1712	6399	200	891	1473	210	555	-546
0.25	400	2500	11125	300	1712	6399	200	891	1473	200	492	-920
0.20	400	2500	11125	300	1712	6399	200	891	1473	200	492	-920
0.15	400	2500	11125	300	1712	6399	200	891	1473	200	492	-920
0.10	400	2500	11125	300	1712	6399	200	891	1473	200	492	-920
0.05	400	2500	11125	300	1712	6399	200	891	1473	200	492	-920

Table 8.2 Seasonal irrigation depth, crop yield and net benefits for full and partial irrigation depths for sorghum.

dr	I											
	14			21			28			35		
	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB
1.0	485	4000	3420	400	4000	3420	395	4000	3420	360	4000	3420
0.95	480	4000	3420	390	4000	3420	390	4000	3420	355	4000	3420
0.90	475	4000	3420	390	4000	3420	385	4000	3420	350	4000	3420
0.85	470	4000	3420	385	4000	3420	380	4000	3420	345	4000	3420
0.80	470	4000	3420	380	4000	3420	375	4000	3420	335	4000	3420
0.75	465	4000	3420	375	4000	3420	370	4000	3420	325	4000	3420
0.70	460	4000	3420	370	4000	3420	360	4000	3420	315	4000	3420
0.65	455	4000	3420	365	4000	3420	350	4000	3420	305	4000	3420
0.60	445	4000	3420	355	4000	3420	340	4000	3420	290	3854	3056
0.55	440	4000	3420	345	4000	3420	330	4000	3420	275	3820	2971
0.50	430	4000	3420	335	4000	3420	315	3889	3144	255	3735	2758
0.45	415	4000	3420	320	3899	3167	295	3818	2965	235	3557	2313
0.40	405	4000	3420	305	3899	3167	270	3637	2513	215	3266	1584
0.35	400	4000	3420	280	3795	2908	250	3522	2226	195	3059	1068
0.30	400	4000	3420	260	3624	2481	225	3283	1627	175	2848	540
0.25	400	4000	3420	250	3551	2297	200	3077	1112	155	2605	-66
0.20	400	4000	3420	250	3551	2297	200	3077	1112	150	2560	-181
0.15	400	4000	3420	250	3551	2297	200	3077	1112	150	2560	-181
0.10	400	4000	3420	250	3551	2297	200	3077	1112	150	2560	-181
0.05	400	4000	3420	250	3551	2297	200	3077	1112	150	2560	-181

Table 8.3 Seasonal irrigation depth, crop yield and net benefits for full and partial irrigation depths for onion.

dr	I											
	14			21			28			35		
	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB
1.0	465	29883	18588	355	28364	17069	355	25392	14097	300	22990	11695
0.95	465	29883	18588	350	28165	16870	345	25225	13930	295	22489	11194
0.90	455	29828	18532	335	27673	16377	335	24475	13179	280	21376	10080
0.85	450	29828	18532	330	27297	16002	320	23477	12182	275	21247	9952
0.80	450	29828	18532	320	26896	15601	310	22914	11619	265	20212	8917
0.75	450	29828	18532	320	26896	15601	295	22076	10781	250	18919	7624
0.70	450	29828	18532	310	26450	15155	290	21472	10177	240	18071	6776
0.65	450	29828	18532	305	26259	14964	275	20487	9192	225	16660	5365
0.60	450	29828	18532	300	26044	14748	265	19995	8700	215	15877	4581
0.55	450	29828	18532	300	26043	14748	255	19451	8155	205	15064	3769
0.50	450	29828	18532	300	26044	14748	250	19305	8010	200	14820	3525
0.45	450	29828	18532	300	26043	14748	250	19305	8010	200	14820	3525
0.40	450	29828	18532	300	26044	14748	250	19305	8010	200	14820	3525
0.35	450	29828	18532	300	26043	14748	250	19305	8010	200	14820	3525
0.30	450	29828	18532	300	26044	14748	250	19305	8010	200	14820	3525
0.25	450	29828	18532	300	26043	14748	250	19305	8010	200	14820	3525
0.20	450	29828	18532	300	26044	14748	250	19305	8010	200	14820	3525
0.15	450	29828	18532	300	26043	14748	250	19305	8010	200	14820	3525
0.10	450	29828	18532	300	26044	14748	250	19305	8010	200	14820	3525
0.05	450	29828	18532	300	26043	14748	250	19305	8010	200	14820	3525

Table 8.4 Seasonal irrigation depth, crop yield and net benefits for full and partial irrigation depths for wheat.

dr	I											
	14			21			28			35		
	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB
1.0	570	3500	6082	510	3500	6082	530	3493	6052	515	3273	5172
0.95	555	3500	6082	500	3500	6082	520	3486	6024	500	3224	4977
0.90	550	3500	6082	495	3500	6082	515	3468	5954	490	3152	4689
0.85	540	3500	6082	490	3500	6082	505	3415	5743	475	3072	4370
0.80	530	3500	6082	485	3500	6082	500	3378	5593	460	2957	3911
0.75	520	3500	6082	480	3500	6082	485	3288	5234	445	2864	3539
0.70	515	3500	6082	470	3492	6050	475	3167	4748	425	701	2884
0.65	510	3500	6082	460	3481	6007	455	3016	4145	405	258	2192
0.60	500	3500	6082	450	3432	5812	440	2838	3434	385	2355	1500
0.55	495	3500	6082	435	3298	5276	410	2379	1596	360	2020	160
0.50	480	3498	6072	410	3005	4102	385	2009	117	330	1665	-1259
0.45	470	3493	6053	385	2646	2664	355	1716	-1054	305	1441	-2154
0.40	460	3477	5991	360	2310	1322	325	1357	-2489	275	1116	-3452
0.35	450	3469	5957	335	2025	182	300	1103	-3508	250	733	-4988
0.30	450	3469	5957	310	1775	-817	270	655	-5297	225	335	-6578
0:25	450	3469	5957	300	1731	-996	250	502	-5909	205	177	-7209
0.20	450	3469	5957	300	1731	-996	250	502	-5909	200	160	-7280
0.15	450	3469	5957	300	1731	-996	250	502	-5909	200	160	-7280
0.10	450	3469	5957	300	1731	-996	250	502	-5909	200	160	-7280
0.05	450	3469	5957	300	1731	-996	250	502	-5909	200	160	-7280

Table 8.5 Seasonal irrigation depth, crop yield and net benefits for full and partial irrigation depths for sunflower.

dr	I											
	14			21			28			35		
	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB
1.0	820	1477	6436	730	1168	4116	630	980	2707	595	491	-958
0.95	810	1466	6350	725	1152	3998	620	939	2398	590	467	-1137
0.90	800	1457	6282	715	1121	3762	610	913	206	585	443	-1317
0.85	790	1432	6097	705	1083	3481	600	862	1820	575	394	-1684
0.80	775	1405	5898	695	1048	3217	590	836	1626	570	370	-1869
0.75	765	1375	5671	680	991	2788	575	782	1221	550	319	-2247
0.70	745	1327	5310	660	932	2349	555	656	274	525	215	-3028
0.65	730	1290	5032	635	823	1533	530	539	-602	495	-	-
0.60	705	1175	4171	605	688	521	505	408	-1584	470	-	-
0.55	675	1002	2874	570	574	-335	485	305	-2354	450	-	-
0.50	650	915	2218	545	482	-1024	455	-	-	415	-	-
0.45	625	833	1608	515	372	-1851	425	-	-	380	-	-
0.40	585	686	500	470	-	-	395	-	-	345	-	-
0.35	540	453	-1245	430	-	-	360	-	-	310	-	-
0.30	505	252	-2753	380	-	-	320	-	-	270	-	-
0.25	460	-	-	335	-	-	275	-	-	225	-	-
0.20	450	-	-	300	-	-	250	-	-	200	-	-
0.15	450	-	-	300	-	-	250	-	-	200	-	-
0.10	450	-	-	300	-	-	250	-	-	200	-	-
0.05	450	-	-	300	-	-	250	-	-	200	-	-

Table 8.6 Seasonal irrigation depth, crop yield and net benefits for full and partial irrigation depths for groundnut.

dr	I											
	14			21			28			35		
	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB
1.0	830	2494	6096	785	2310	4991	675	1623	866	600	995	-2901
0.95	825	2492	6084	775	2295	4899	675	1623	866	600	995	-2901
0.90	815	2490	6072	765	2274	4776	670	1623	866	600	995	-2901
0.85	805	2484	6034	755	2252	4639	665	1623	866	600	995	-2901
0.80	795	2469	5941	745	2223	4470	660	1623	866	600	995	-2901
0.75	785	2454	5852	725	2170	4151	655	1588	660	590	995	-2901
0.70	770	2430	5708	705	2058	3476	635	1508	175	580	995	-2901
0.65	755	2390	5472	680	1879	2405	600	1359	-719	560	942	-3217
0.60	735	2312	5002	650	1731	1518	575	1234	-1466	535	841	-3825
0.55	705	2119	3842	620	1610	791	555	1140	-2027	505	738	-4443
0.50	665	1979	3005	585	1450	-169	520	984	-2964	465	599	-5274
0.45	635	1889	2466	555	1283	-1170	480	754	-4344	420	429	-6294
0.40	600	1763	1707	505	1007	-2829	440	569	-5457	390	326	-6915
0.35	550	1541	378	460	818	-3961	400	404	-6445	345	-	-
0.30	500	1315	-980	415	629	-5099	355	-	-	295	-	-
0.25	445	1066	-2471	365	437	-6246	315	-	-	255	-	-
0.20	405	924	-3324	310	-	-	270	-	-	215	-	-
0.15	400	912	-3396	300	-	-	250	-	-	200	-	-
0.10	400	912	-3396	300	-	-	250	-	-	200	-	-
0.05	400	912	-3396	300	-	-	50	-	-	200	-	-

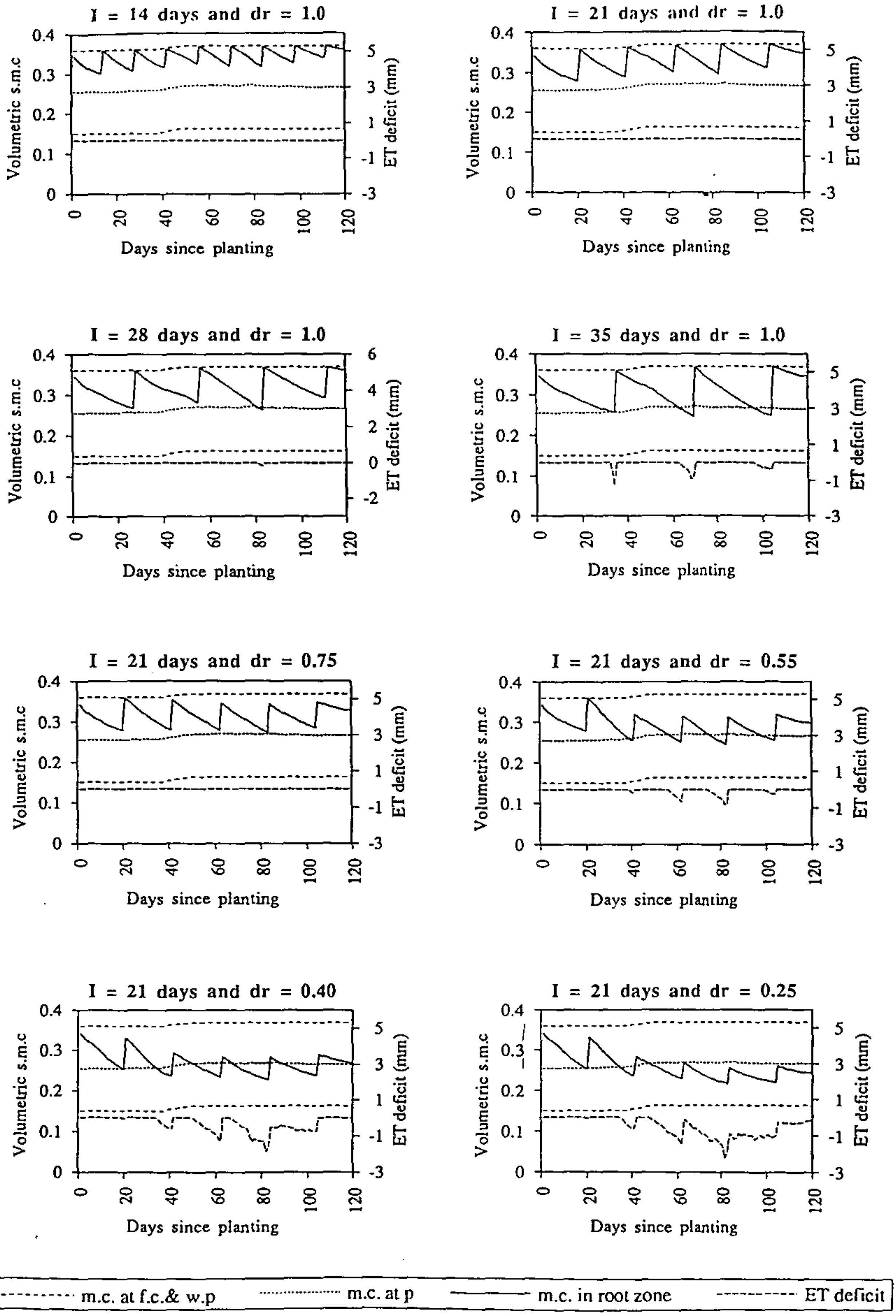


Figure 8.1 Soil moisture profile and ET deficit for wheat grown on SG-2 and applied with full and partial irrigations (Approach-1 and Approach-2)

increased, the crop is subjected to stress at the end of the irrigation interval, producing less crop yields and net benefits. The seasonal irrigation depth varied according to the combination of the number of irrigations and the full irrigation depth. The similar results are obtained for other crops, soils and climatic series.

In the case of full irrigation, the irrigations with I=14 and 21 days and I =14, 21, 28 and 35 days are the cases of adequate irrigation for wheat and gram and for sorghum, respectively. The adequate irrigation could not be applied to onion, sunflower and groundnut using a minimum irrigation interval of 14 days. However full irrigation with I=14 days for these crops is close to adequate irrigation. The other irrigation intervals i.e. I=28 and 35 days for gram and wheat and I=14, 21, 28 and 35 days for onion, sunflower and groundnut are the cases of Approach-1 i.e. prolonging the irrigation interval beyond the one not causing stress (adequate irrigation interval) and applying water to bring soil moisture in the root zone to field capacity at every irrigation.

Thus the increase in interval between two irrigations beyond a certain limit causes the moisture content in the soil to drop below the depletion level and occurrence of ET deficit. This results in reduction in crop yield. At the same time in many cases, due to the prolonged interval, the seasonal irrigation depth is also reduced. However it remains to be seen whether the deficit caused due to prolonging the irrigation interval is beneficial.

8.2.2 Partial Irrigation

The crop yields and net benefits are obtained for different levels of partial irrigation obtained by reducing deficit ratio (dr) below one by an interval of 0.05 till 0.05. However the deficit ratio was kept the same for all the irrigations, meaning that the application of irrigation water in relation to irrigation water needed for full irrigation is the same for all the irrigations but the irrigation depth is different. The results are presented in Tables 8.1 to 8.6. The seasonal irrigation depth for some lower levels of partial irrigation are the same because these are limited by minimum prescribed irrigation depth at every irrigation. At the lower irrigation interval for gram and sorghum (I=14 days), the same crop yields (equivalent to maximum crop yields) are obtained with all levels of partial irrigation. This indicates that the minimum possible irrigation depth is sufficient when irrigation interval is small not to cause deficit, instead giving full irrigation.

When the irrigation interval is increased further (for gram and sorghum) or for other crops at a lower irrigation interval (e.g. wheat) the maximum crop yields are obtained up to certain levels of partial irrigation (I=21 days and dr=0.70 for gram, I=21 days and dr=0.5 for sorghum and I=14 days and dr=0.55 for wheat). All these cases represent the adequate irrigation. For the remaining irrigation intervals and other crops, the crop yields and seasonal irrigation depth decrease with the level of partial irrigation (dr) till the deficit ratio at which the irrigation depth is limited by minimum possible irrigation depth.

Thus it is seen that adequate irrigation is possible without full irrigation also. This is due to the fact that the partial irrigation depth equivalent to a certain value of deficit ratio is sufficient to maintain drop the soil moisture content above the allowable depletion level, and does not cause ET deficit when the interval between two irrigations is small. However if the deficit ratio is further reduced, the corresponding irrigation depth can not maintain soil moisture in the root zone above depletion level or avoid occurrence of ET deficit. This is demonstrated in Figure 8.1 for wheat when I=21 days and dr varies from 0.75 (adequate irrigation) to 0.25.

When the level of partial irrigation increases for the same value of irrigation interval, there is a tendency for the soil moisture content to fall below allowable depletion level for most of the days during the irrigation interval. For example, when dr=0.25 the soil moisture content is below allowable depletion level for all the days during 3^{rd}, 4^{th}, and 5^{th} crop irrigations. This is unlike in full irrigation, in which when the irrigation interval is increased, the soil moisture falls below allowable depletion or ET deficit occurs at the end of irrigation interval, but the soil moisture is again brought to field capacity at the beginning of the next irrigation.

Thus when the irrigation interval is equivalent to the adequate irrigation interval but the level of partial irrigation is increased beyond a certain value, the crop yields and net benefits are reduced due to the occurrence of ET deficit. This level of partial irrigation is termed as the "adequate level of partial irrigation". Thus the levels of partial irrigations, if increased beyond the adequate level of partial irrigation (i.e. applying water less than the amount required to bring the soil moisture in the root zone to field capacity) with irrigation interval equivalent to adequate irrigation interval (i.e. an irrigation interval which does not cause any stress if the root zone is filled up to field capacity), represent the cases of Approach-2. It needs to be evaluated whether the deficit caused due to the Approach-2 is beneficial.

The cases with an irrigation interval greater than the adequate irrigation interval and with partial irrigations represent the Approach-3. In this approach when the values of dr are high, the soil moisture content falls below the allowable level and ET deficit occurs at the end of the irrigation interval. For the lower values of dr, the moisture content below allowable level and ET deficit are found during most of the days in the irrigation interval. All levels of partial irrigations when I = 28 and 35 days for gram and wheat, and when I=14, 21, 28 and 35 days for onion, sunflower and groundnut, are the cases of Approach-3. The variation of soil moisture content and deficit in ET over the crop period for Approach-3 for wheat are shown in Figure 8.2.

8.2.3 Fixed Irrigation Depth

In this section the Approaches-1, 2 and 3 are described with fixed irrigation depth. In fixed irrigation depth the irrigation depth is kept the same for all the irrigations. The results of seasonal irrigation depth, crop yield and net benefits are obtained for different values of fixed depth of irrigation (varied from minimum irrigation depth to maximum irrigation depth at an interval of 5 mm per irrigation) for all the irrigation intervals and crops. These are presented in Tables 8.7 to 8.12.

The crop yield and net benefits increase with the increasing fixed irrigation depth for a particular irrigation interval. In some cases these increase up a certain fixed irrigation depth and after that these are constant (and therefore not reported in the tables). The minimum possible irrigation depth (Id=50 mm) was sufficient for the smaller irrigation interval (I=14 days) for gram and sorghum to produce maximum output. Wheat required a slightly higher fixed irrigation depth to produce maximum crop yield and net benefits (Id=55 mm). Other crops (onion, sunflower and groundnut) could not produce maximum crop yield and net benefits for any of the irrigation intervals under consideration, even with the maximum possible irrigation depth. However a smaller irrigation interval (I=7 days) could produce maximum output for these crops. Onion requires I=7 days mainly because of little available soil moisture due to limited depth of root zone, and sunflower and groundnut because of high ET during the summer season. Groundnut and sunflower could not produce the crop yield at a higher irrigation interval for some lower values of fixed irrigation depth.

Sorghum could produce maximum output for all irrigation intervals. Gram and wheat produced maximum output up to I=21 days. The fixed irrigation depth to produce maximum crop yield increased with irrigation interval due to requirement for greater irrigation depth to bring the soil moisture to the level which would not cause stress to

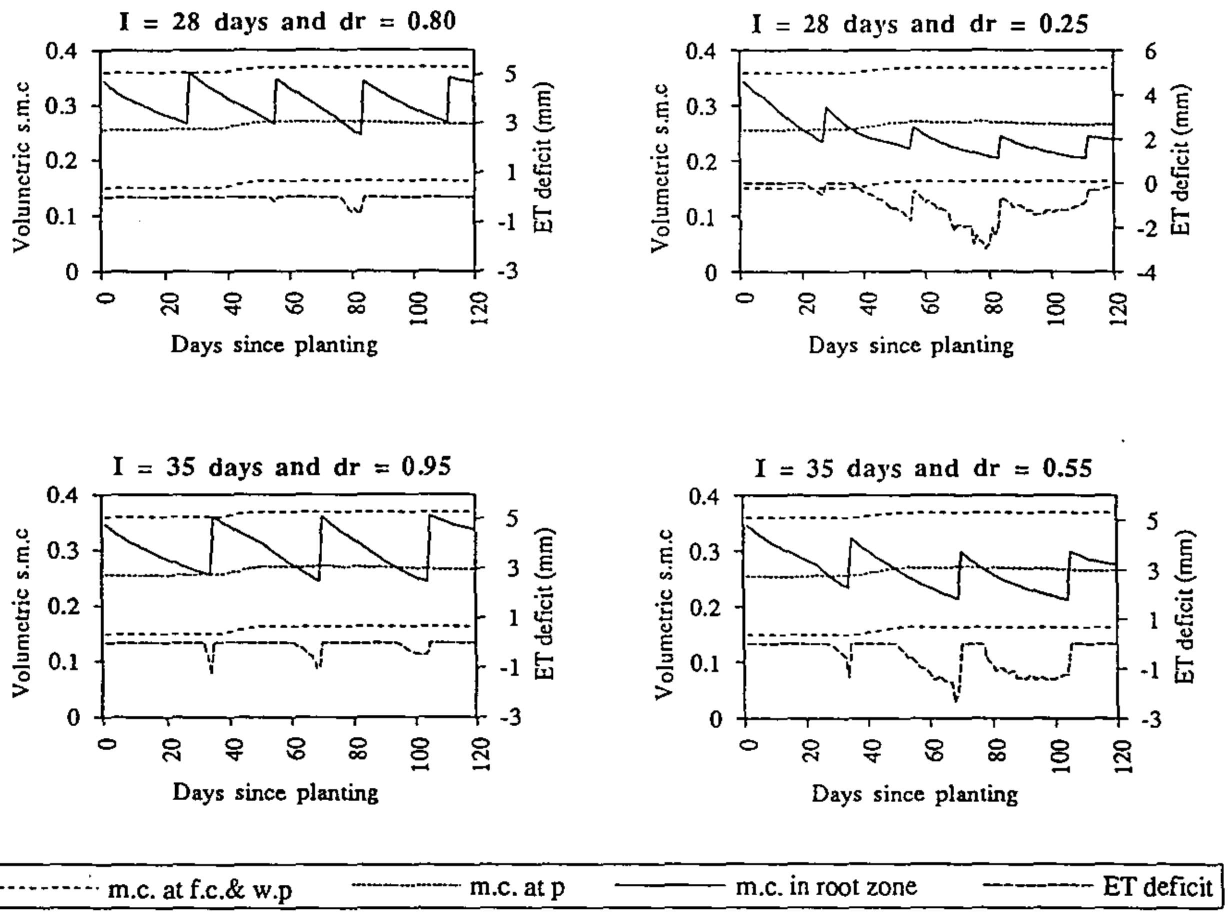


Figure 8.2 Soil moisture profile and ET deficit for wheat grown on SG-2 and applied with partial irrigations (Approach-3)

Table 8.7 Seasonal irrigation depth, crop yield and net benefits by fixed irrigation depth for gram

Id	I											
	14			21			28			35		
	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB
50	400	2500	11125	300	1712	6399	200	891	1473	200	492	-920
55	440	2500	11125	330	2027	8288	220	1185	3232	220	731	509
60				360	2280	9806	240	1461	4891	240	981	2013
65				390	2441	10773	260	1726	6480	260	1233	3525
70				420	2500	11125	280	1966	7923	280	1467	4930
75				450	2500	11125	300	2180	9205	300	1699	6320
80							320	2330	10106	320	1904	7550
85							340	2428	10694	340	2077	8587
90							360	2464	10908	360	212	9397
95							380	2464	10908	380	2306	9962
100										400	2346	10202
105										420	2346	10202
110												
115												
120												
125												
130												
135												
140												
145												

Table 8.8 Seasonal irrigation depth, crop yield and net benefits by fixed irrigation depth for sorghum

Id	I											
	14			21			28			35		
	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB
50	400	4000	3420	250	3551	2297	200	3077	1112	150	2560	-181
55	440	4000	3420	275	3764	2830	220	3300	1671	165	2770	346
60				300	3899	3167	240	3405	1931	180	2970	844
65				325	4000	3420	260	3585	2383	195	3153	1304
70				350	4000	3420	280	3818	2965	210	3281	1623
75							300	3888	3139	225	3434	2005
80							320	3895	3157	240	3743	2778
85							340	4000	3420	255	3828	2990
90							360	4000	3420	270	3860	3069
95										285	3875	3107
100										300	4000	3420
105										300	4000	3420
110												
15												
120												
125												
130												
135												
140												
145												

Table 8.9 Seasonal irrigation depth, crop yield and net benefits by fixed irrigation depth for onion

Id	I											
	14			21			28			35		
	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB
50	450	29828	18532	300	26044	14748	250	19305	8010	200	14820	3525
55	495	29883	18588	330	27449	16154	275	21762	10467	220	16977	5702
60	540	29890	18594	360	27881	16585	300	23466	12171	240	18578	7283
65	585	29890	18594	390	28181	16885	325	24854	13558	260	19986	8691
70				420	28284	16988	350	25244	13949	280	21286	9991
75				450	28379	17084	375	25434	14139	300	22417	11122
80				480	28386	17091	400	25506	14211	320	22923	11628
85				510	28386	17091	425	25506	14211	340	23087	11792
90										360	23184	11889
95										380	23198	11902
100										400	23198	11902
105												
110												
15												
120												
125												
130												
135												
140												
145												

Table 8.10 Seasonal irrigation depth, crop yield and net benefits by fixed irrigation depth for wheat

Id	I											
	14			21			28			35		
	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB
50	450	3469	5957	300	1731	-996	250	502	-5909	200	-	-
55	495	3500	6082	330	2090	441	275	887	-4371	220	471	-6036
60	540	3500	6082	360	2438	1834	300	269	-2841	240	751	-4913
65				390	2985	4022	325	1542	-1752	260	1080	-3597
70				420	3370	5561	350	1821	-634	280	1324	-2624
75				450	3491	6045	375	274	1177	300	1642	-1350
80				480	3500	6082	400	2690	2842	320	1943	-146
85				510	3500	6082	425	2981	4006	340	2226	984
90							450	3220	4962	360	2452	1888
95							475	3396	5664	380	2653	2695
100							500	3465	5940	400	2830	3402
105							525	3484	6019	420	2993	4055
110							550	3494	6058	440	3083	4412
15							575	3494	6058	460	3115	4542
120										480	3146	4666
125										500	3175	4781
130										520	3202	4888
135										540	3226	4984
140										560	347	5071
145										580	3267	5149

Table 8.11 Seasonal irrigation depth, crop yield and net benefits by fixed irrigation depth for sunflower

Id	I											
	14			21			28			35		
	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB
50	450	-	-	300	-	-	250	-	-	200	-	-
55	495	193	-3198	330	-	-	275	-	-	220	-	-
60	540	399	-1651	360	-	-	300	-	-	240	-	-
65	585	640	154	390	-	-	325	-	-	260	-	-
70	630	835	1619	420	-	-	350	-	-	280	-	-
75	675	1088	3515	450	-	-	375	-	-	300	-	-
80	720	1270	4884	480	261	-2688	400	-	-	320	-	-
85	765	1337	5384	510	420	-1490	425	-	-	340	-	-
90	810	1368	5617	540	561	-431	450	-	-	360	-	-
95	855	1397	5834	570	721	766	475	-	-	380	-	-
100	900	1425	6044	600	877	1934	500	-	-	400	-	-
105	945	1435	6133	630	991	2788	525	238	-2859	420	-	-
110	990	1449	6222	660	1049	3224	550	341	-2089	440	-	-
15	1035	1459	6298	690	1068	3367	575	447	-1289	460	-	-
120	1980	1465	6348	720	1084	3488	600	576	-324	480	-	-
125	1125	1472	6396	750	1100	3606	625	711	688	500	-	-
130	1170	1477	6436	780	1115	3719	650	814	1462	520	226	-2945
135	1215	1477	6436	810	1130	3829	675	906	2152	540	301	-2387
140				840	1143	3933	700	931	2337	560	373	-1842
145				870	1157	4035	725	955	2522	580	445	-1308

Table 8.12 Seasonal irrigation depth, crop yield and net benefits by fixed irrigation depth for groundnut

Id	I											
	14			21			28			35		
	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB	SID	Ya	NB
50	400	912	-3396	300	-	-	250	-	-	200	-	-
55	440	1040	-2628	330	279	-7199	275	-	-	220	-	-
60	480	1200	-1671	360	388	-6542	300	-	-	240	-	-
65	520	1368	-664	390	488	-5945	325	-	-	260	-	-
70	560	1520	248	420	589	-5335	350	-	-	280	-	-
75	600	1670	1148	450	678	-4801	375	-	-	300	-	-
80	640	1797	1912	480	791	-4123	400	280	-7193	320	-	-
85	680	1910	2587	510	896	-3497	425	367	-6668	340	-	-
90	720	2023	3268	540	1013	-2791	450	453	-6154	360	-	-
95	760	2203	4347	570	1132	-2079	475	537	-5646	380	-	-
100	800	2396	5508	600	1311	-1007	500	625	-5118	400	289	-7135
105	840	2466	5927	630	1421	-343	525	729	-4498	420	350	-6768
110	880	2493	6087	660	1530	310	550	839	-3839	440	414	-6384
15	920	2493	6087	690	1643	986	575	950	-3171	460	492	-5916
120				720	1751	1637	600	1043	-2613	480	565	-5478
125				750	1882	2419	625	1136	-2057	500	664	-4888
130				780	2042	3379	650	1227	-1508	520	729	-4494
135				810	2192	428	675	1332	-880	540	796	-4095
140				840	2262	4699	700	1435	-260	560	862	-3698
145				870	2305	4962	725	1520	248	580	921	-3345

the crop, but no specific trend was found for the seasonal irrigation depth, mainly because of variation of matching of irrigation events with the crop growth stages. Tables 8.7 to 8.12 show the minimum fixed irrigation depth required to produce maximum possible crop yield for all irrigation intervals and crops (by shaded box).

For gram and wheat, the cases of I=28 and 35 days and with fixed irrigation depth equal to or more than indicated in shaded box are the cases of Approach-1. The fixed irrigation depths less than indicated in shaded box with I=14 and 21 days for gram and wheat and for all irrigation intervals for sorghum are the cases of Approach-2. All remaining cases for these crops and all cases of onion, sunflower and groundnut are the cases of Approach-3. The different approaches with fixed irrigation depth are described in Figures 8.3 and 8.4 for wheat.

8.2.4 Influence of Irrigation Interval on Deficit Irrigation

Deficit irrigation was defined as deliberately stressing the crop to reduce the irrigation water requirement which may result in reduction in crop yield. This can be caused by prolonging the interval between two irrigations. The results summarised in Sections 8.2.1, 8.2.2 and 8.2.3 indicate that prolonging the irrigation interval tends to reduce crop yield and irrigation water requirement due to stress to the crop. However prolonging the irrigation interval did not always reduce the irrigation water requirement e.g. some cases of full irrigations. Thus prolonging the interval between two irrigations may or may not result in deficit irrigation. The reduction in water requirement due to prolonging the irrigation interval may produce additional production by bringing more area under irrigation in a water scarce region, but it needs to be evaluated whether the benefits gained from the additional area exceed the loss in benefits resulting from and prolonging the irrigation interval over the original area. It has also been shown that the full irrigation is not always adequate irrigation, but there is maximum irrigation interval up to which full irrigation is adequate irrigation, and after that full irrigation may be deficit irrigation.

8.2.5 Influence of Irrigation Depth on Deficit Irrigation

Under the analysis of fixed irrigation depth per irrigation or fixed deficit ratio per irrigation it was found that reducing the irrigation depth or deficit ratio always results in deficit irrigation. For adequate irrigation interval, crop and given set of conditions, there is a maximum irrigation depth or deficit ratio up to which deficit irrigation is not caused. Like prolonging the irrigation interval, reducing the irrigation depth can produce

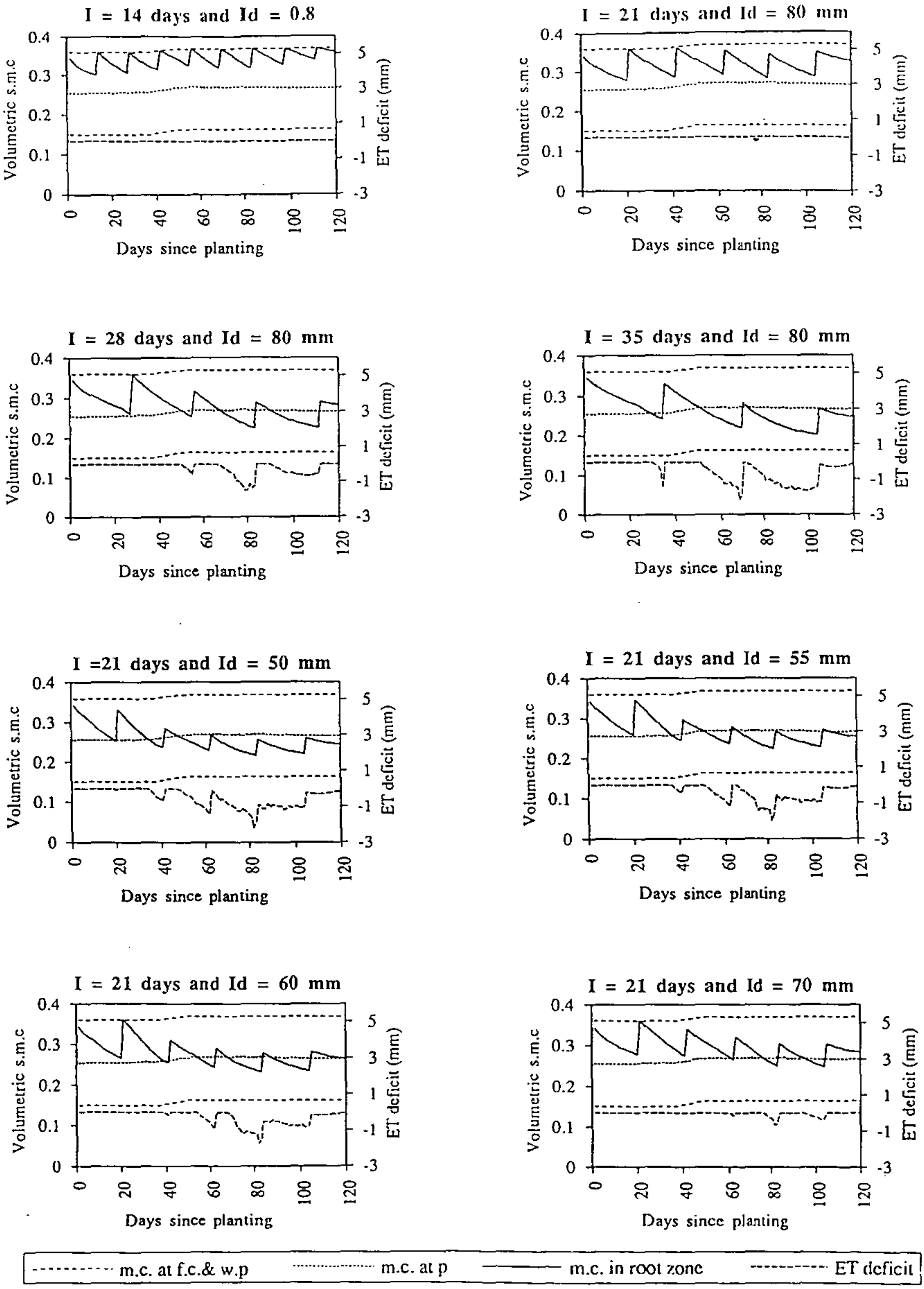


Figure 8.3 Soil moisture profile and ET deficit for wheat grown on SG-2 and applied with fixed irrigation depth (Approach-1 and Approach-2)

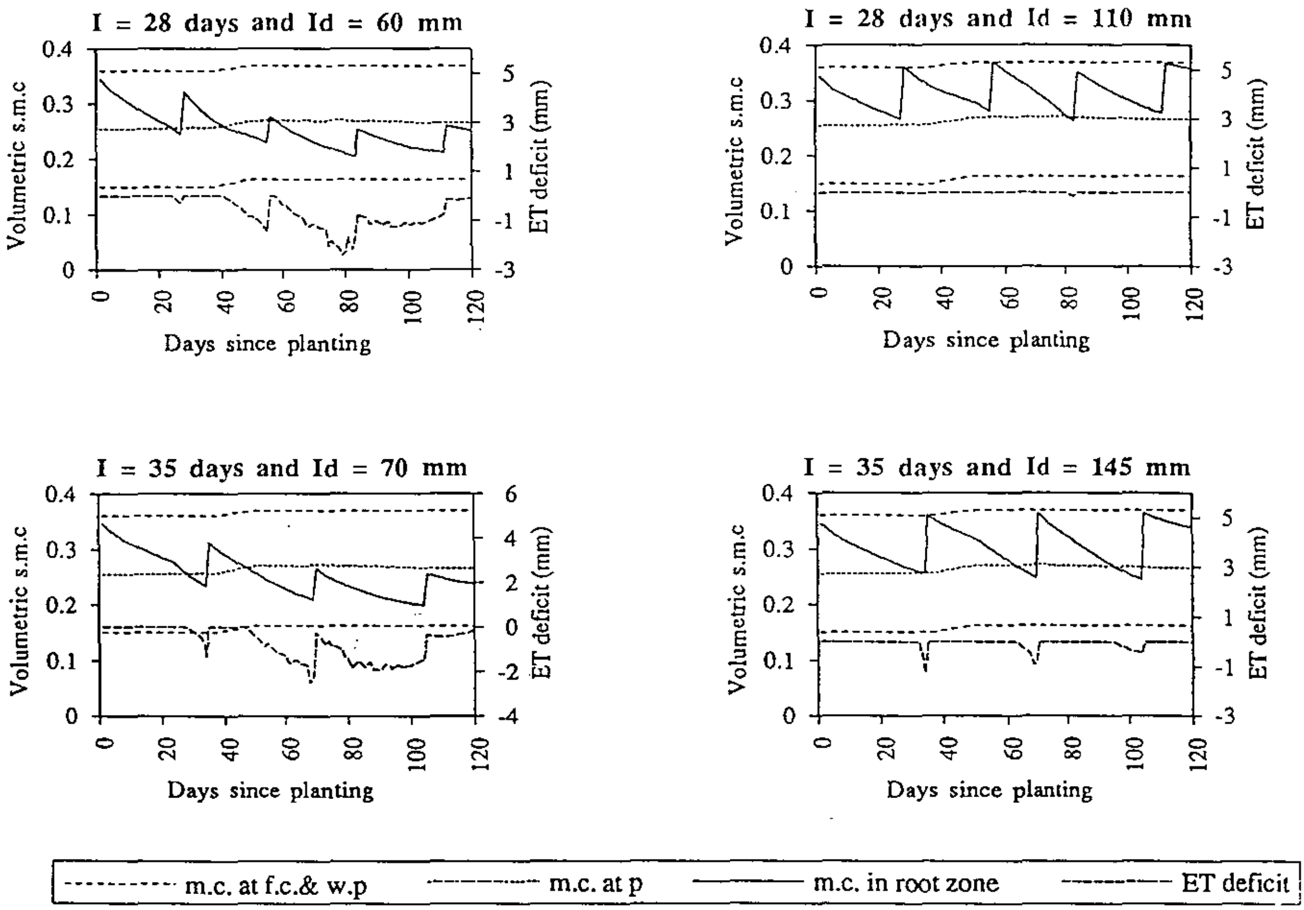


Figure 8.4 Soil moisture profile and ET deficit for wheat grown on SG-2 and applied with fixed irrigation depth (Approach-3)

benefits from crop production over an additional area, but again it needs to be seen whether the benefits from irrigating the additional area compensate for the reduction in benefits over the original area.

8.2.6 Comment on Hypothesis-1

The results discussed in previous sections confirm the first hypothesis i.e. prolonging the interval between two irrigations and/or applying water less than needed for full irrigation results in deficit irrigation. However it needs to be found out whether deficit irrigation is beneficial for the irrigation scheme in time of water scarcity, which is the subject of second hypothesis.

The above discussion is based on either applying a fixed depth of water per irrigation or replenishing the root zone by a fixed proportion. But the amount of water to replenish the root zone may vary during different irrigations depending on the ET and development of roots. Similarly the response of different crops differ with different amounts of water application in different periods of growth. Therefore if the irrigation depth is varied at every irrigation, it is possible to obtain higher output with the same seasonal amount of water applied; or to obtain similar output, less seasonal depth of irrigation water might be needed. This can be achieved by application of the proper amount of water at every irrigation, depending on the sensitivity of the crop growth stage within the limitation of minimum and maximum possible irrigation depths, or skipping of irrigations. This approach in this study is referred to as "variable irrigation depth". To find out the optimum combination of irrigation depths per irrigation for a particular seasonal irrigation depth for varying depth irrigation needs the examination of several alternatives. In the present study this is achieved by generating several irrigation strategies by varying the deficit ratio at every irrigation to vary the irrigation depth at every irrigation.

8.2.7 Variable Irrigation Depth

The method of generation of irrigation strategies in which the deficit ratio, and in turn irrigation depth, is varied every irrigation, is described in Chapter V. Unlike fixed irrigation depth, there are several combinations in variable irrigation depth, corresponding to each irrigation strategy. The irrigation strategies for wheat grown on SG-2 for irrigation interval of 21 days are shown in Figure 8.5. The interval between deficit ratio for generating irrigation strategies was chosen as 0.1. The total number of feasible irrigation strategies generated and thus the number of feasible irrigation

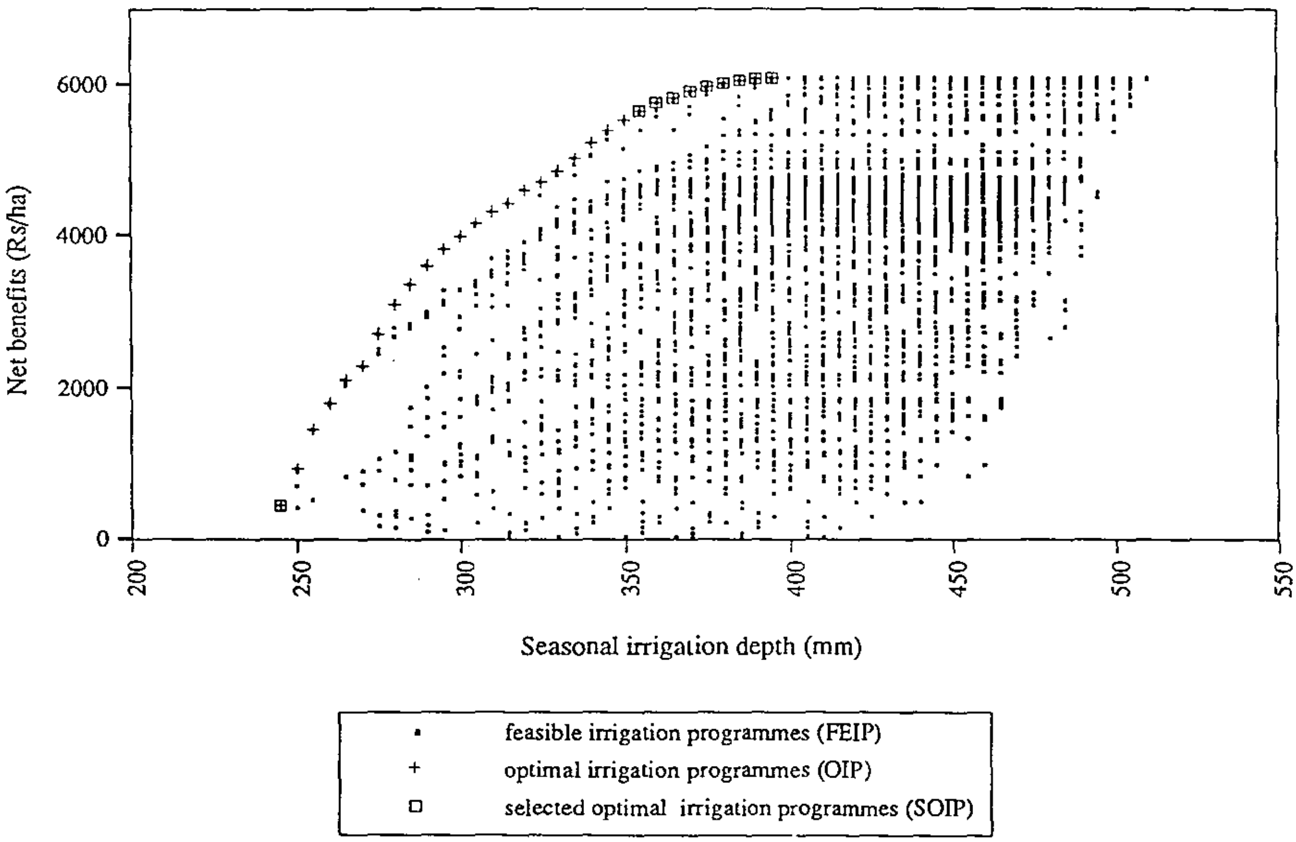


Figure 8.5 Irrigation programmes for wheat grown on SG-2 when irrigation interval is 21 days

programmes (FEIP) is 7282. The number of optimal irrigation programmes (OIP) is 31. The ten SOIPs are selected. FEIP, OIP and SOIPs are also shown in Figure 8.5. The details of all OIPs are presented in Table 8.13. The OIPs shown with shaded boxes in Table 8.13 are SOIPs.

It can be seen from Tables 8.4, 8.10 and 8.13 that the seasonal irrigation depth is reduced from 480 mm to 395 mm for adequate irrigation by variable irrigation depth. Similarly it is also observed that a lower seasonal irrigation depth is required by using variable irrigation depth than by using a fixed irrigation depth to obtain the similar crop yield.

8.2.8 Fixed, Variable and Full Irrigation Depths

The net benefits are obtained for all the crops grown on SG-2 for all irrigation intervals by using variable, fixed and full irrigation depths. The results are presented in Figures 8.6 to 8.11. The seasonal irrigation depths for variable irrigation depth in the figure correspond to the OIPs. It is seen that the benefit-depth curve for variable irrigation depth lies above fixed irrigation depth (except for onion with I = 35 days). This indicates that for the similar seasonal irrigation depth, the net benefits are higher by using a variable irrigation depth, than fixed irrigation depth and each unit of water delivered is utilised for the consumptive use more efficiently by the variable irrigation depth. The difference between the two curves for net benefit value indicates the additional water lost by the non consumptive use in the fixed irrigation depth.

For onion the benefit-depth curve for both the depths is similar or the difference is little. This is due to the small depth of the root zone and the minimum limit to irrigation depth every irrigation. For onion the variable irrigation depth results in small irrigation depth for little lower values of deficit ratio and due to greater sensitivity of onion to drought, the skipping of irrigations results in a large drop in crop yield and thus net benefits.

Another advantage with variable irrigation depth as observed from Figures 8.6 to 8.11 is the possibility of delivering water in small amounts of seasonal irrigation depth (though producing less benefits). This is done by prioritising the irrigations during crop growth stages more sensitive to water application. This is especially useful when limited water is required to be spread over a large area.

It is observed from the figures that the full irrigation depth, though producing maximum crop yield, needs a larger amount of water than variable irrigation depth. The difference

Table 8.13 The details of OIPs for wheat grown on SG-2 when irrigation interval is 21 days

OIP NO.	SID (mm)	NB (Rs./ha.)	Deficit ratios for different irrigations					
			1	2	3	4	5	6
1	245	450.25	1.00	.00	.40	.50	.00	.00
2	250	942.11	1.00	.00	.50	.50	.00	.00
3	255	1452.01	1.00	.00	.60	.50	.00	.00
4	260	1797.72	1.00	.00	.80	.40	.00	.00
5	265	2106.65	1.00	1.00	.00	.60	.00	.00
6	270	2294.77	1.00	.00	.90	.50	.00	.00
7	275	2711.01	1.00	1.00	.60	.40	.00	.00
8	280	3091.25	1.00	1.00	.70	.40	.00	.00
9	285	3354.08	1.00	1.00	.70	.50	.00	.00
10	290	3593.62	1.00	1.00	.80	.50	.00	.00
11	295	3811.42	1.00	1.00	.90	.50	.00	.00
12	300	3984.40	1.00	1.00	.80	.60	.00	.00
13	305	4150.44	1.00	1.00	.90	.60	.00	.00
14	310	4307.24	1.00	1.00	.90	.70	.00	.00
15	315	4417.03	1.00	1.00	1.00	.70	.00	.00
16	320	4594.69	1.00	1.00	.90	.80	.00	.00
17	325	4692.36	1.00	1.00	1.00	.80	.00	.00
18	330	4849.49	1.00	1.00	.90	.90	.00	.00
19	335	5017.89	1.00	1.00	.70	.50	.30	.00
20	340	5218.36	1.00	1.00	.80	.50	.30	.00
21	345	5389.02	1.00	1.00	.90	.50	.30	.00
22	350	5524.76	1.00	1.00	.80	.60	.30	.00
23	355	5647.64	1.00	1.00	.90	.60	.40	.00
24	360	5751.86	1.00	1.00	.90	.70	.40	.00
25	365	5814.37	1.00	1.00	1.00	.70	.40	.00
26	370	5907.97	1.00	1.00	.90	.80	.40	.00
27	375	5967.55	1.00	1.00	.90	.80	.50	.00
28	380	6015.81	1.00	1.00	.90	.90	.50	.00
29	385	6050.63	1.00	1.00	.90	.70	.60	.00
30	390	6072.88	1.00	1.00	.90	1.00	.50	.00
31	395	6081.60	1.00	1.00	.90	1.00	.60	.00

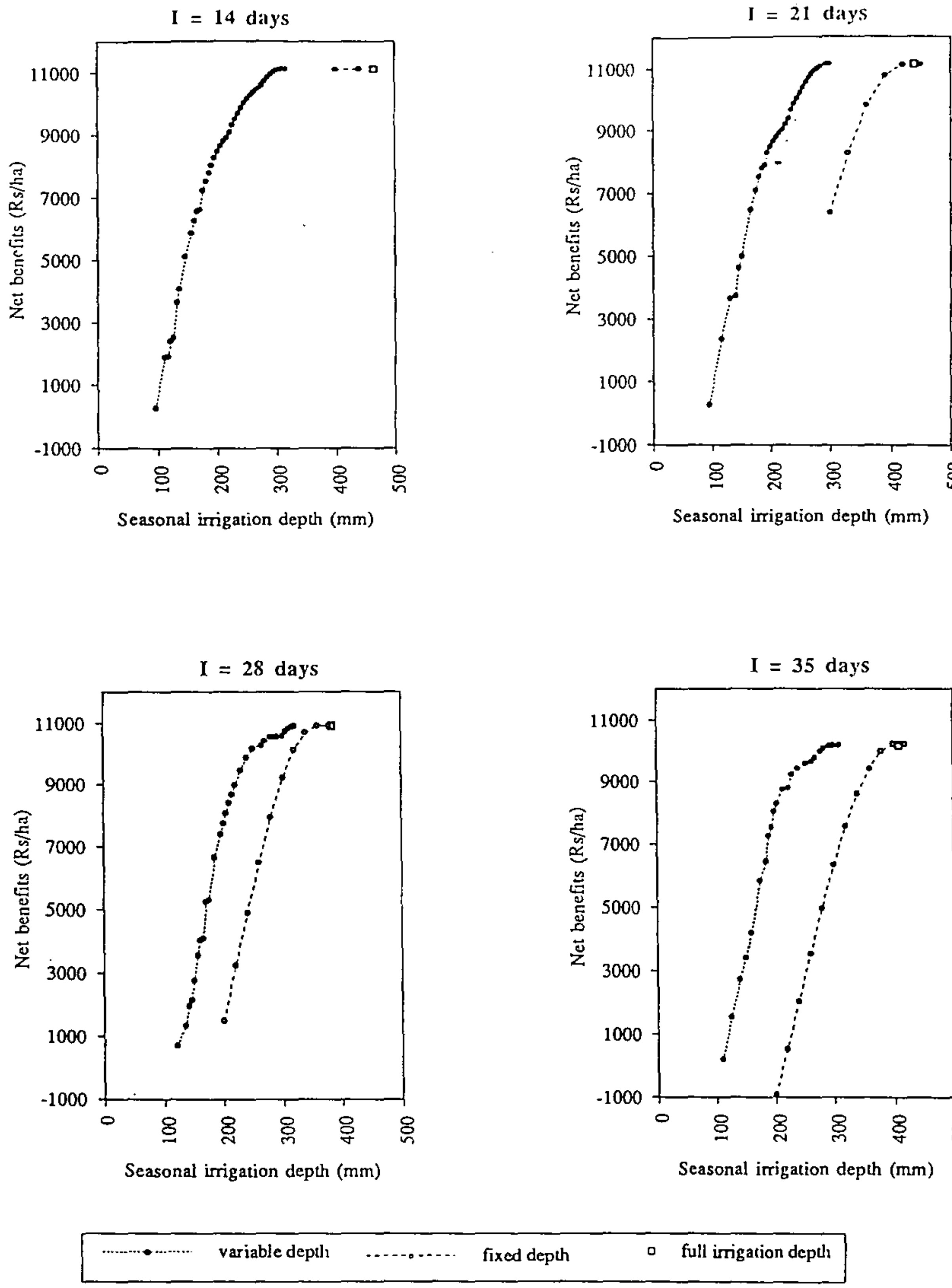


Figure 8.6 Seasonal irrigation depth and net benefits for gram by variable depth, fixed depth and full irrigation depth approaches

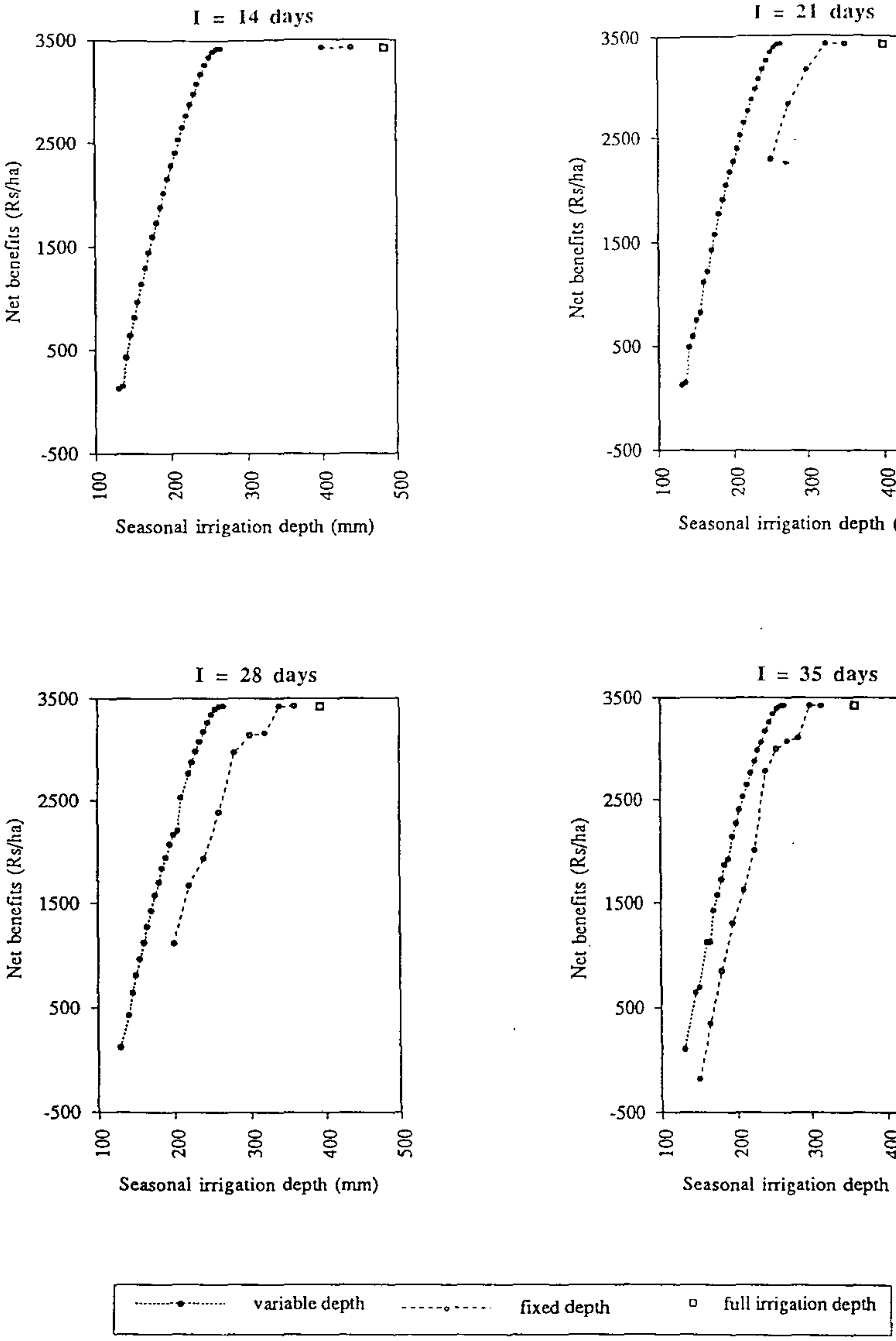


Figure 8.7 Seasonal irrigation depth and net benefits for sorghum by variable depth, fixed depth and full irrigation depth approaches

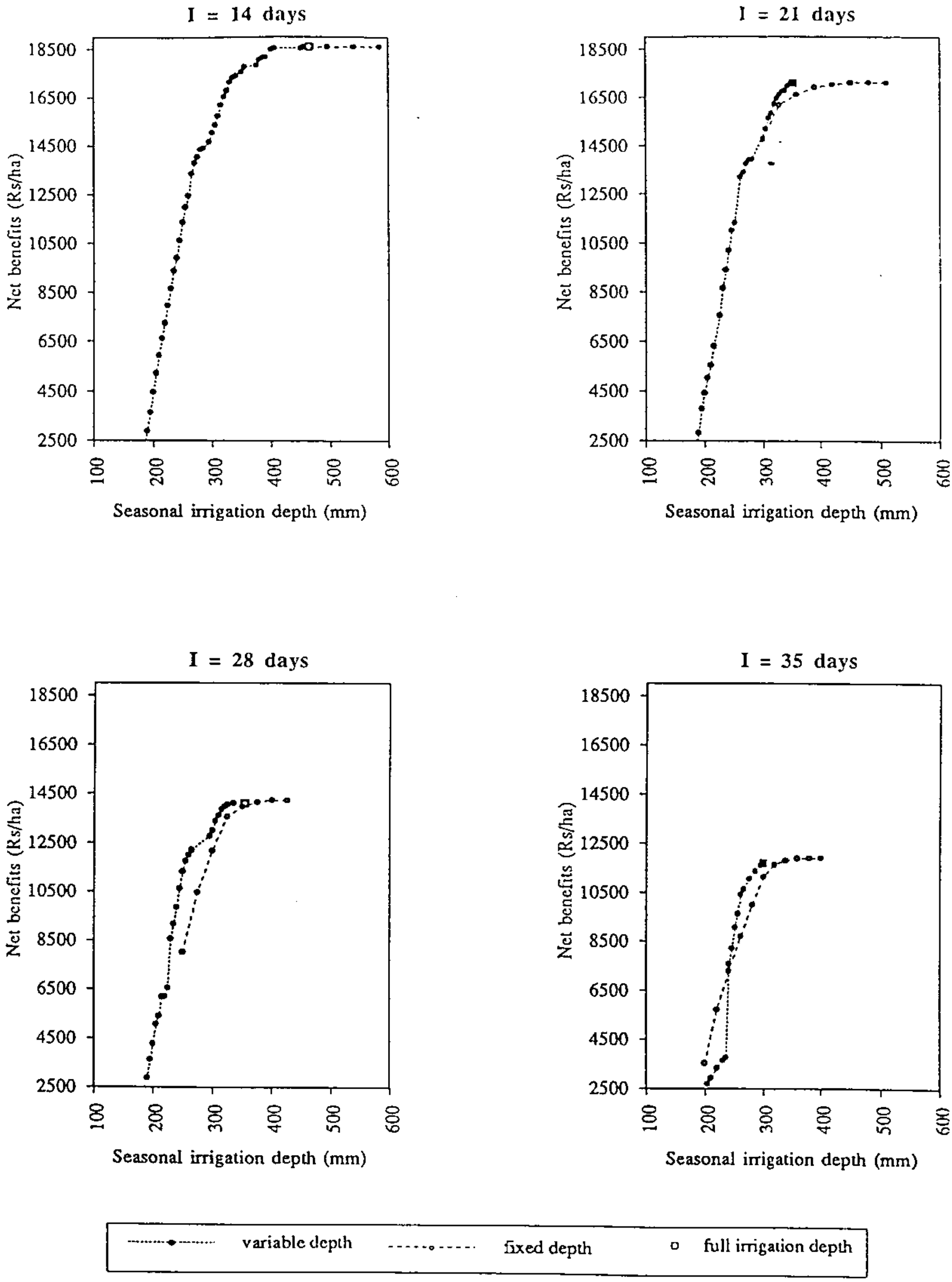


Figure 8.8 Seasonal irrigation depth and net benefits for onion by variable depth, fixed depth and full irrigation depth approaches

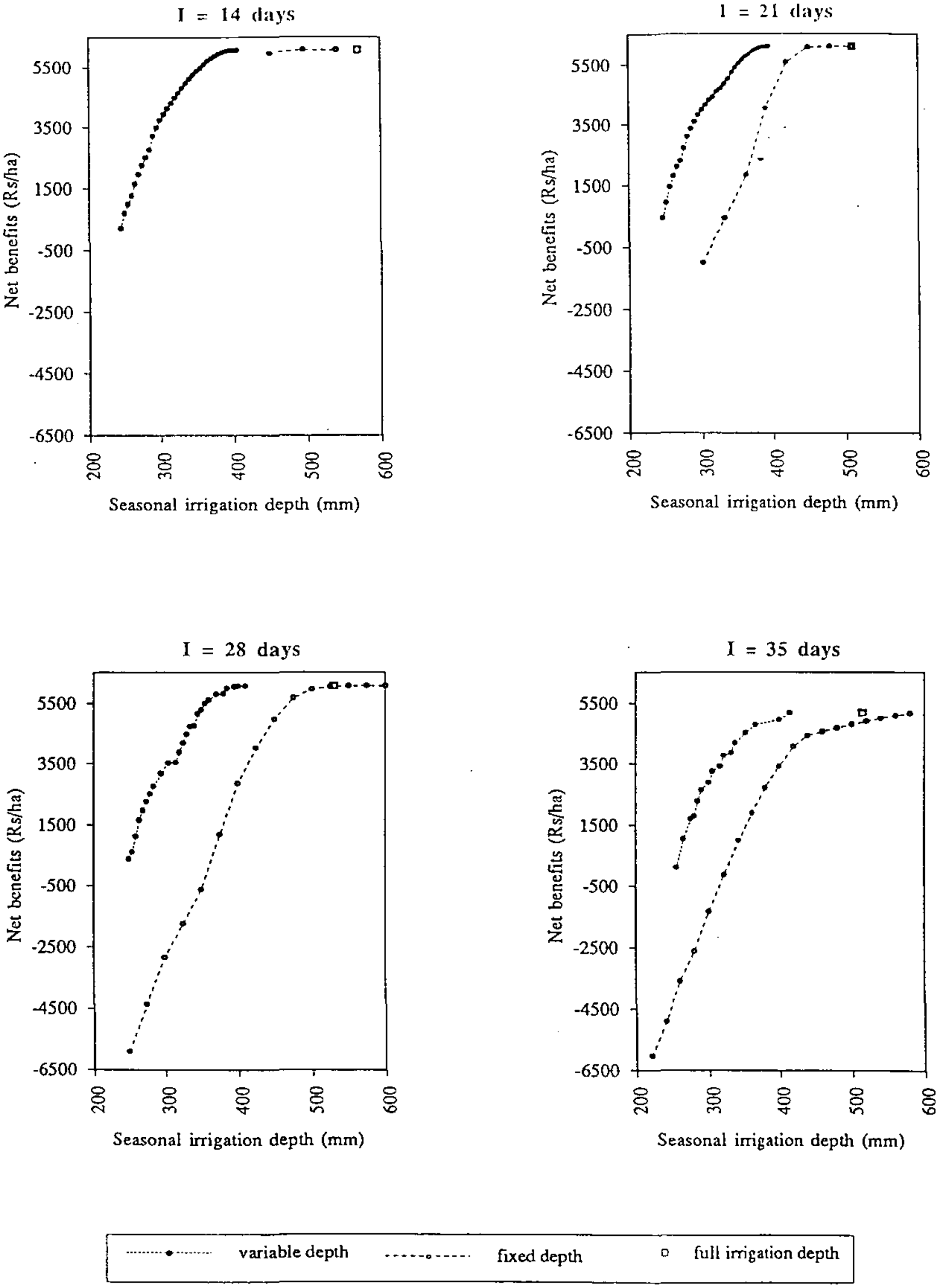


Figure 8.9 Seasonal irrigation depth and net benefits for wheat by variable depth, fixed depth and full irrigation depth approaches

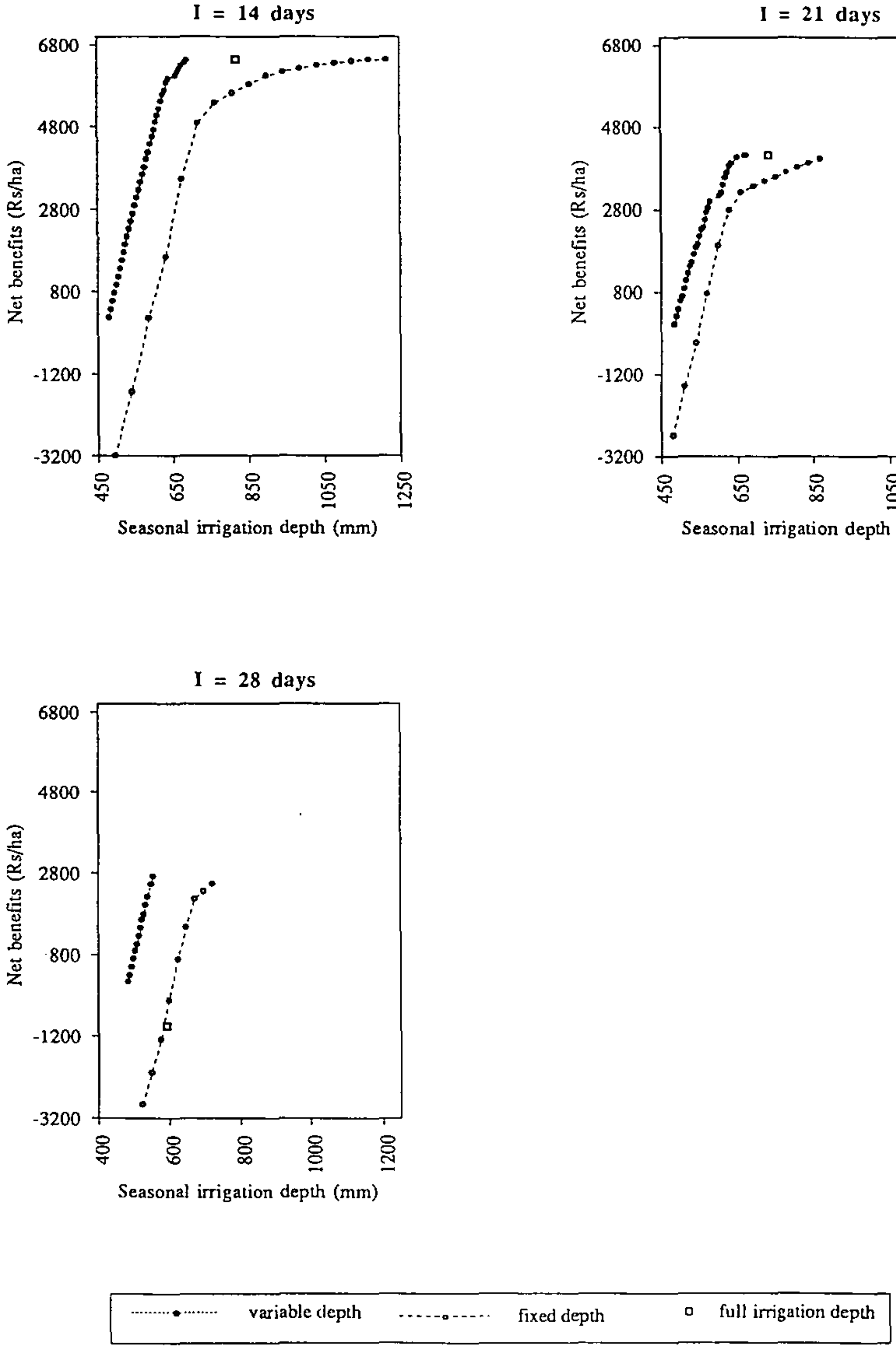


Figure 8.10 Seasonal irrigation depth and net benefits for sunflower by variable depth, fixed depth and full irrigation depth approaches

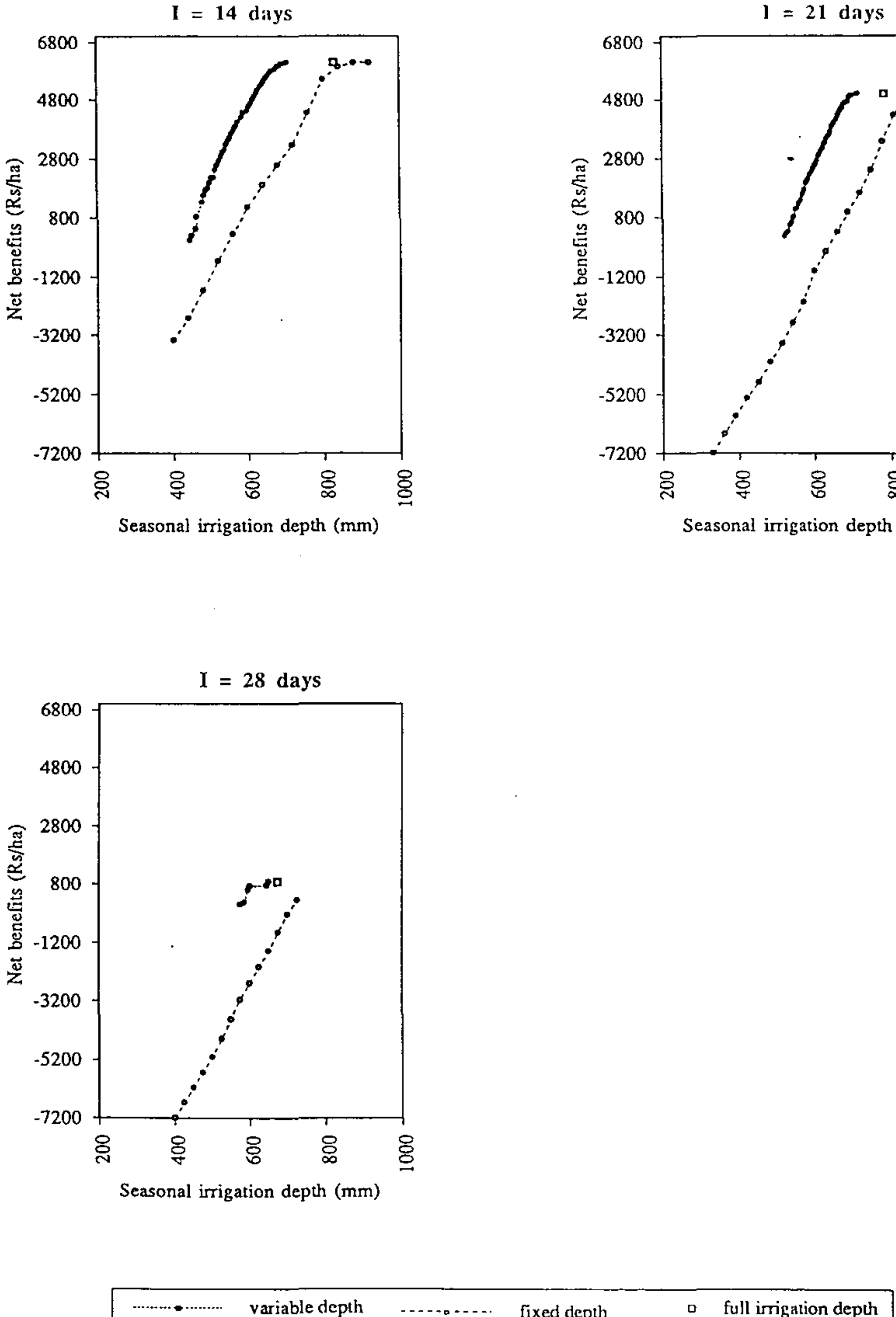


Figure 8.11 Seasonal irrigation depth and net benefits for groundnut by variable depth, fixed depth and full irrigation depth approaches

is more for a small irrigation interval and less for a large irrigation interval. This is because irrigations can be skipped in variable irrigation depth. Thus irrigations can be prolonged at certain crop growth stages when the irrigation interval is small, to obtain maximum benefits. However the difference is small with large irrigation intervals as the irrigations are prolonged any way.

The above discussion indicates that the variable irrigation depth is beneficial over full irrigation or fixed irrigation depths even when the water is not scarce or the maximum crop yields need to be obtained. When water is not scarce, there will be some saving in the cost of application of water (labour or energy) with variable irrigation depth (in the present analysis uniform cost of water application is considered irrespective of amount and number of irrigations). When water is scarce the additional benefits may be obtained by spreading the water over the large area, instead of applying full irrigation or fixed depth irrigation to obtain maximum crop yield or benefits over less area. The present work is based on investigating the influence of deficit irrigation in a water scarce area. Therefore more emphasis is given on the latter aspect (when water is scarce). As the irrigation scheme under consideration presently charges for the water on the basis of area irrigated rather than volume used and that to these are little, the former aspect (water is not scarce) is not investigated. But the comment can be added that the there will be saving in labour and energy utilisation (English and Nuss, 1982; Hargreaves and Samani, 1984 and English et al., 1990) but also adding to the operational difficulties in applying variable irrigation depth.

8.3 EFFECT OF DEFICIT IRRIGATION

In the previous section, the means to cause the deficit irrigation were discussed and based on these means a variable irrigation depth approach was suggested. The variable irrigation depth which systematically sequences the application of water when it is scarce over the different crop growth stages to economise the use of water is considered more beneficial over fixed and full irrigation depths. In this section an attempt is made to test whether deficit irrigation is beneficial over adequate irrigation for the entire irrigation scheme when water is scarce. This is the subject of Hypothesis 2. The variable irrigation, fixed irrigation and full irrigation depths are also compared in context of the entire irrigation scheme.

The reservoir was assumed to be at its full capacity at the beginning of the irrigation season (15^{th} October). The climatological data of the year 1991-92 was used. The water required for other purposes was diverted according to the scheduled requirements (see

Section 7.5.3.4). To isolate and study the effect of deficit irrigation and various irrigation depths, the analysis was done by considering that only one crop is grown in the irrigation scheme. As there are different soils in the irrigation scheme, the allocation is affected by the soil type. Therefore the water was allocated to each soil group in proportion to the area of the respective soil group. This was done to ensure that nearly the same amount of water is allocated in different situations of irrigation to particular soil group, which is needed for comparing these situations.

The total net benefits were obtained for each crop, irrigation interval and different approaches of applying water (in variable depth, fixed depth and full depth) using the AWAM in 'Generation of Irrigation Programme Mode' and 'Optimisation Mode' together. The data described in the Section 7.5 was used. The total net benefits for each soil group were obtained from these results. To study the effect of deficit irrigation, the net benefits were obtained for two different situations for fixed and variable irrigation depths. In one situation the total net benefits were obtained with the irrigation strategy or fixed depth (subsequently this is just referred to as irrigation strategy) which cause the minimum stress. In fact the intention was to obtain the results with the irrigation strategy with no stress. But as some irrigation intervals could not produce adequate irrigation with any amount of irrigation depth, the results with minimum stress were obtained. This is referred to as irrigation strategy with minimum stress. In another situation the irrigation strategies which give maximum total net benefits are obtained. These are referred to as the optimised irrigation strategies. Thus for a particular irrigation interval if the total net benefits are the same with the irrigation strategy with minimum stress and with the optimised irrigation strategies, and if the irrigation strategy with minimum stress is the irrigation strategy causing no stress, the deficit irrigation is not beneficial and vice versa. The deficit irrigation and adequate irrigation for different crops are compared below. The soil type selected for comparison is SG-2.

8.3.1 Gram

The irrigation interval = 21 days is the adequate irrigation interval for gram. Therefore the irrigation strategy with minimum stress for this irrigation interval represents the case of adequate irrigation. The results of deficit irrigation and adequate irrigation are shown in Figure 8.12. In case of fixed and full irrigation depths, the net benefits are increased if the irrigation interval is increased to 28 days, but after that (for I = 35 days) the total net benefits are decreased. In the case of variable irrigation depth the total net benefits are decreased beyond the adequate irrigation interval. However as indicated earlier the water delivery interval is not fixed in the variable irrigation depth approach.

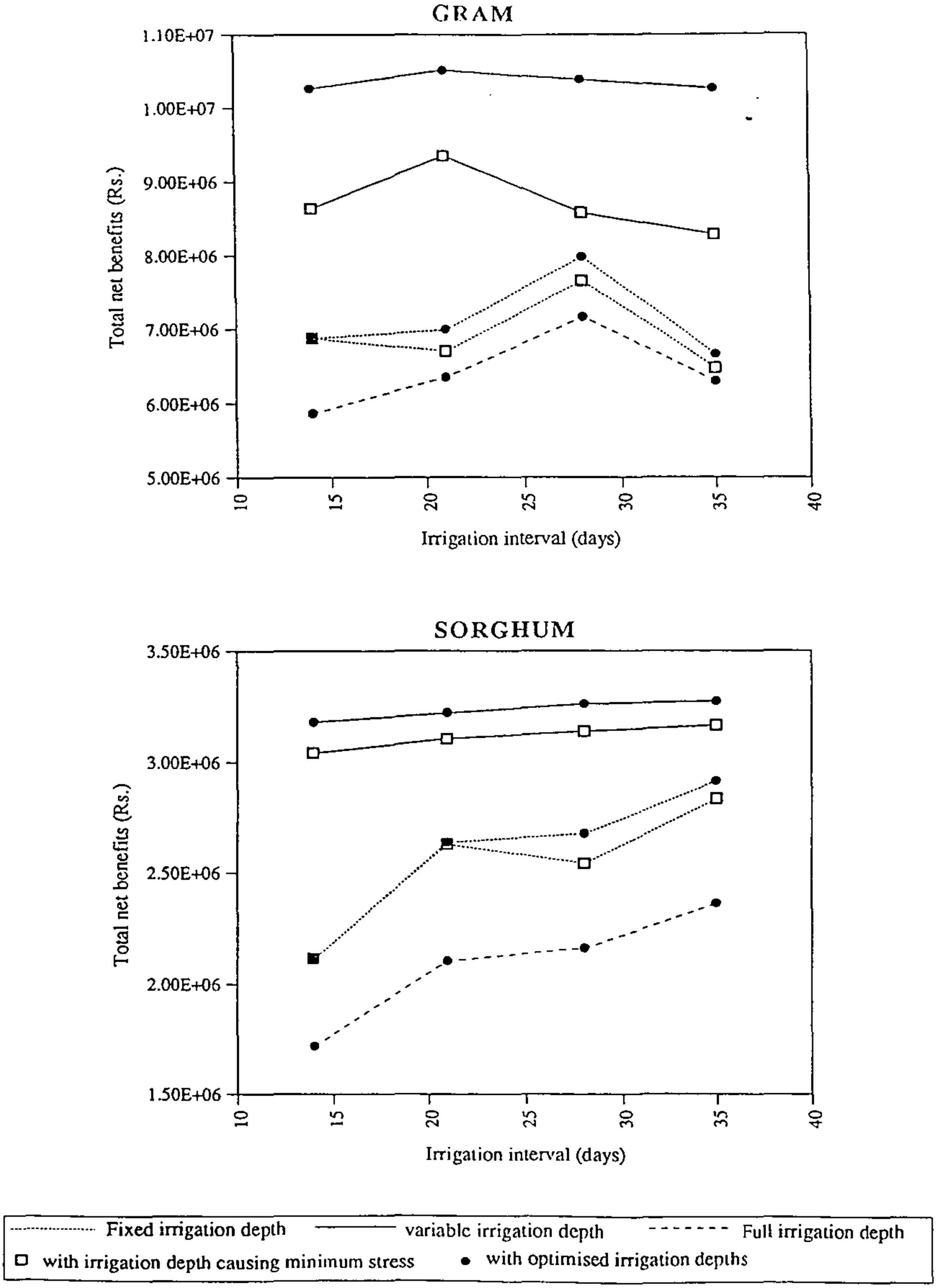


Figure 8.12 Total net benefits for different irrigation intervals for SG-2 obtained by fixed and variable irrigation depths (optimised and with minimum stress) and full irrigation depth for gram and sorghum

The total net benefits from optimised irrigation strategies are more than from the irrigation strategies with minimum stress, for all irrigation intervals (except irrigation interval of 14 days for fixed irrigation depth, where the irrigation strategy contains the irrigation depth equivalent to minimum irrigation depth). The total net benefits with the optimised irrigation strategies are also more than with the adequate irrigation.

8.3.2 Sorghum

In the case of sorghum all irrigation intervals are the adequate irrigation intervals. The total net benefits from optimised irrigation strategies are higher than from irrigation strategies with minimum stress (in this case no stress), except for I = 14 days with fixed irrigation depth where the irrigation strategy contains the irrigation depth which is minimum possible (Figure 8.12).

8.3.3 Onion

None of the studied irrigation intervals is the adequate irrigation interval in the case of onion. So there is no case of adequate irrigation. However in all cases the total net benefits from optimised irrigation strategies are higher than those obtained from the irrigation strategy with minimum stress (Figure 8.13).

8.3.4 Wheat

The I=21 days is the adequate irrigation interval and therefore irrigation strategies with I=21 days represent the adequate irrigation. The results of deficit and adequate irrigation are indicated in Figure 8.13. When the irrigation interval is increased beyond the adequate irrigation interval, the total net benefits are decreased. Higher total net benefits are obtained from the optimised irrigation strategies than from those with minimum stress. All the cases of deficit irrigation were found not beneficial over the adequate irrigation. If irrigation interval is increased beyond the adequate irrigation, the deficit irrigation was not beneficial over the adequate irrigation.

8.3.5 Sunflower

From the range under consideration, there is no adequate irrigation interval for sunflower. The total net benefits were found to decrease with irrigation interval. Nearly

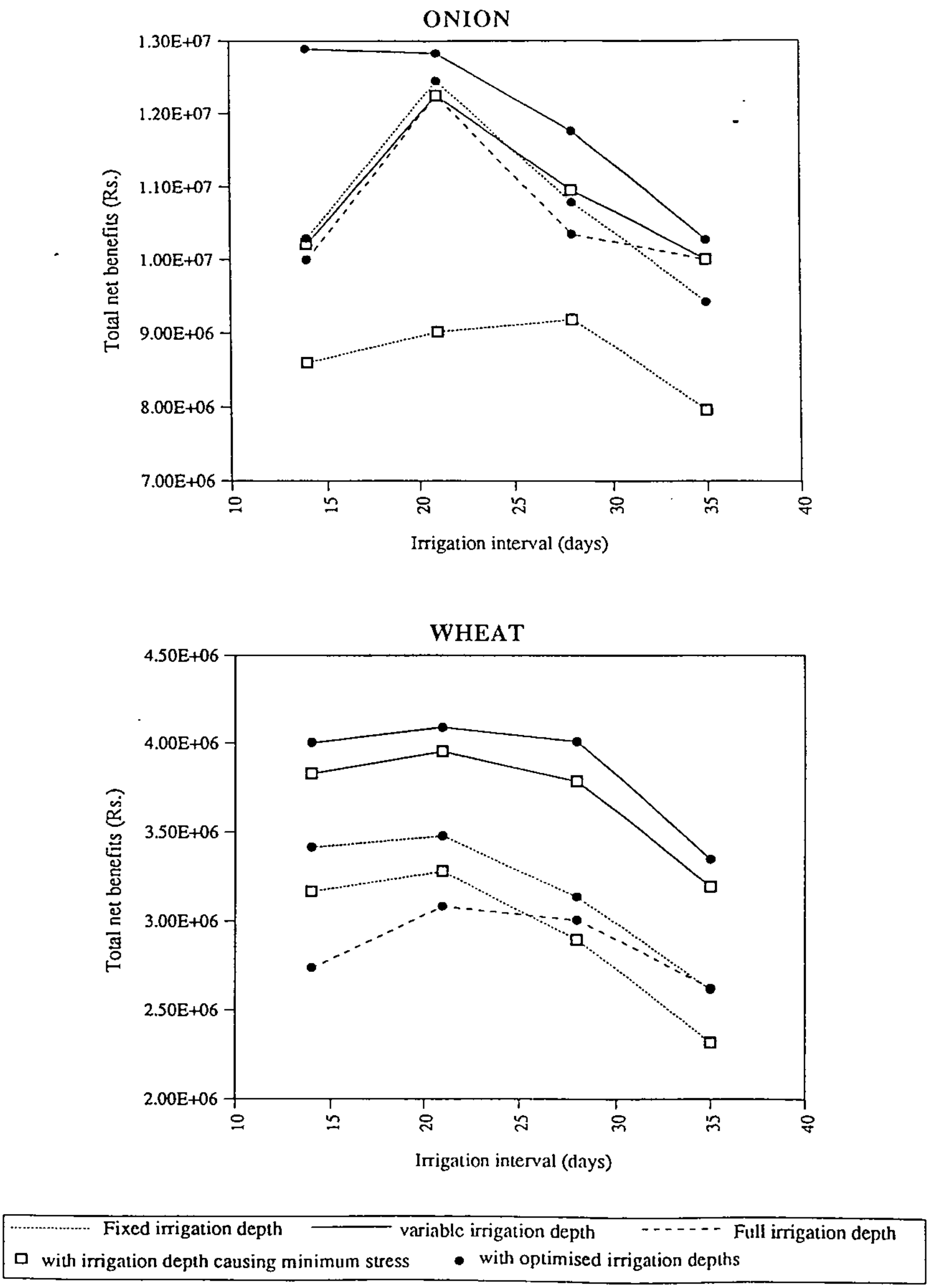


Figure 8.13 Total net benefits for different irrigation intervals for SG-2 obtained by fixed and variable irrigation depths (optimised and with minimum stress) and full irrigation depth for onion and wheat

the same total net benefits were found from the optimised irrigation strategies and from the irrigation strategies with the minimum stress (Figure 8.14).

8.3.6 Groundnut

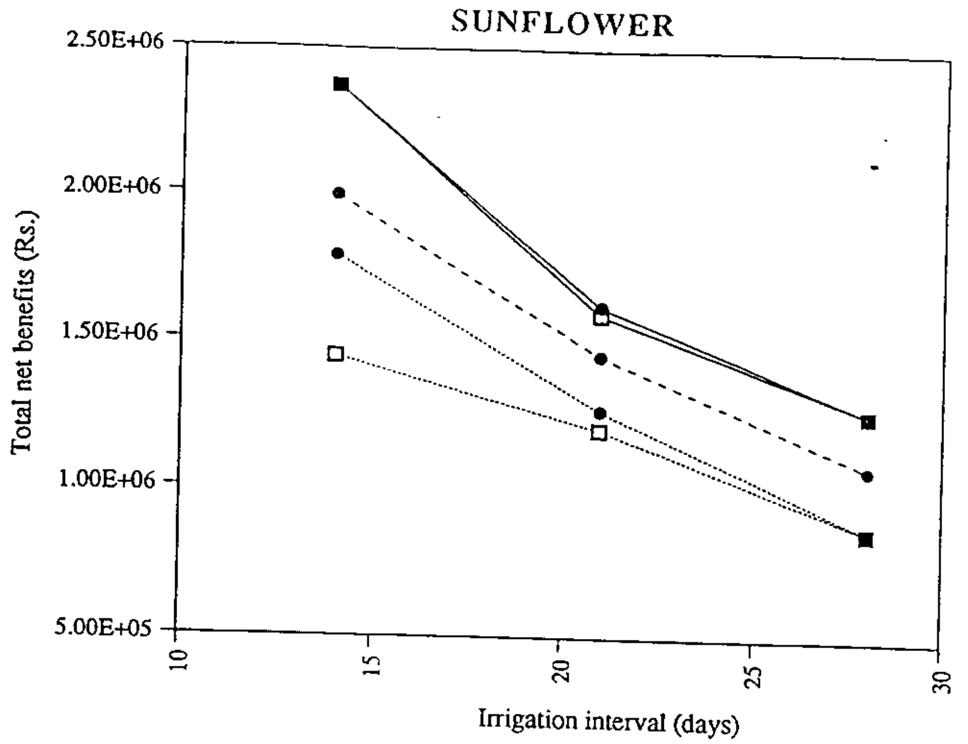
The results similar to sunflower are obtained for the groundnut. These are shown in Figure 8.14.

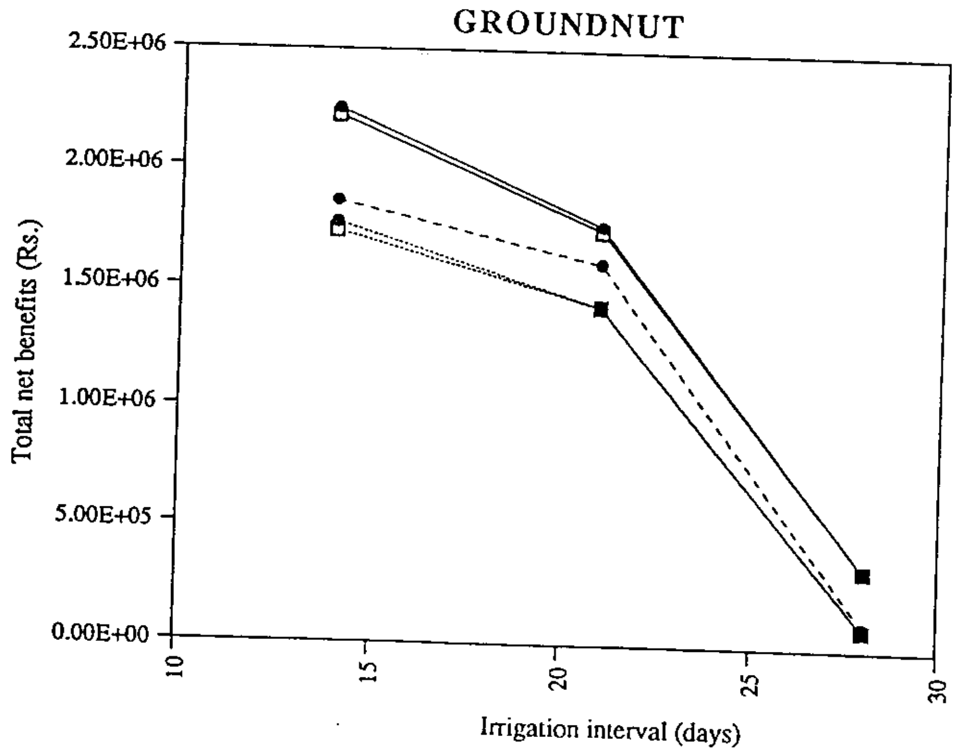
The above results indicate that the deficit caused due to prolonging the irrigation interval is not always beneficial. However the deficit in irrigation depth is mostly beneficial. This shows that the deficit caused due to application of irrigation depth smaller than those needed for full irrigation is the factor which makes deficit irrigation beneficial. Thus practising Approach-2 can prove beneficial over adequate irrigation. However Approach-1 and Approach-3 may or may not prove beneficial. Thus the Hypothesis 2 is partly verified. Thus the variable irrigation depth approach which is mostly based on the Approach-2 proves to be beneficial.

8.4 COMPARISON OF VARIABLE, FIXED AND FULL IRRIGATION DEPTHS OVER ENTIRE IRRIGATION SCHEME

The Figures 8.12, 8.13 and 8.14 indicate that the total net benefits are always more with variable irrigation depth than fixed and full irrigation depths. The results presented in these figures are obtained with only one soil group under consideration i.e. SG-2 with CCA of 1178 ha. (refer Section 8.3). The total net benefits with variable irrigation depth are more by 23 to 35, 11 to 33, 8 to 20, 14 to 22, 20 to 32 and 20 to 74% over fixed irrigation depth and by 30 to 43, 27 to 46, 2 to 23, 21 to 32, 10 to 16 and 8 to 18% over full irrigation depth for gram, sorghum, onion, wheat, sunflower and groundnut, respectively. Thus the variable irrigation depth suggested in this study is more appropriate over the full irrigation depth which is adopted in many previous studies (refer Section 2.4.1) and also over the fixed irrigation depth which is presently being practised in many irrigation schemes in semiarid regions of India for its operational conveniency. These results are for SG-2 and for year 1991-92 with the reservoir initially at its full capacity. However the similar results are also obtained with other soils, climatalogical years and different initial reservoir storage volumes.

The total net benefits form the entire irrigation scheme with CCA=3539 ha. is also obtained. Thus this includes all the soil groups in the allocation process but the actual allocation is done depending on the optimum use of the resources. The total net benefits





------ Fixed irrigation depth —— variable irrigation depth - - - - Full irrigation depth
□ with irrigation depth causing minimum stress • with optimised irrigation depths

Figure 8.14 Total net benefits for different irrigation intervals for SG-2 obtained by fixed and variable irrigation depths (optimised and with minimum stress) and full irrigation depth for sunflower and groundnut obtained for the entire irrigation scheme are presented in Figures 8.15, 8.16 and 8.17. The total net benefits with variable irrigation depth are more by 17 to 29, 9 to 30, 2 to 16, 12 to 22, 19 to 27 and 20 to 45% over fixed irrigation depth and by 24 to 36, 26 to 39, 0.4 to 18, 16 to 29, 11 to 17 and 3 to 17% over full irrigation depth for gram, sorghum, onion, wheat, sunflower and groundnut, respectively. These figures indicate that higher total net benefits are obtained with the variable irrigation depth compared to fixed and full irrigation depth. In general higher net benefits are obtained with fixed irrigation depth than full irrigation depth. The reason is with fixed irrigation depth the deficit irrigation could be followed due to application of smaller irrigation depth (fixed) however in full irrigation, the deficit was exerted only because of prolonging the irrigation interval beyond the adequate irrigation interval.

8.5 CONCLUSIONS

In this chapter the means to cause deficit irrigation and effect of deficit irrigation on the total output from the irrigation scheme were investigated with the methodology developed in Chapters III to V. It was revealed from the study that prolonging the interval between two irrigations and/or applying water less than needed for full irrigation results in deficit irrigation. The deficit irrigation influenced crop yield and water consumption (Section 8.2). Thus the results obtained in Section 8.2 verified the Hypothesis 1.

Based on this the application of water in variable irrigation depth was suggested. The results in Section 8.3 indicate that the deficit irrigation is more beneficial over the entire irrigation scheme when water is scarce than adequate irrigation or irrigation with minimum stress. This verified the Hypothesis 3. However deficit caused due to application of less depth was more beneficial than extending the irrigation interval. The application of water in variable irrigation depth gave higher net benefits over the application of water in full irrigation and fixed irrigation depths. However application of variable irrigation depths when compared to fixed irrigation depths, will require greater control and improved management in the irrigation scheme. The additional cost of these requirements could not be considered in this study.

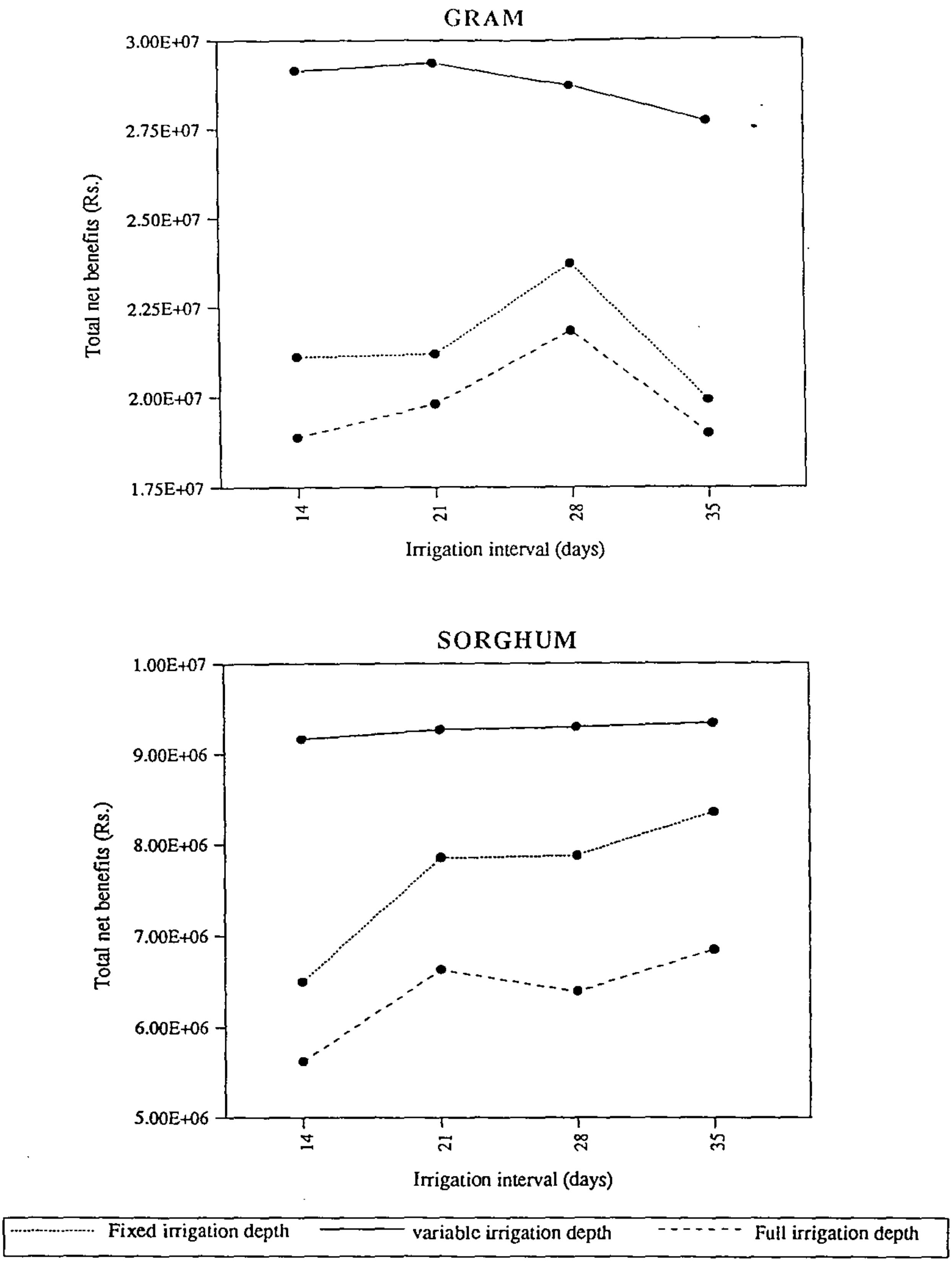
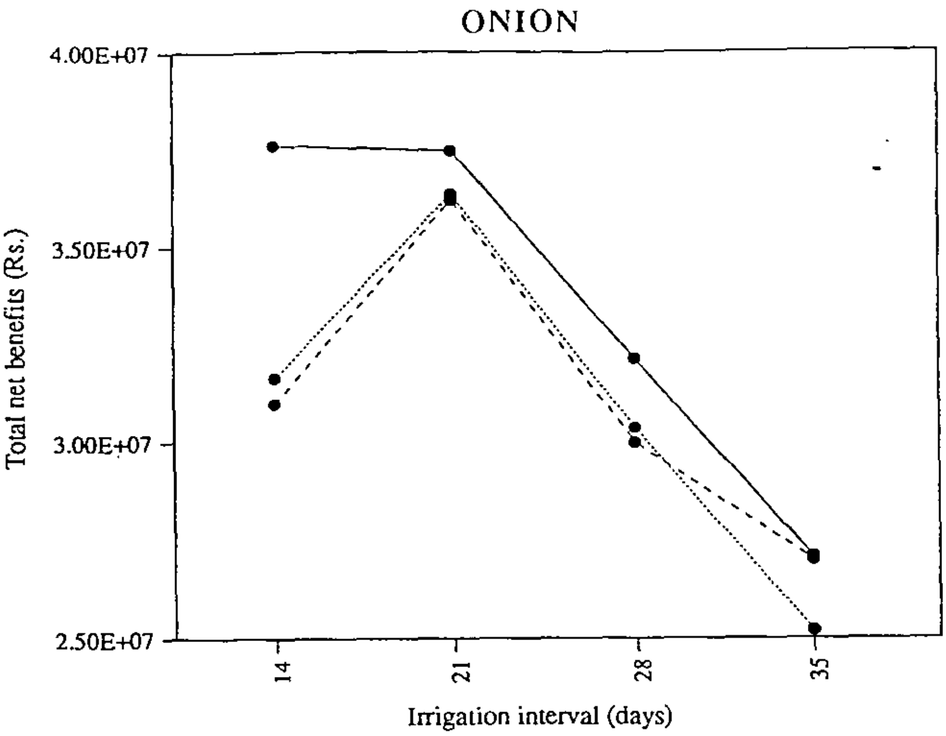


Figure 8.15 Total net benefits for different irrigation intervals obtained for entire irrigation scheme by fixed, variable and full irrigation depths for gram and sorghum



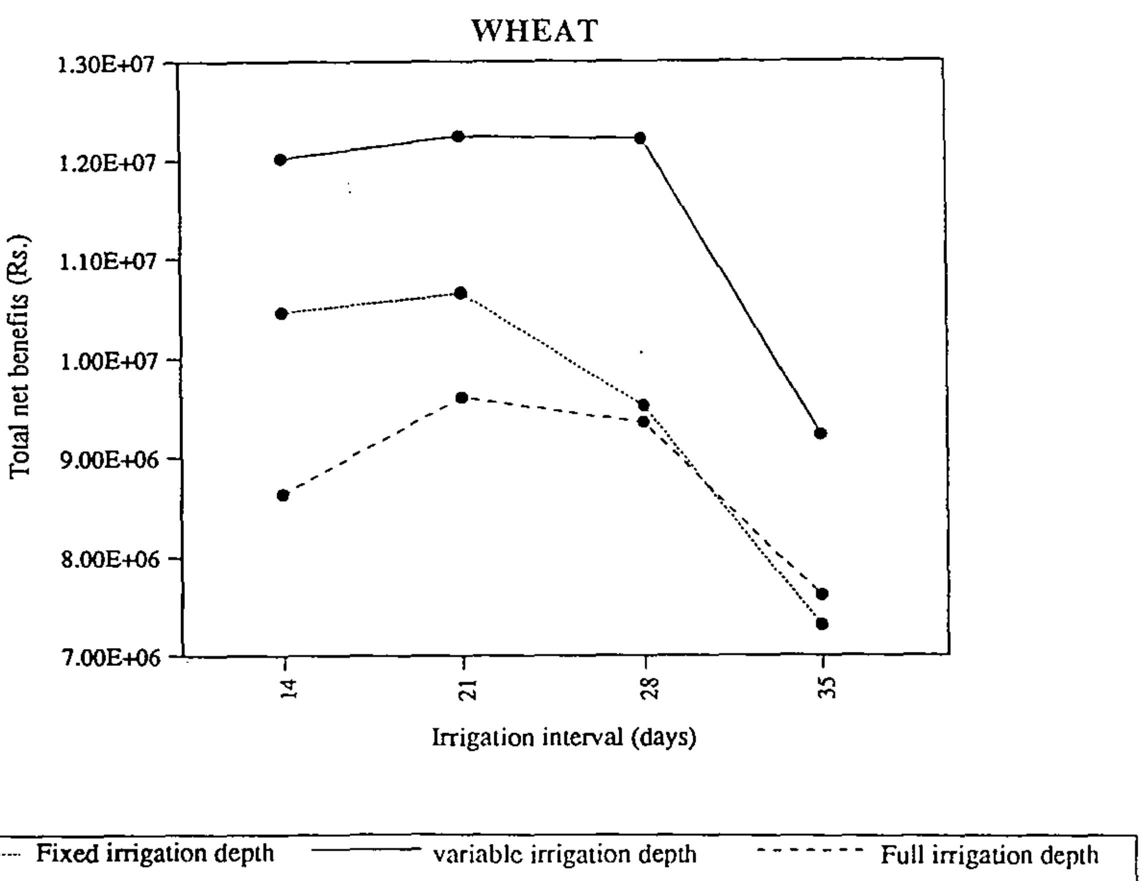


Figure 8.16 Total net benefits for different irrigation intervals obtained for entire irrigation scheme by fixed, variable and full irrigation depths for onion and wheat

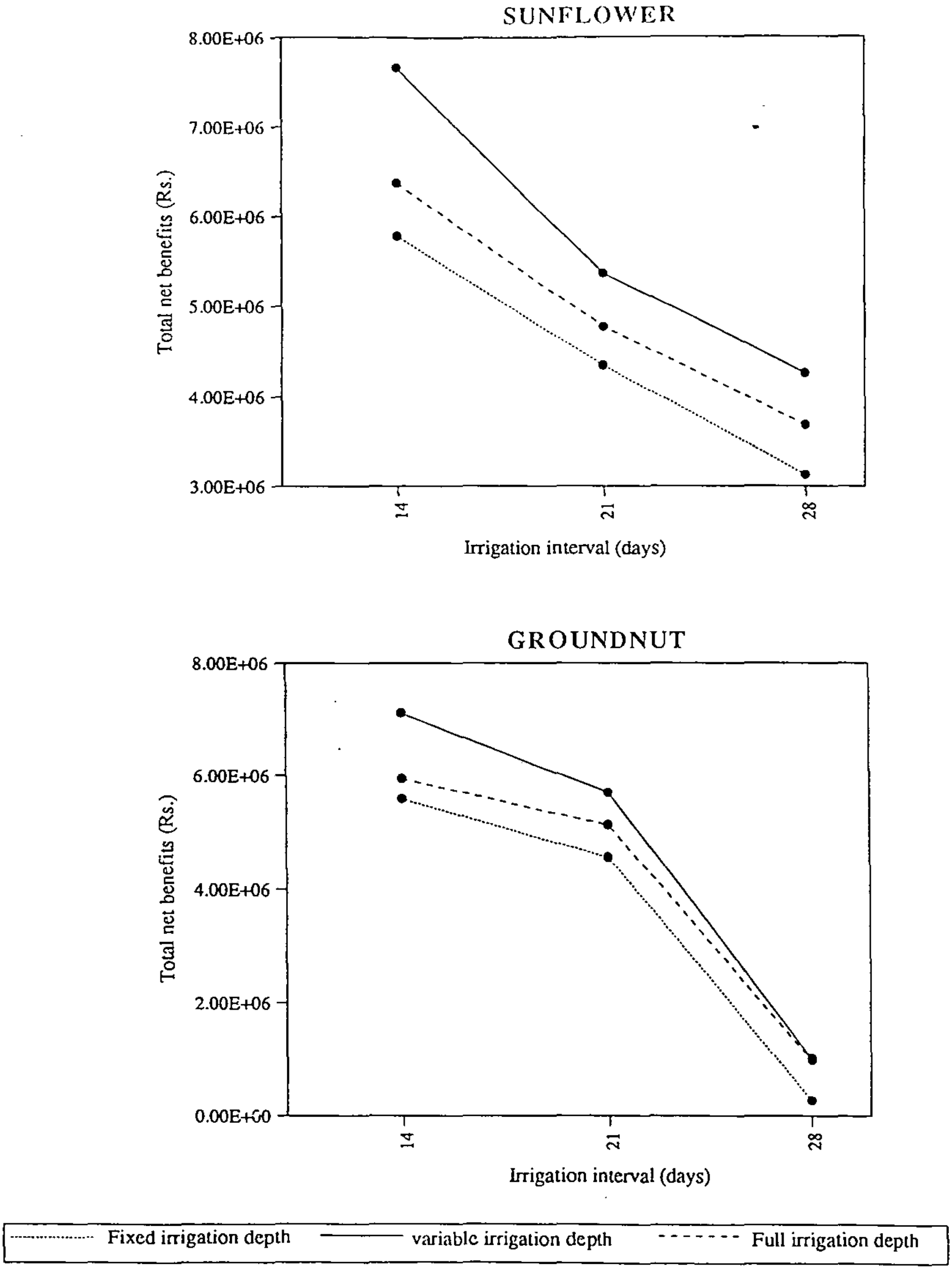


Figure 8.17 Total net benefits for different irrigation intervals obtained for entire irrigation scheme by fixed, variable and full irrigation depths for sunflower and groundnut

CHAPTER IX

ALLOCATION PLANS AT PLANNING STAGE WITH AWAM

Summary. In this chapter part of Hypothesis 3 is verified, that is the concept of deficit irrigation can be included in the computer model while obtaining the allocation plans at the planning stage. Using the case study irrigation scheme, the variable depth irrigation with deficit irrigation is compared with the other approaches (fixed depth and full depth irrigation approaches). The results are obtained by varying and considering several parameters (crop, soil type, reservoir capacity, irrigation interval, irrigation efficiencies and canal and outlet capacities) which are encountered in the irrigation scheme. The computer model developed could be used to prepare the allocation plans with deficit irrigation.

9.1 INTRODUCTION

The means to cause the deficit and their influence on the output (Hypothesis 1 and Hypothesis 2) were discussed in Chapter VIII. The application of water in variable depths at different irrigations over the crop season and skip application (or zero irrigation depth) i.e. Variable Depth Irrigation (VDI) was suggested based on the results of these hypotheses. The VDI approach was found more beneficial over traditional Fixed Depth Irrigation (FXDI) and Full Depth Irrigation (FLDI) approaches. In certain cases, for some sets of irrigation intervals, the VDI approach was found beneficial over VDI with minimum stress (VDI(MS)).

The efficient utilisation of water at scheme level calls for the optimum allocation of land and water resources to different crops at the planning and operational stages, with consideration to different physical constraints and resources restrictions and requirements. The deficit irrigation which is envisaged as beneficial , therefore, needs to be incorporated in the process of allocation of resources at planning and operation stages. This was effected by constructing the simulation-optimisation type model, AWAM, with the inclusion of the deficit irrigation through variable depth irrigation approach. The model is described in Chapters IV to VI. In this chapter, the AWAM is tested for Nazare Medium Irrigation Project for verifying that the concept of deficit irrigation can be included in a computer model for the allocation of resources at the planning stage. This is part of Hypothesis 3. The remaining part i.e. to verify the inclusion of deficit irrigation for allocation of resources at operational stage is not actually tested but discussed in Chapter X. The VDI approach is also compared with FXDI and FLDI at appropriate places. The VDI has already been compared with FXDI and FLDI for the single crop case in Chapter VIII but in this chapter the comparison is made with considerations to all the crops. The inclusion of deficit irrigation (through VDI approach) for allocation of resources is tested with different parameters which influence the allocation and their effect on the allocation. The parameters discussed are initial reservoir storage volume, irrigation interval, soil type, cropping distribution, food requirement, application, distribution and conveyance efficiencies and outlet and canal capacities.

The AWAM in generation mode, optimisation mode and planning mode was used to obtain the results. In the first part of the chapter these parameters are discussed and in the second part the results obtained with these parameters are presented.

9.2 THE PARAMETERS

This section describes the range of values of different parameters and how these were included while obtaining the results.

9.2.1 Irrigation Interval

The interval between irrigations distinguishes between adequate and deficit irrigation (Hypothesis 1). As described earlier, the model operates on a uniform irrigation interval for all regions, crops and soils during each particular stage in the planning period. However these intervals can be varied over the planning period or irrigation season. But these are known or decided before obtaining the allocation plan for the planning. In fact the allocation plans are obtained for the particular known set of irrigation intervals. The water delivery interval which is different than irrigation interval in case of VDI approach (due to skipping of irrigation) might be different for different regions, soils and crops but only by addition of consecutive irrigation intervals. The water delivery intervals are the results of optimum allocation. The following sets of irrigation interval are chosen for this study.

1. 14 days
2. 21 days
3. 28 days
4. 35 days
5 21 days in winter season and 14 days in summer season (21-14 days)
6. 28 days in winter season and 21 days in summer season (28-21 days)

7. 35 days in winter season and 28 days in summer season (35-28 days)

9.2.2 Initial Reservoir Storage Volume

In this study the planning period is considered to be comprised of winter and summer seasons. As discussed earlier the remaining season i.e. rainy season receives most of the rainfall and therefore the irrigations are required in protective forms during this season. As most of the inflow to the reservoir is also received in rainy season, the water available in the reservoir during the planning period is fairly predictable. In the present study the results are obtained for the various known initial reservoir storage volumes in terms of water available in reservoir at the start of planning period (winter season) in percentages of maximum utilisable capacity of the reservoir (the difference between the maximum storage capacity and dead storage capacity). The percentages chosen are from 100 to 10% at an interval of 10%. The water required for other purposes are assumed to be the same for all the levels of reservoir capacities.

9.2.3 Soil Types

The four soils existing in the command and as described in Chapter VII (Section 7.5.5) are considered. These are referred as SG-1, SG-2, SG-3 and SG-4.

9.2.4 Cropping Distributions

The following two options of cropping distributions are considered. These are
1. Free cropping distribution and
2. Fixed cropping distribution

1. Free cropping distribution: In this cropping distribution no restrictions are put on the allocation of area or water or output to be obtained from the different crops. The model is therefore free to select any crops depending on which crops produce maximum total net benefits from the irrigation scheme.

2. Fixed cropping distribution: In the allocation plan of free cropping distribution, only those crops which contribute towards obtaining maximum total net benefits appear. Often the crops appearing in the solution may be few or some times just one. However obtaining maximum total net benefits irrespective of irrigation to any crops may not be the only objective. The restrictions on area or water to be allocated or production to be obtained depending on several requirements in the scheme might also be the influential

factors. In such cases the restrictions on the area to be irrigated, water to be allocated or the level of production to be obtained from the different crops are put. The model then selects the area under different crops according to these restrictions while obtaining the maximum total net benefits from the scheme. Restricting the area under different crops according to particular requirement is referred to as the fixed cropping distribution.

In this chapter the results are obtained for free cropping distribution and one particular fixed cropping distribution. The fixed cropping distribution is selected to bring all the crops in the solution so that the influence of other parameters and various irrigation depth approaches can be studied with all selected crops being irrigated rather than only one or two. The selected fixed cropping distribution is restricting the area under different crops in a certain range at scheme level. The ranges for different crops are given on Chapter VII (Section 7.5.8).

9.2.5 Food Requirements

The farmers in the irrigation scheme quite often like to select the cropping distribution which tends to give first preference to satisfying the food requirement of their family and then obtaining maximum monetary returns. The farmers may adjust some of their food requirement during the rainy season. Some of the food requirements (for the crops which are not grown in rainy season) is expected to be adjusted by cultivating and irrigating these crops with the help of ground water in winter and summer season. Of course it is recognised that each farmer in the irrigation scheme may not have the ground water lifting facilities. Thus the irrigation authority has to try to produce the cropping pattern which helps to adjust the remaining food requirements.

The AWAM has the provision to produce the allocation plan for satisfying the food requirement according to specific needs at scheme or AU level. In the present study no specific data could be made available on the food requirements of the farmers or inhabitants depending on the irrigation scheme. But to demonstrate the utility of the model by considering deficit irrigation in this regard and explain the effect of considering food requirement on the total net benefits, it is assumed that the food requirement is equivalent to the crop production calculated from the minimum value of range of area specified for particular crop of the total area that can be irrigated with the existing rule multiplied by the crop yield per unit area obtained with the existing rule. The AWAM is run for the existing rule to simulate the crop yield and irrigation water requirement and compute the maximum area that can be irrigated with the initial reservoir storage volume as 100% of maximum utilisable capacity of the reservoir and minimum and maximum ranges of area in terms of percentage of total area that can be irrigated for each crop.

The minimum production to be obtained for different crops at scheme level with this assumption area given below.

1. Gram : 377 t
2. Sorghum : 1231 t
3. Onion :2134 t
4. Wheat :499 t
5. Sunflower :116 t
6. Groundnut :459 t

9.2.6 Application, Distribution and Conveyance Efficiencies

In AWAM, the application, distribution and conveyance efficiencies are considered separately. The application efficiency can be varied with the CSR unit and distribution and conveyance efficiencies can be varied with the AU units in the model. In this chapter the influence of varying each efficiency on the total net benefits and the allocation plan is discussed. While obtaining the results for the variation of one efficiency, other efficiencies are considered as constant and the values are assumed as those described in Chapter VII (Sections 7.5.3.2, 7.5.3.3 and 7.5.7).

The application efficiencies in this study are assumed the same for all CSR units, at 0.75. The other values considered for comparing the results are 0.65, 0.70, 0.80 and 0.85. The distribution efficiency is assumed as 86.5% in this study. For comparing the results, these are varied by 5% and 10 % on either side of assumed efficiency. The conveyance efficiency is assumed as 98% per 1000m. It was varied by 1% and 2% on either side for studying the influence of varying the conveyance efficiency on the total net benefits.

9.2.7 Canal and Outlet Capacities

The results are obtained with and without restrictions on canal and outlet capacities for discussing the role of capacity of the canal network in deciding the allocation plans.

9.2.8 Various Irrigation Depth Approaches

The results are obtained with variable depth irrigation (VDI), fixed depth irrigation (FXDI) and full depth irrigation (FLDI) approaches. The VDI which is the result of application of deficit irrigation is included in the model through the irrigation strategy generator (Section 5.2.3). The optimisation model (Section 6.3) selects those combination or combinations of variable depths for different CS units of AUs, which are beneficial in view of the entire irrigation scheme. Results are also obtained with the variable depth which causes minimum stress for different CS units of AUs. This approach is referred as VDI with Minimum Stress (VDI(MS)). This is particularly important for comparing the deficit irrigation with the adequate irrigation when the irrigation interval is small. Adequate irrigation was not possible for all crops with the chosen sets of irrigation intervals, but the results with VDI(MS) are considered close to the adequate irrigation.

By fixed depth irrigation (FXDI) approach water is delivered in fixed depth at every irrigation irrespective of CSR unit and the event of irrigation during the planning period. The range of fixed depth considered is from minimum possible irrigation depth (50 mm) to maximum possible irrigation depth (150 mm). The fixed depths are varied in this range by 5 mm. The model was run for each fixed depth separately and the fixed depth which produced maximum total net benefits was considered as the appropriate or optimum fixed depth and the results with this fixed depth are compared with other approaches. In full depth irrigation approach, the full irrigation is applied to each CSR unit.

9.3 THE ALLOCATION RESULTS

This section describes the results of allocation for different parameters.

9.3.1 Initial Reservoir Storage Volume, Cropping Distribution, Irrigation Depth Approach

The total net benefits for different initial reservoir storage volumes, cropping distributions, irrigation depth approaches and sets of irrigation intervals are shown in Figures 9.1 through 9.7. Feasible solutions could not be obtained with 10, 20 and 30% of initial maximum reservoir storage. This was due to the commitment of delivery of water for other uses throughout the planning period. This indicates that the irrigation is possible only when reservoir is 40 % full or above, if other requirements are to be fulfilled. The total net benefits increase linearly with the reservoir capacity.

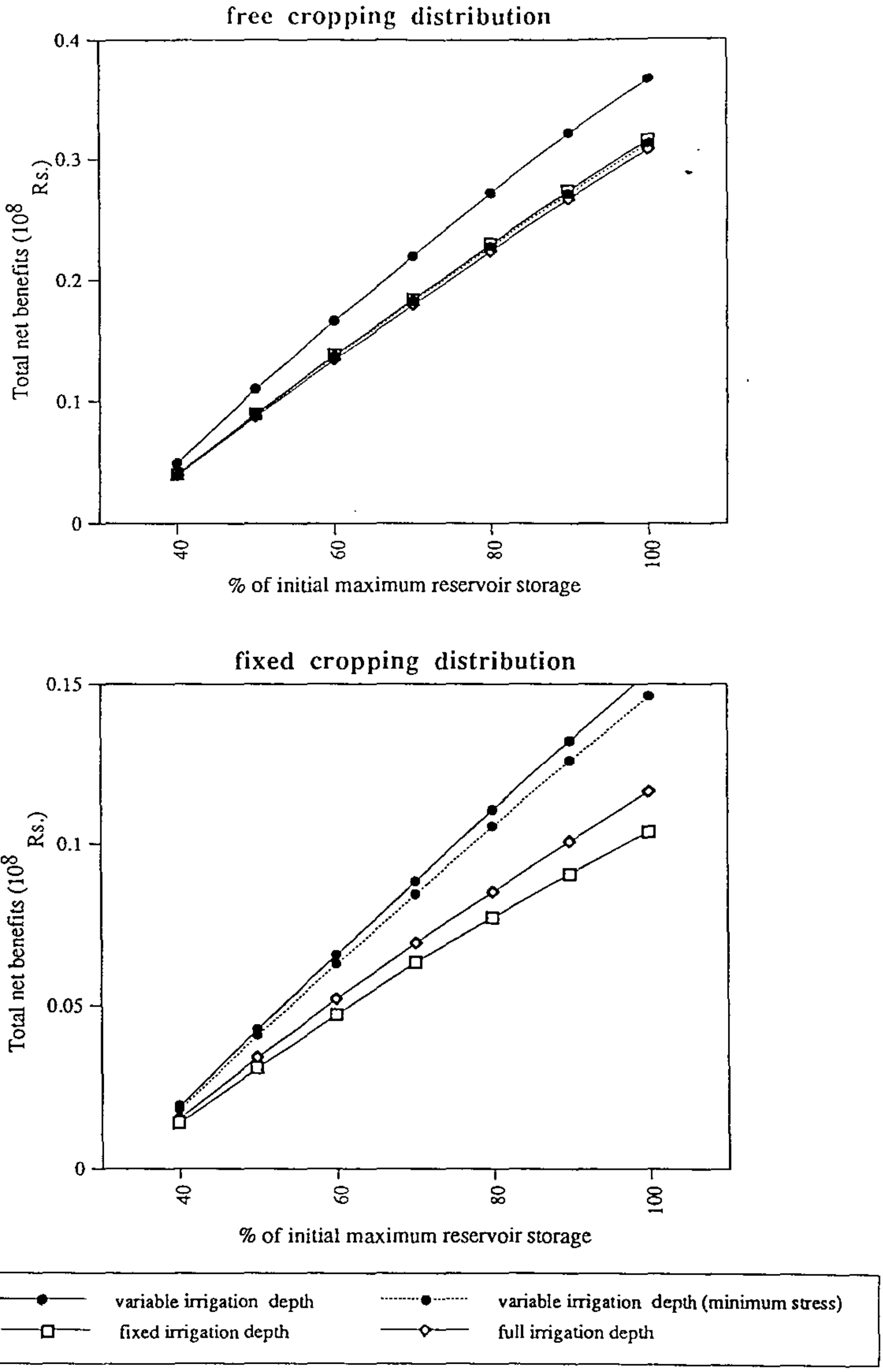


Figure 9.1 The total net benefits obtained by variable, fixed and full irrigation depths for different initial reservoir storage volumes when irrigation interval is 14 days

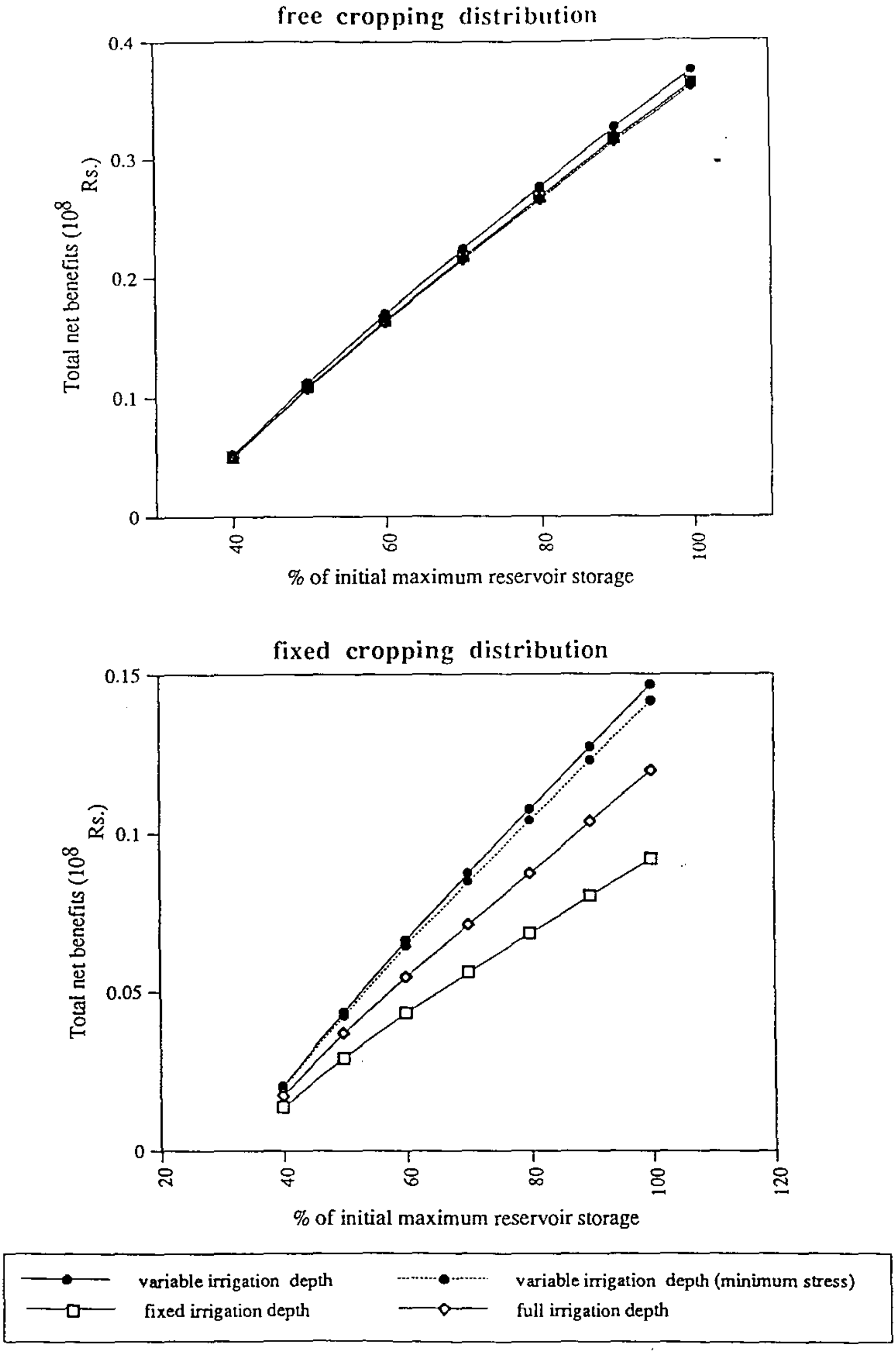


Figure 9.2 The total net benefits obtained by variable, fixed and full irrigation depths for different initial reservoir storage vilumes when irrigation interval is 21 days

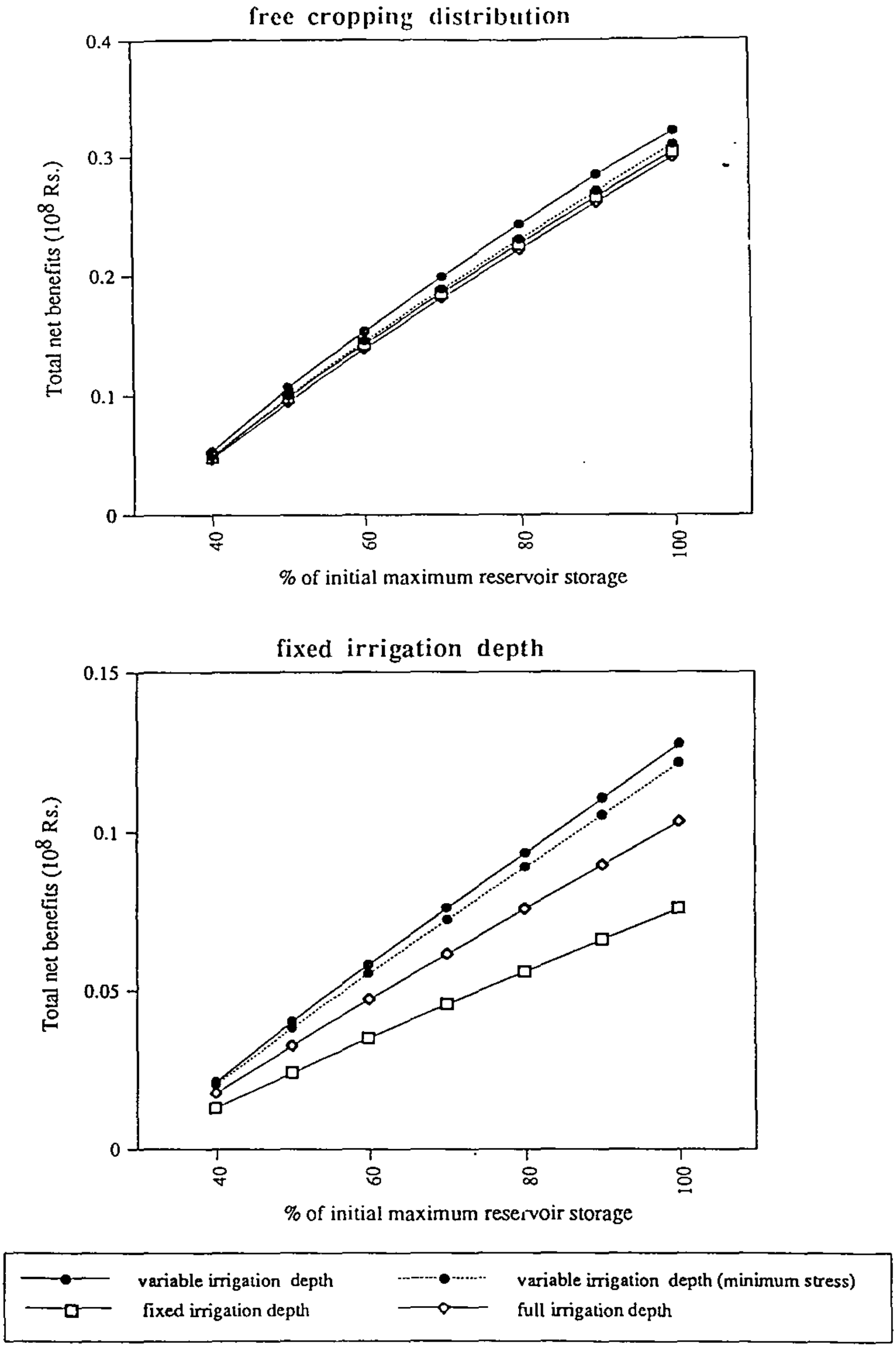


Figure 9.3 The total net benefits obtained by variable, fixed and full irrigation depths for different initial reservoir storage volumes when irrigation interval is 28 days

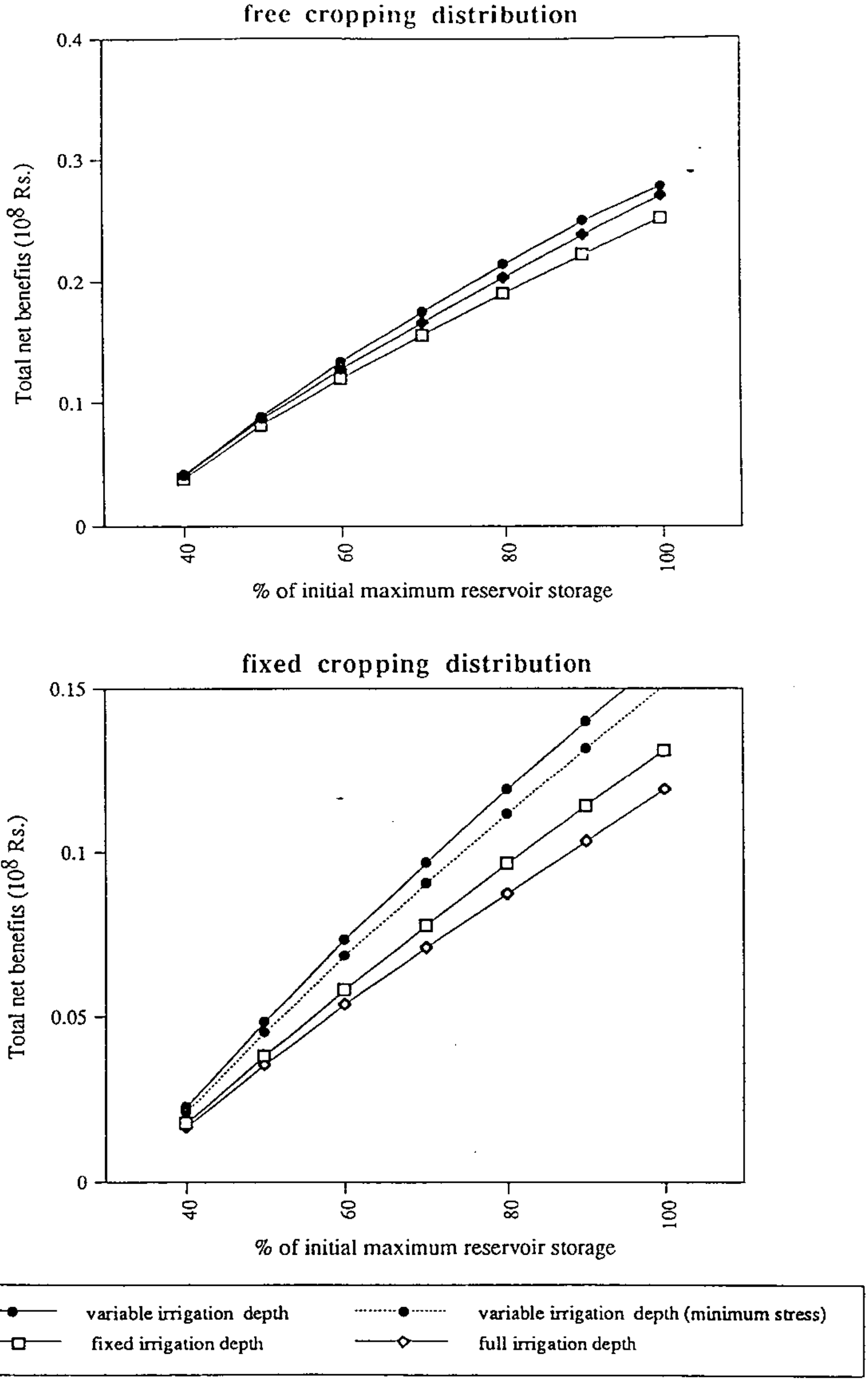


Figure 9.4 The total net benefits obtained by variable, fixed and full irrigation depths for different initial reservoir storage volumes when irrigation interval is 35 days

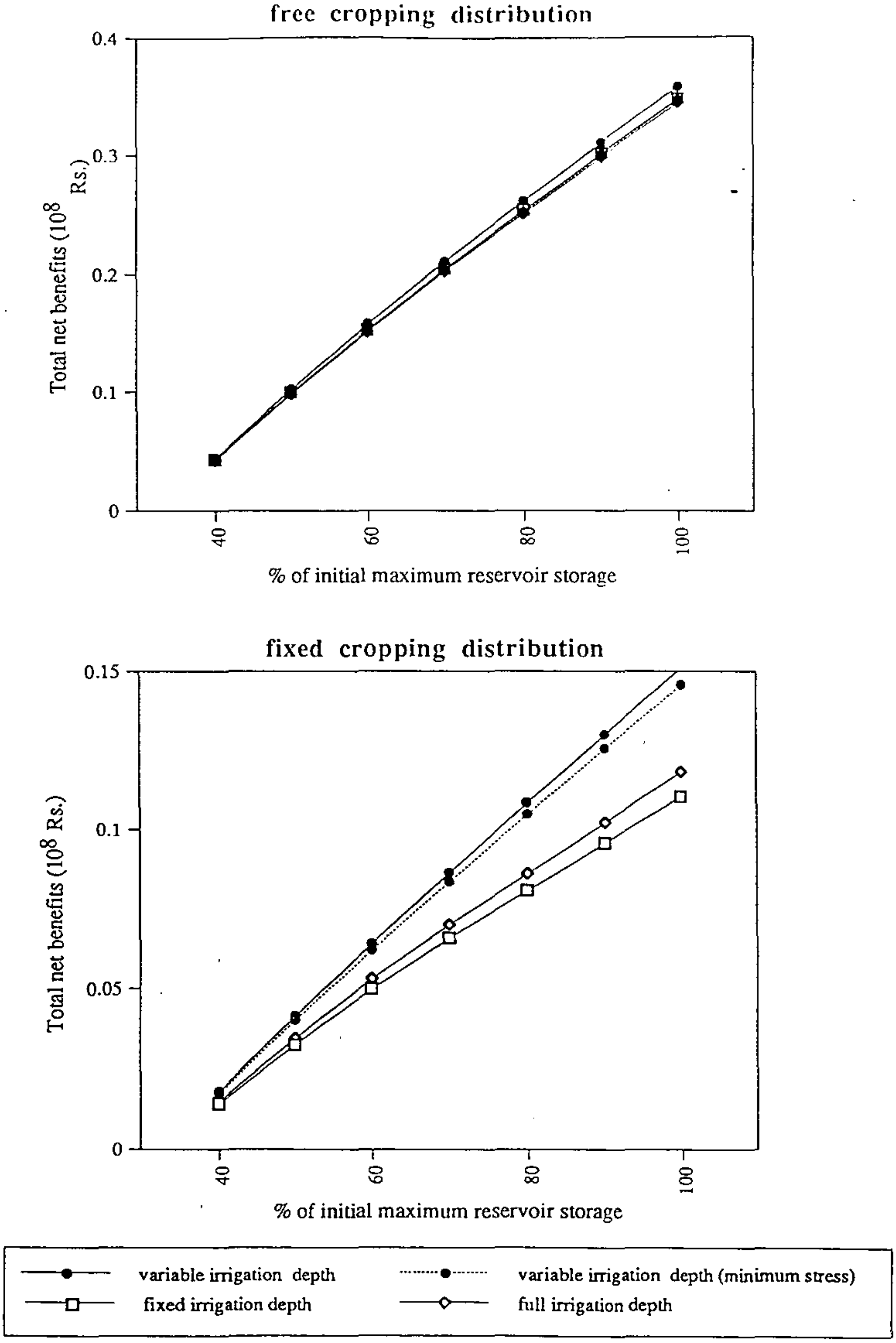


Figure 9.5 The total net benefits obtained by variable, fixed and full irrigation depths for different initial reservoir storage volumes when irrigation interval is 21 (winter season) and 14 (summer season) days

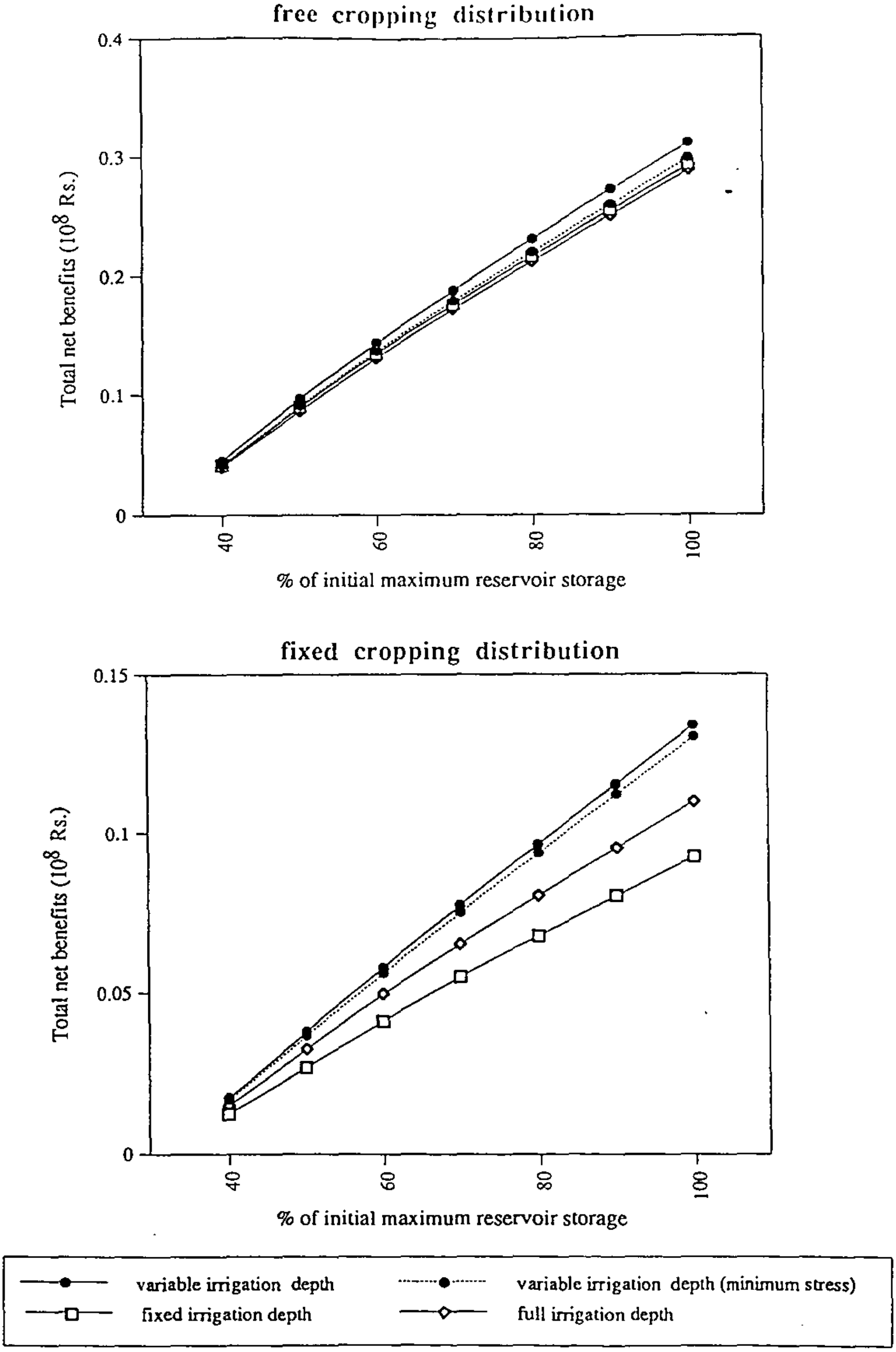


Figure 9.6 The total net benefits obtained by variable, fixed and full irrigation depths for different initial reservoir storage volumes when irrigation interval is 28 (winter season) and 21 (summer season) days

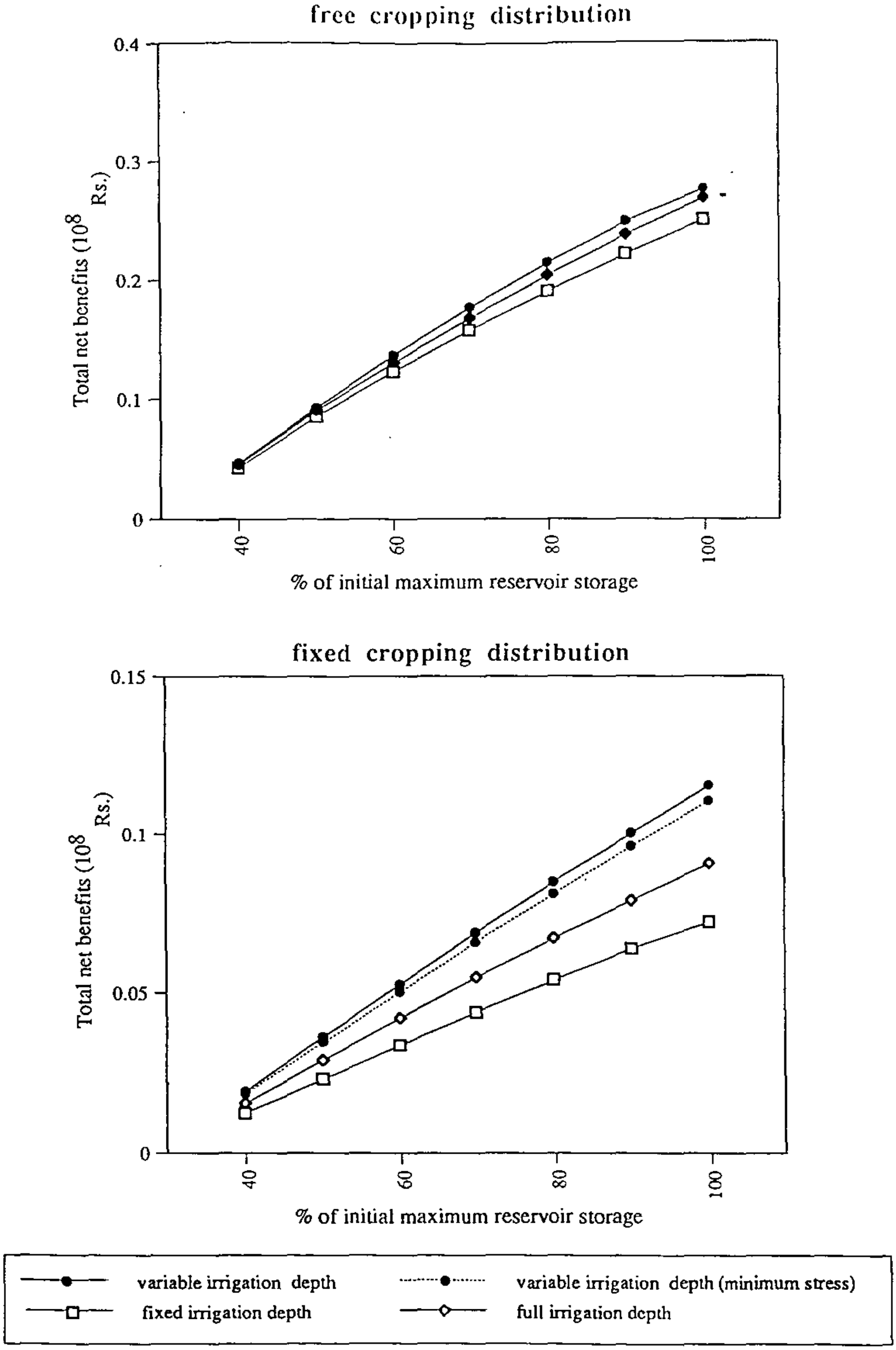


Figure 9.7 The total net benefits obtained by variable, fixed and full irrigation depths for different initial reservoir storage volumes when irrigation interval is 35 (winter season) and 28 (summer season) days

In free cropping distribution onion was predominately selected in the allocation plans of all irrigation intervals and irrigation depth approaches (Table 9.5 shows the cropping distribution in free cropping distribution for one case). This was due to the high monetary returns from onion (Figures 8.6 through 8.11) (the effect of increased production on prices is not included in the model) and its cultivation in winter season during which ET requirements are less than summer season. The feasible solution could not be obtained with the prescribed fixed cropping distribution for I=35 days. The sunflower and groundnut could not produce crop yield for this large irrigation interval. The total net benefits with free cropping distribution are found to be approximately 2 to 3 times more over fixed cropping distribution. The drastic reduction in net benefits by adopting fixed cropping distribution is due to forced irrigation to the crops giving less monetary returns (such as sorghum) and to the crops needing more water (such as sunflower and groundnut).

When the cropping distribution is free, the total net benefits with FLDI and VDI(MS) are almost the same for all sets of irrigation intervals depending on the initial reservoir storage volumes. Figure 8.8 explains this. In case of onion the crop yield and seasonal irrigation depth with VDI causing minimum stress almost match with those obtained with full irrigation depth. While for other crops, they differ distinctly. The total net benefits with FXDI are almost equal to the total net benefits obtained with FLDI and VDI(MS) for I=14, 21 and 28 days. However when the irrigation interval is increased to 35 days, the total net benefits by FXDI decrease. In case of onion the irrigations are required in smaller depth due to less root zone depth. Therefore VDI(MS), FLDI and FXDI produce the similar effect. However in VDI there is more flexibility to skip the irrigations which therefore resulted in higher total net benefits.

In the fixed cropping distribution the highest total net benefits are obtained with VDI followed by VDI(MS), FLDI and FXDI in all the cases. The rigidity of applying the same irrigation depth to all the crops explains the lowest net benefits obtained with FXDI. The higher total net benefits with VDI is due to deficit irrigation by skipping the irrigation and applying lower irrigation depths than the full irrigation depths. As such in VDI(MS) the irrigation depths at every irrigation are adjusted such that minimum stress is caused with minimum irrigation depth. Where as in case of FLDI there is no adjustment of irrigation depths. Therefore though FLDI and VDI (MS) produce similar crop yield, VDI(MS) is more beneficial when water is scarce at the scheme level. In fixed cropping distribution the total net benefits with VDI(MS) are close to those obtained with VDI. This indicates that the adequate irrigation could be equally beneficial if applied in variable depths. Figure 8.14 indicates that VDI and VDI(MS) are nearly same for groundnut and sunflower. The difference in the total net benefits of VDI and VDI(MS) in fixed cropping distribution is due to other crops (Figures 8.12 and 8.13).

9.3.2 Irrigation Interval

The total net benefits obtained with different irrigation intervals for different irrigation depth approaches and two initial reservoir storage volumes for free and fixed cropping distributions are shown in Figures 9.8 and 9.9, respectively. In free cropping distribution, at both the initial reservoir storage volumes, the irrigation interval of 21 days is found to be producing maximum crop yield among all sets of irrigation intervals for all the irrigation depth approaches. Generally the total net benefits increased from I=14 days to I=21 days and then decreased.

In fixed cropping distribution there is no specific trend except more total benefits are obtained with smaller irrigation intervals and less with larger irrigation intervals. This is mainly due to the considerations to sunflower and groundnut grown in summer season. Generally VDI should generate maximum total net benefits at smaller irrigation intervals due to greater flexibility in adjusting the actual delivery of water which is not possible with large irrigation intervals. Similarly in FXDI, when the irrigation interval is large, small irrigation depths may subject the crop to stress immediately and the water holding capacity may restrict large irrigation depths. A large irrigation depth may result in loss of water during initial crop growth stages. Therefore small irrigation intervals are found appropriate for fixed irrigation depth also. On the other hand FLDI may reduce the loss of water during initial stages caused in FXDI, and therefore the reduction in total net benefits with FLDI is less than with the FXDI approach. Thus while practising irrigation in a heterogeneous irrigation scheme the irrigation interval needs to be decided by obtaining the total net benefits for each possible set of irrigation intervals, taking account of the varying behaviour of different crops grown on different soils and to different water applications.

9.3.3 Soil Types

The area irrigated and water delivered to each soil group were computed for all irrigation intervals when the reservoir was full at the start of planning period. The proportion of area irrigated (the ratio of area to be irrigated and CCA of soil group) and the proportion of water delivered (the ratio of water delivered to soil group and the product of ratio of CCA of soil group to CCA of scheme and the total water delivered)

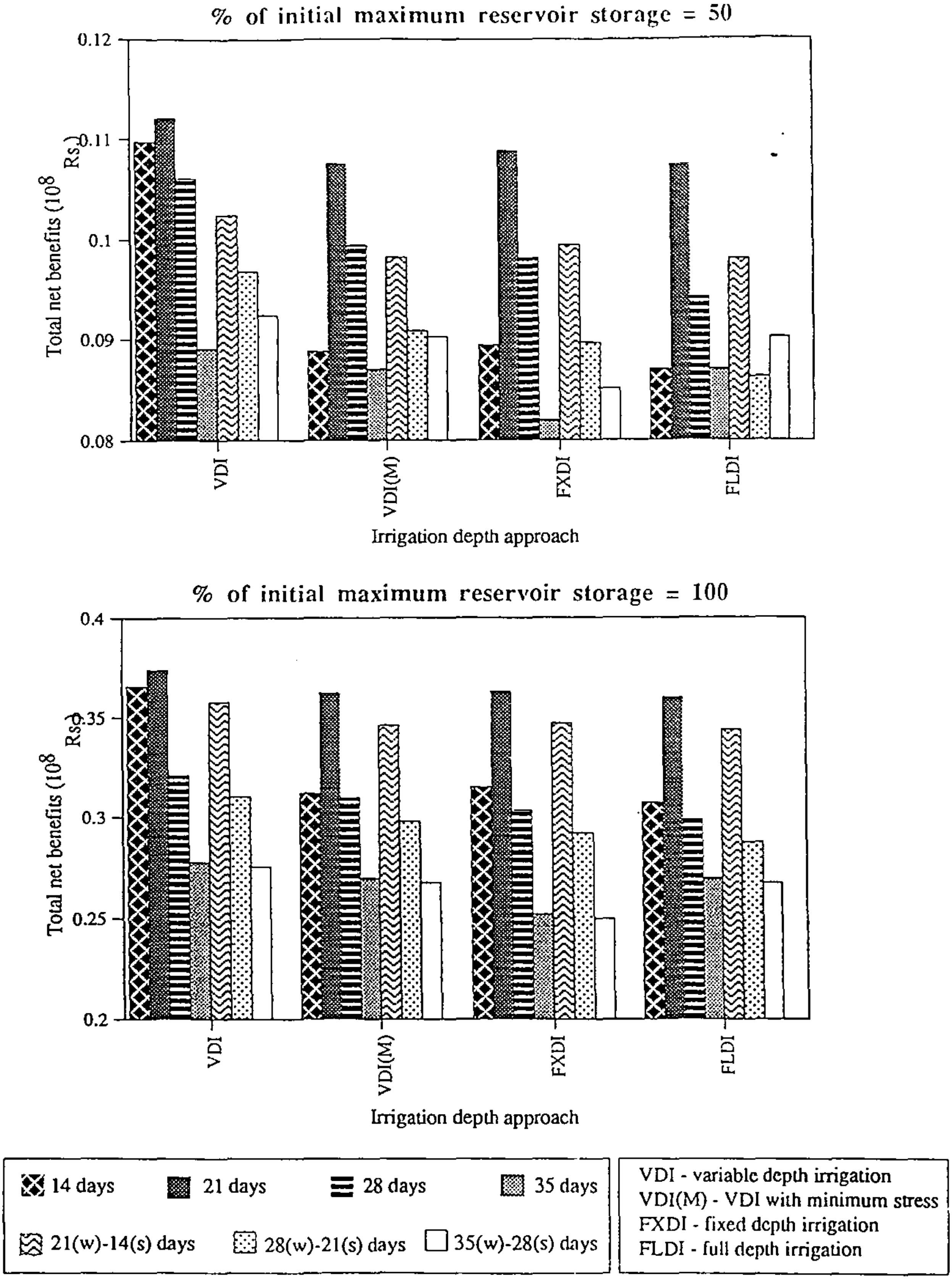


Figure 9.8 Total net benefits with free cropping distribution for 50 and 100 % of initial maximum reservoir storages for different irrigation depth approaches

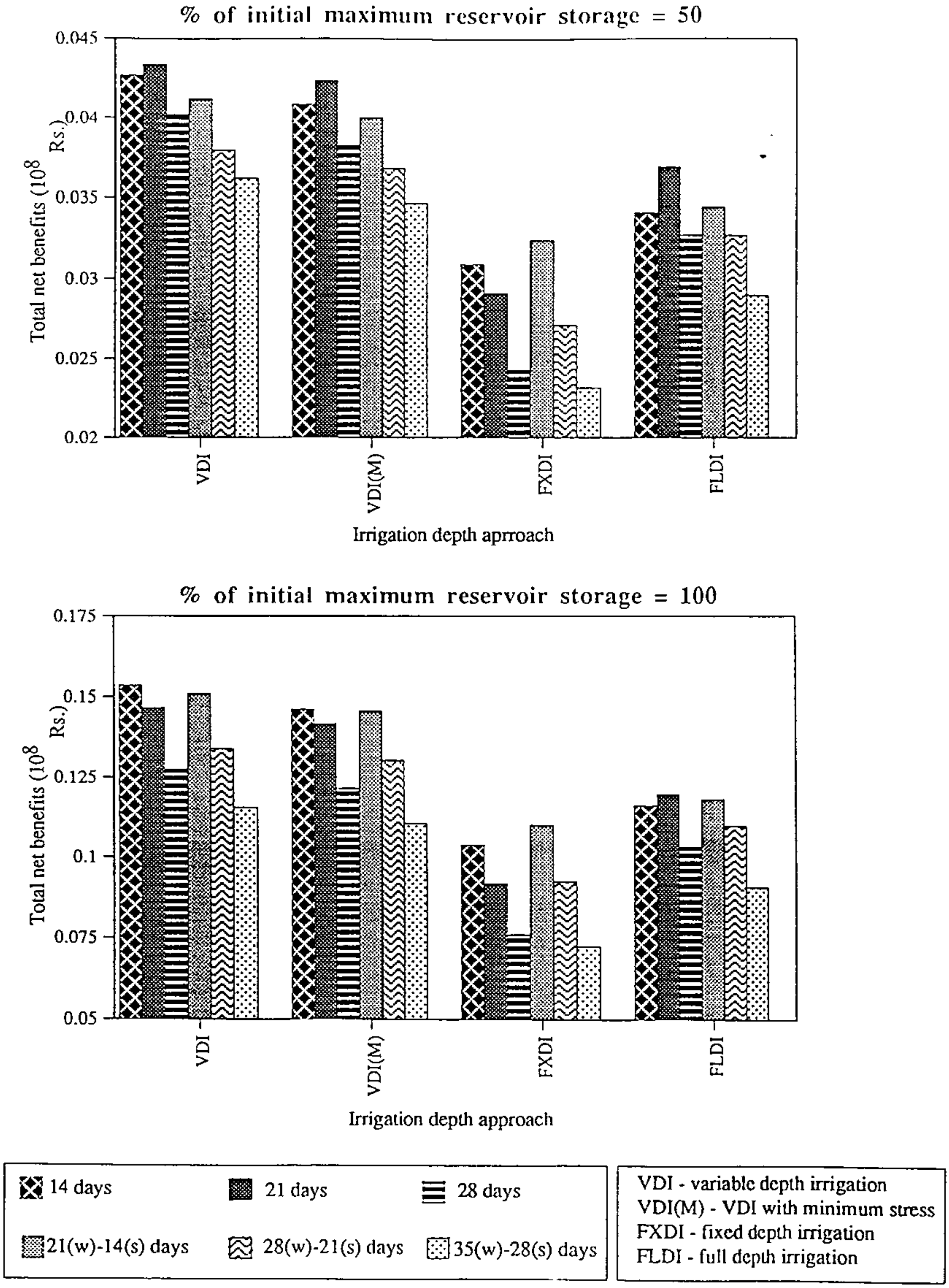


Figure 9.9 Total net benefits with fixed cropping distribution for 50 and 100 % of initial maximum reservoir storages for different irrigation depth approaches

for free and fixed cropping distributions were computed for VDI (Figures 9.10 and 9.11), FLDI (Figures 9.12 and 9.13) and FXDI (Figures 9.14 and 9.15) approaches for comparing the allocation of land and water resources to different soil groups.

As described earlier (Chapter VII), soil SG-1 has a low water holding capacity (WHC) and the AUs with this soil group mostly lie towards the head of the scheme. Other soils (SG-2, SG-3 and SG-4) have higher WHC. AUs with SG-4 are towards the tail of the scheme. AUs with SG-2 are closer to the headworks than AUs with SG-3 (Figure 7.10).

The higher proportion of area is irrigated and water is delivered to SG-2 and SG-3 in VDI approach for free cropping distribution. The area or water is allocated to SG-1 mainly due to lower conveyance losses for the soil group. The allocation to this soil group decreases with an increase in irrigation interval and there is no allocation to this soil group when I=35 days. This is due to the lower WHC of this soil group. While for SG-4, allocation is increased with increase in irrigation interval. Thus when irrigation interval is increased it became more beneficial to allocate the resources to soil with higher WHC than to soil with lower WHC even it lies towards the head of the scheme. The allocation to SG-2 and SG-3 is nearly the same for all irrigation intervals. The similar results are obtained with the fixed cropping distribution except that more water is delivered to SG-2 compared to water allocated to other soil groups and area allocated to this soil group. This was due to greater allocation of area of this soil group to a summer crop. SG-1 is not much suitable for summer crop and AUs with SG-2 are comparatively near to the headworks.

In FXDI approach the similar results are obtained but with increased allocation to SG-1. This was due to the application of a constant depth of water for all soil groups and as AUs with SG-1 are closer to the headworks and more water is stored in the root zone than in other soil groups. For smaller irrigation intervals this was sufficient to obtain the crop yield with winter crops (sorghum, onion and gram) to compensate for the loss of water due to conveyance in AUs with other soil groups. The similar kind of allocation results are obtained with full irrigation depth approach.

Figures 9.9 through 9.15 show that the type of soil considerably influences the allocation of resources. The AWAM appropriately considers the soil types with other parameters while allocating the resources due to the simulation model (SWAB-CRYB) in first stage (Sections 5.3.3 and 5.3.4).

9.3.4 The Best Allocation Plans

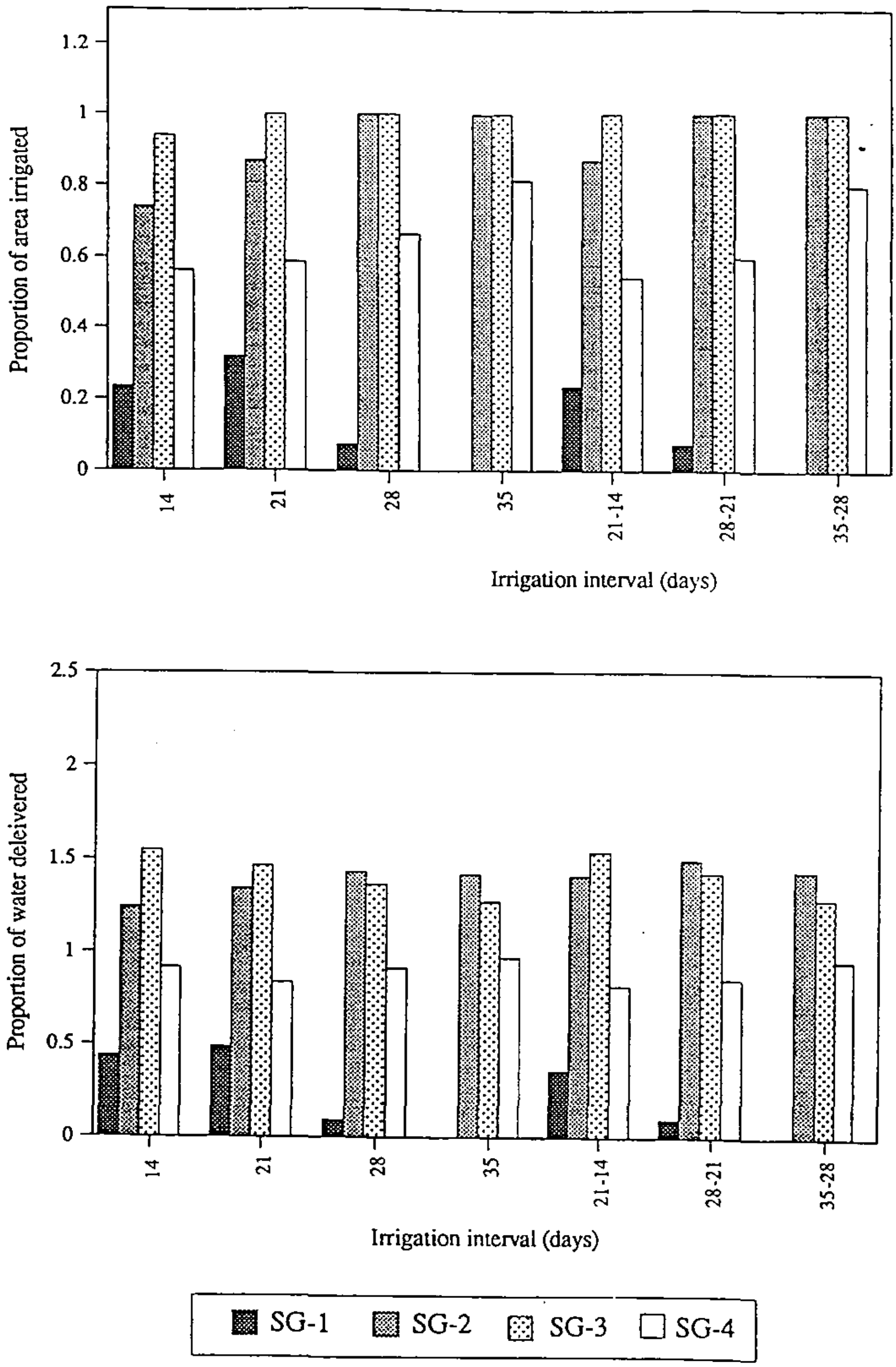


Figure 9.10 The proportion of area irrigated and water delivered to each soil group for variable irrigation depth approach and free cropping distribution

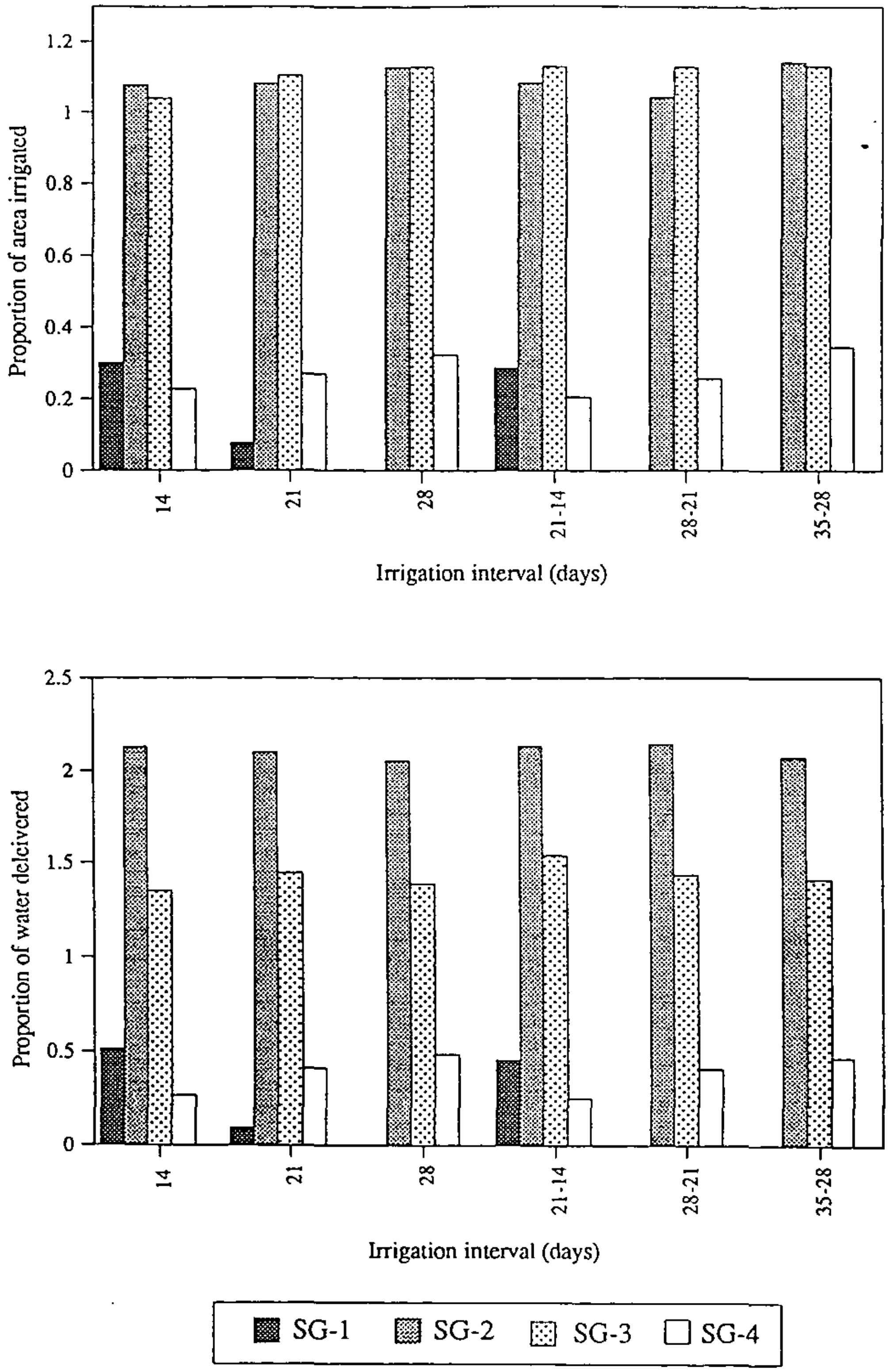


Figure 9.11 The proportion of area irrigated and water delivered to each soil group for variable irrigation depth approach and fixed cropping distribution

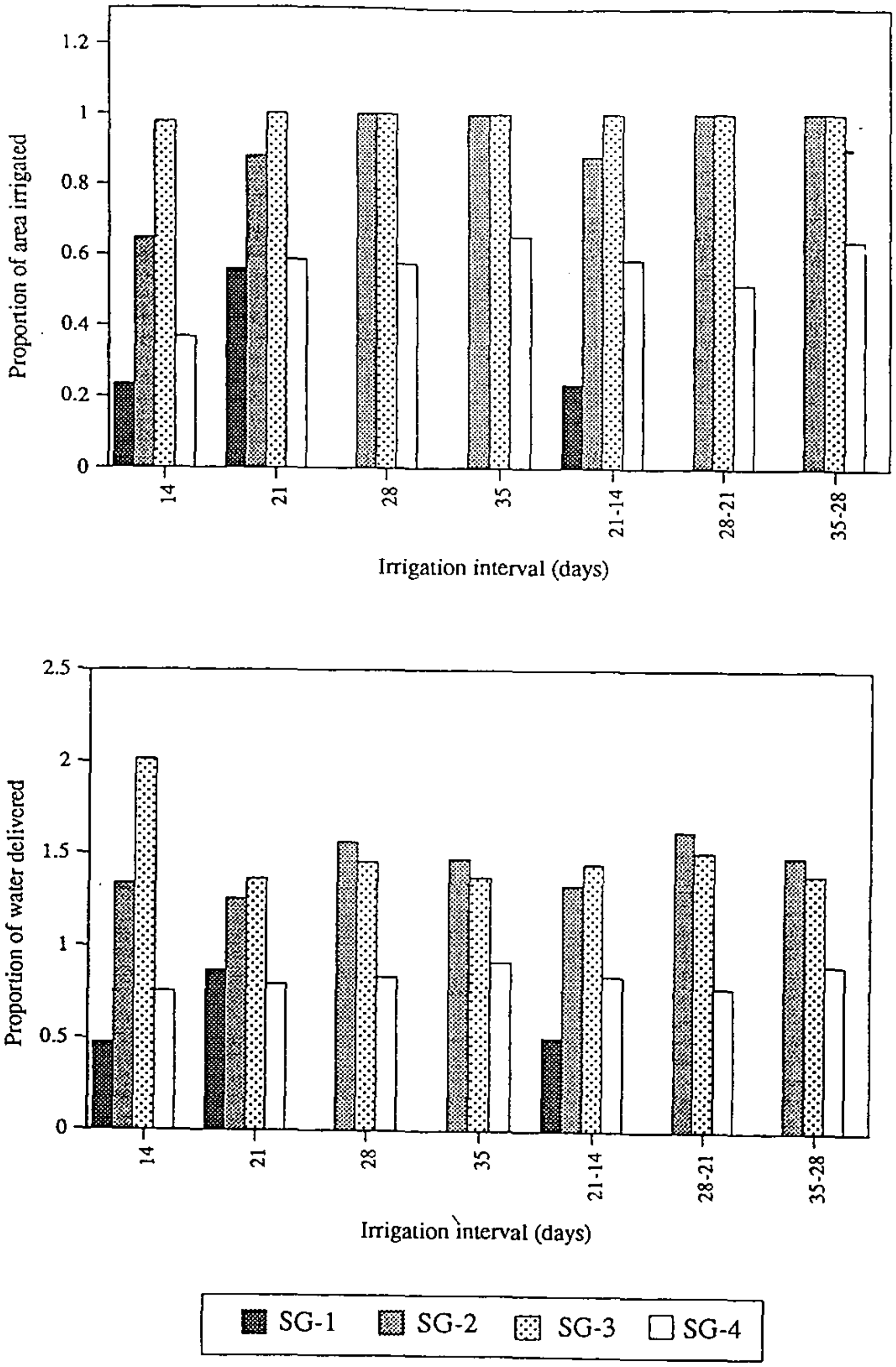
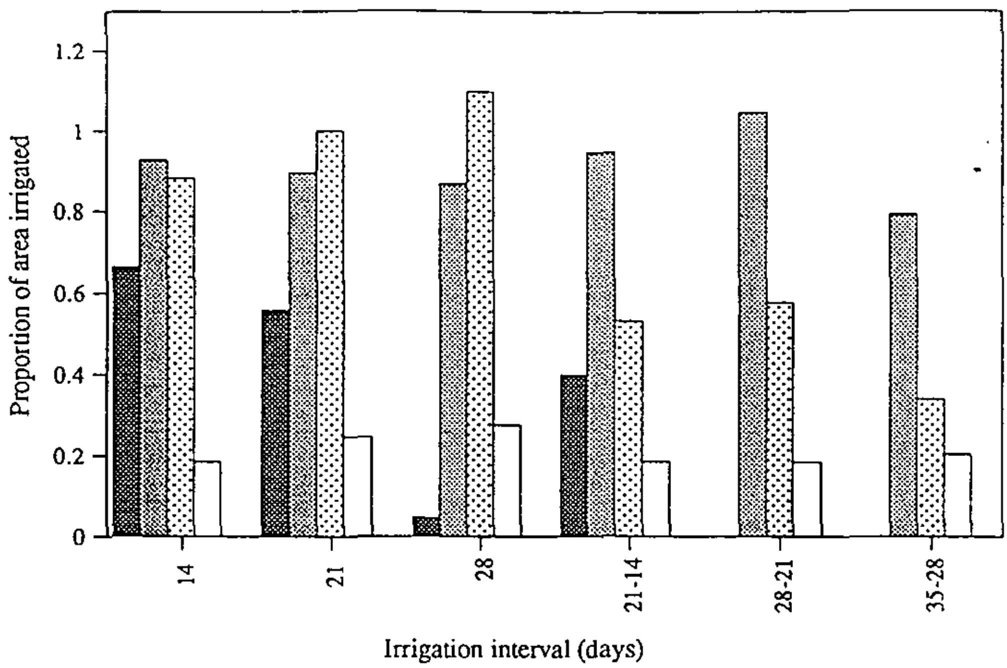


Figure 9.12 The proportion of area irrigated and water delivered to each soil group for fixed irrigation depth approach and free cropping distribution



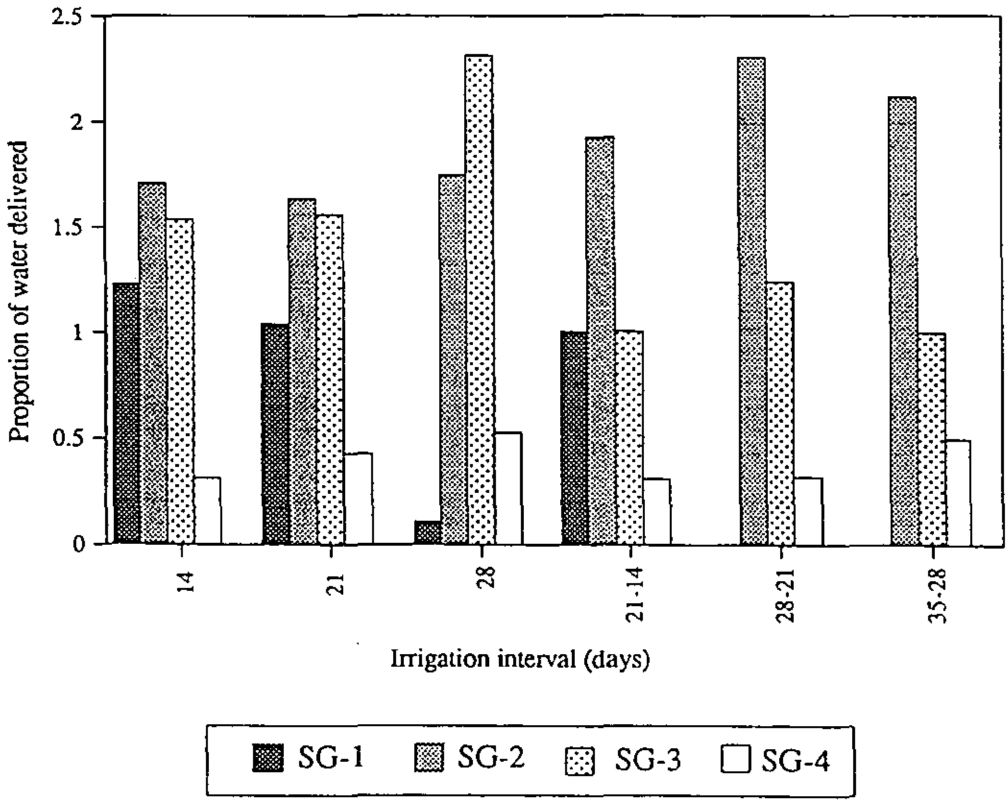


Figure 9.13 The proportion of area irrigated and water delivered to each soil group for fixed irrigation depth approach and fixed cropping distribution

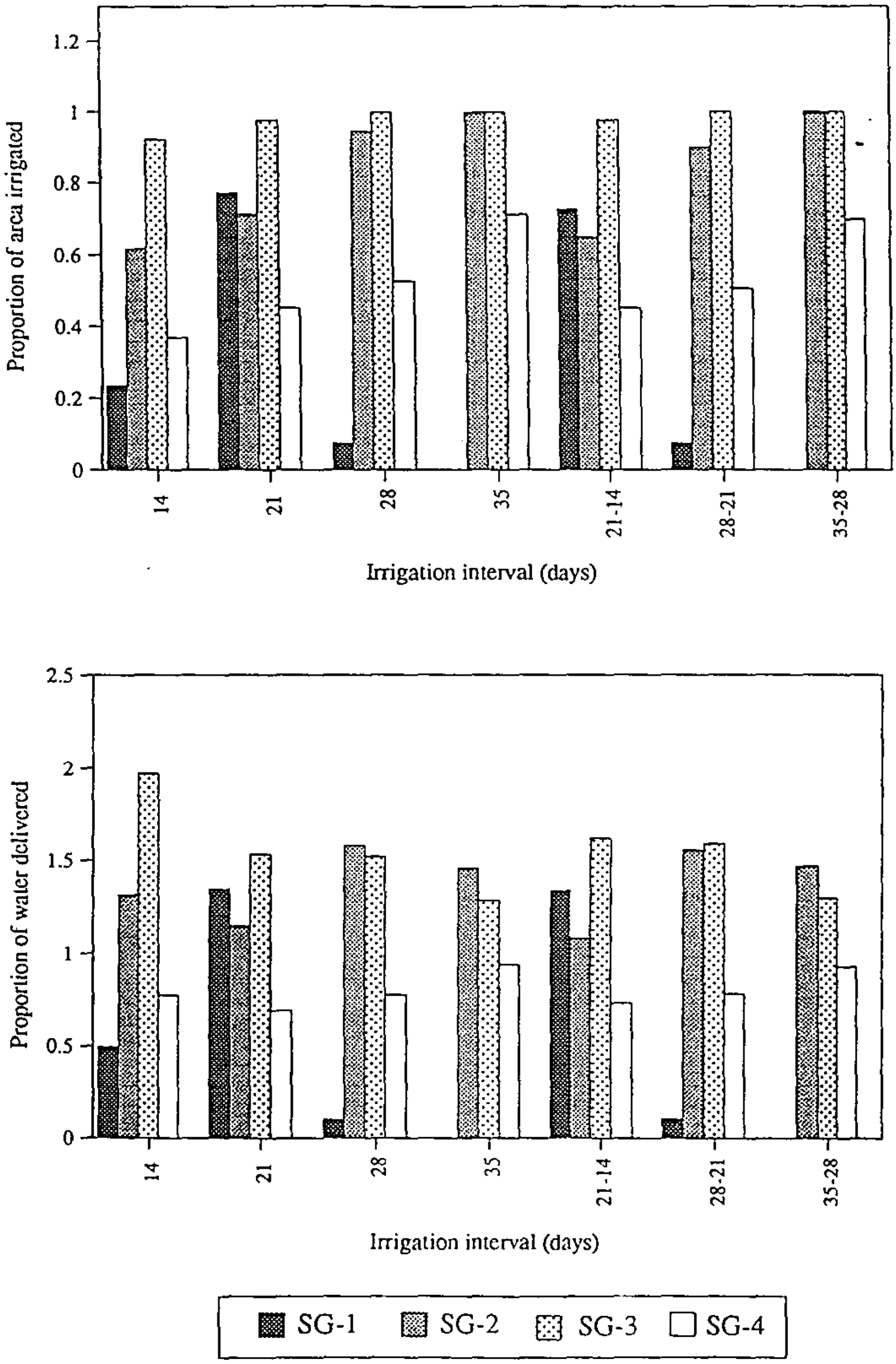


Figure 9.14 The proportion of area irrigated and water delivered to each soil group for full irrigation depth approach and free cropping distribution

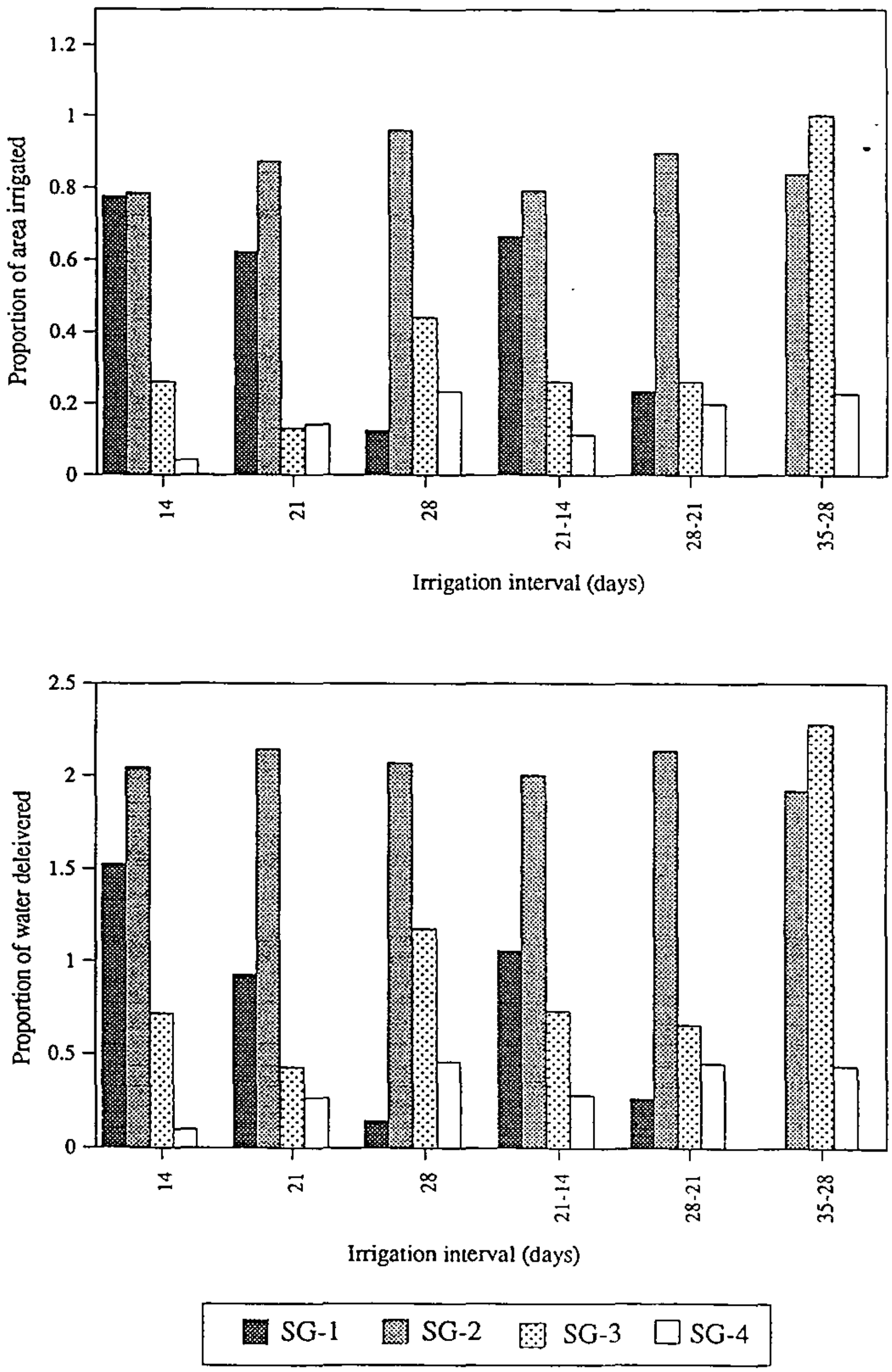


Figure 9.15 The proportion of area irrigated and water delivered to each soil group for full irrigation depth approach and fixed cropping distribution

The best allocation plans (the plans giving maximum total net benefits) were found for each irrigation depth approach for free and fixed cropping distributions when the reservoir is full at the start of planning period. These are with I=21 days for all the irrigation depth approaches for free cropping distributions, and with I=14 days for VDI, I=21 days for FLDI and I=21(winter) and I=14 (summer) days for FXDI when the cropping distribution is fixed. The total net benefits of the best plans of these approaches are compared with the total net benefits obtained from the allocation plan of the existing rule in Figure 9.16.

In free cropping distribution there is not much difference in total net benefits obtained from VDI, FLDI and FXDI. The total net benefits with VDI approach is more than FLDI (4%) and FXDI (3%). This was due to the most of the allocation going to onion which was found to be responding similarly to all approaches. The net benefits obtained from the existing rule (I=21 days in winter season and I=14 days in summer season with irrigation depth of 70 mm per irrigation to all CS units of AUs) are considerably lower than the total net benefits obtained from other approaches. However the irrigation interval and irrigation depth in the existing rule are decided with all crops into consideration. The total net benefits obtained from FXDI (which is similar to existing rule) are for the optimised fixed irrigation depth and irrigation interval for only few crops appearing in the allocation plan.

In fixed cropping distribution where in irrigations are given to all the crops, the VDI approach was found to be more beneficial over FXDI and FLDI approaches and existing rule. Interestingly the allocation plans and the results from the FXDI approach and existing rules are the same. The total net benefits from VDI approach is 22% and 28% more than FLDI and FXDI (and existing) approaches, respectively. This indicates that VDI approach where in deficit irrigation is appropriately included is considerably beneficial over traditional fixed depth irrigation or full depth irrigation approaches.

The AWAM gives the detailed allocation plan at the planning stage for operating the irrigation scheme. This includes the area to be irrigated under different crops in each soil group (CS unit) of each allocation unit, the water to be delivered to these CS units at each irrigation, the water to be delivered to each AU, the water to be released in each canal, the water to be released from the reservoir for different purposes (irrigation, other uses etc.), evaporation, seepage and other losses, the estimated crop production and net benefits at CS unit of AU, AU and irrigation scheme. The summary of allocation plan in terms of area to be irrigated under different crops, water to be delivered to different

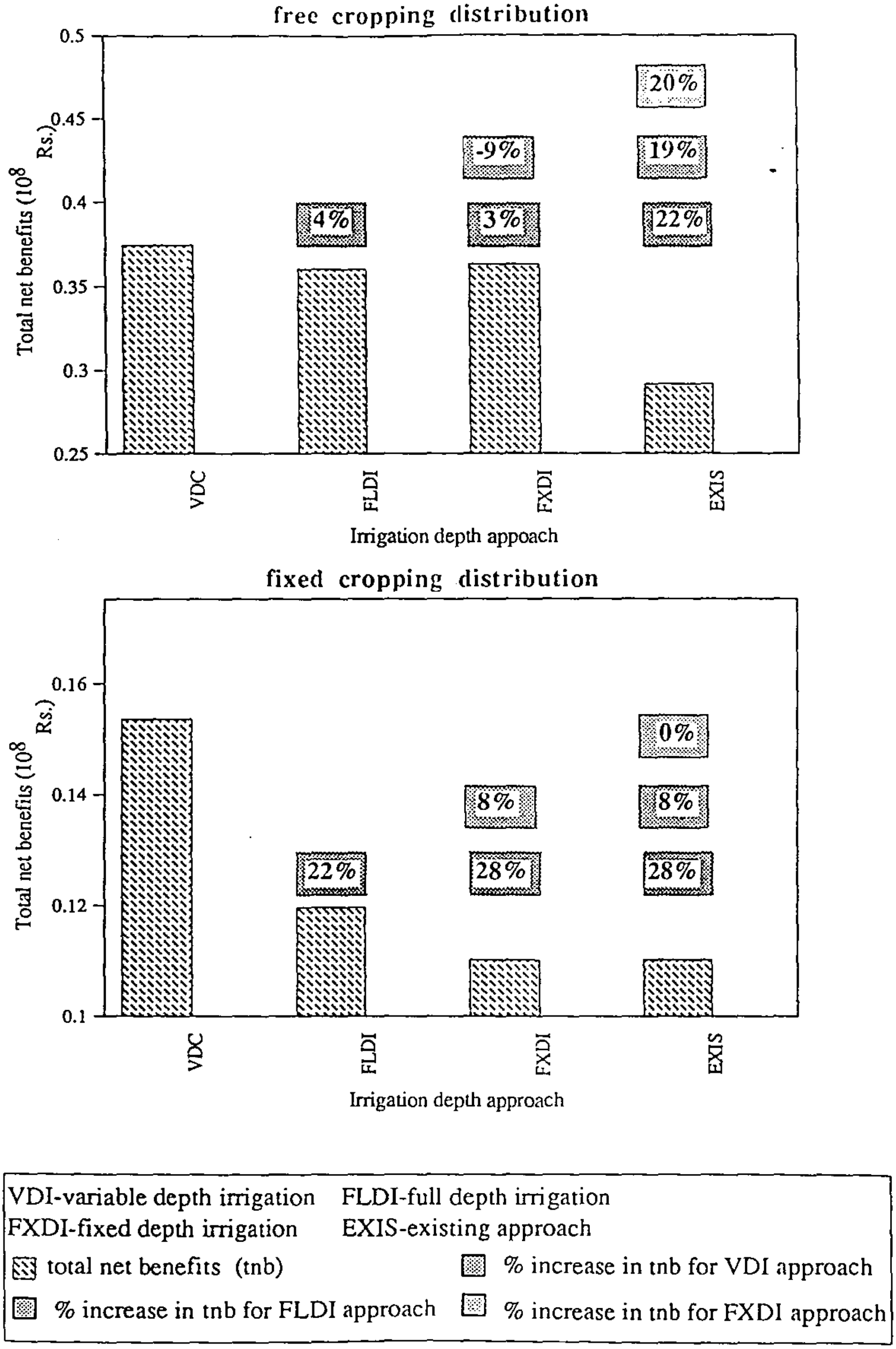


Figure 9.16 The total net benefits obtained from the best set of irrigation intervals for different irrigation depth approaches and cropping distributions

crops in each AU, water to be delivered to each AU at each irrigation and release of water from reservoir with the losses is presented in Tables 9.1, 9.2, 9.3 and 9.4 for fixed cropping distribution with variable depth irrigation and in Tables 9.5, 9.6, 9.7 and 9.8 for free cropping distribution with variable depth irrigation. The detail allocation plan for fixed cropping distribution with variable depth irrigation is given in Appendix C.

9.3.5 Crops

The results in Chapter VIII indicate that each crop produces different net benefits and needs different amount of water. When the cropping distribution is free the maximum total net benefits are obtained (Figures 9.1 through 9.7) as the crops giving maximum total net benefits are free to be selected in the allocation plan. But this may not match with other requirements such as food production. The total net benefits in fixed cropping distribution decrease depending on the restrictions put on the area to be irrigated, water to be delivered and production to be obtained from different crops.

In this section the importance of different crops in the allocation plan is explained. The total net benefits are obtained by omitting the most beneficial crop from the allocation plan every time starting from all crops to the most non-beneficial crop. The total net benefits obtained in this way for all irrigation intervals when the reservoir is full at the beginning of the planning period are shown in Figure 9.17. It is seen from this figure that two crops are economically more efficient. The total net benefits are drastically reduced when they are omitted from the allocation plan. These are onion and gram. The total net benefits decrease in smaller steps after omission of these crops. The other crops in order of their economic significance in this irrigation scheme with water scarcity are wheat, sorghum, sunflower and groundnut.

Thus in a free cropping distribution there will always be a tendency to irrigate onion and gram in different situations. The other crops may not appear or less resources might be allocated to these crops. However the cultivation of these crops may be necessary to satisfy food requirements or market needs. The total net benefits have therefore been calculated for cases which to satisfy the food requirement in the irrigation scheme. The prescribed food requirement could be satisfied only when initial maximum reservoir storage was 90 % or above. The total net benefits when initial reservoir storage is 90 and 100 % for all irrigation interval with and without food requirement constraints are shown in Figure 9.18. It is seen that to satisfy the specified food needs, the total net benefits could be reduced considerably. This is due to the certain restriction on irrigation to the most economically beneficial crops and least beneficial crops. In this

Table 9.1 The allocation of area to be irrigated (ha) to different crops in different allocation units (AU) for fixed cropping distribution with variable depth irrigation approach, when irrigation interval is 14 days (best allocation plan)

AU No.	Crops					
	Gram	Sorghum	Onion	Wheat	Sunflower	Groundnut
1	39	0.0	0.0	0.0	0.0	39.0
2	2.6	0.0	0.0	33.4	2.6	33.4
3	0.0	0.0	0.0	8.0	0.0	8.0
4	3.1	0.0	5.25	18.7	8.3	16.7
5	0.0	0.0	0.0	0.0	0.0	0.0
6	33.0	0.0	0.0	0.0	33.0	0.0
7	0.0	0.0	19.0	40.0	19.0	31.1
8	0.0	0.0	0.0	16.7	5.3	16.7
9	5.3	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	28.0	40.0	20.6	29.4
11	39.2	0.0	0.0	22.8	20.6	29.4
12	0.0	0.0	0.0	0.0	0.0	0.0
13	18.5	13.4	66.8	24.2	20.6	29.4
14	55.6	16.4	0.0	9.0	24.6	25.4
15	63.6	30.2	85.8	37.4	50.1	50.1
16	7.0	0.0	0.0	0.0	0.0	69.6
17	52.5	50.0	0.0	42.5	0.0	0.0
18	69.5	62.9	0.0	14.6	0.0	0.0
19	54.8	39.5	0.0	0.0	0.0	31.4
20	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	65.0	0.0	0.0	0.0	0.0
22	68.2	65.3	0.0	0.0	0.0	0.0
23	0.0	30.0	0.0	0.0	0.0	0.0
24	0.0	37.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0
26	0.0	0.0	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0	0.0	0.0
31	0.0	0.0	0.0	0.0	0.0	0.0
32	0.0	0.0	0.0	0.0	0.0	0.0
Total	512	410	205	307	205	410

Table 9.2 The allocation of water (ha-m) to different crops in different allocation units for fixed cropping distribution with variable depth irrigation, when irrigation interval is 14 days (best allocation plan)

AU No.	Crops					
	Gram	Sorghum	Onion	Wheat	Sunflower	Groundnut
1	14.1	0.0	0.0	0.0	0.0	22.7
2	0.9	0.0	0.0	14.3	2.0	26.4
3	0.0	0.0	0.0	3.4	0.0	6.3
4	1.1	0.0	2.4	8.0	6.4	13.2
5	0.0	0.0	0.0	0.0	0.0	0.0
6	11.1	0.0	0.0	0.0	27.6	0.0
7	0.0	0.0	8.8	17.2	14.6	24.6
8	1.8	0.0	0.0	7.2	4.1	13.2
9	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	11.5	17.2	15.9	23.3
11	13.5	0.0	0.0	9.8	15.9	23.3
12	0.0	0.0	0.0	0.0	0.0	0.0
13	6.1	3.6	27.6	10.3	15.9	23.3
14	19.1	4.4	0.0	3.9	19.0	20.1
15	21.4	8.1	35.4	16.1	38.7	39.7
16	2.2	0.0	0.0	0.0	0.0	32.3
17	17.7	12.8	0.0	18.3	0.0	0.0
18	23.4	16.6	0.0	6.3	0.0	0.0
19	18.8	10.5	0.0	0.0	0.0	24.8
20	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	16.6	0.0	0.0	0.0	0.0
22	20.2	16.7	0.0	0.0	0.0	0.0
23	0.0	8.0	0.0	0.0	0.0	0.0
24	0.0	9.9	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0
26	0.0	0.0	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0	0.0	0.0
31	0.0	0.0	0.0	0.0	0.0	0.0
32	0.0	0.0	0.0	0.0	0.0	0.0
Total	171	107	86	132	160	293

Table 9.3 Water to be delivered (ha-m) to each allocation unit at each irrigation period for fixed cropping distribution with variable depth irrigation approach, when irrigation interval is 14 days (best allocation plan)

Irr.	Allocation Unit No.											
No.	1	2	3	4	5	6	7	8	9	10	11	12
1	.00	.00	.00	.31	.00	.00	1.10	.00	.00	1.63	.00	.00
2	2.49	.28	.00	.63	.00	3.26	1.10	.49	.00	1.63	4.10	.00
3	2.49	5.02	1.16	2.91	.00	2.11	5.82	2.89	.00	5.82	5.82	.00
4	2.27	.15	.00	.48	.00	1.92	1.10	.43	.00	1.63	2.28	.00
5	2.27	2.67	.60	1.90	.00	1.92	4.13	1.26	.00	4.65	4.00	.00
6	2.27	.15	.00	.48	.00	1.92	1.10	.40	.00	1.63	2.28	.00
7	2.27	3.10	.74	2.04	.00	.00	4.83	1.55	.00	5.35	2.12	.00
8	.00	1.94	.47	1.39	.00	.00	3.43	.97	.00	4.12	1.32	.00
9	.00	1.94	.47	1.39	.00	.00	3.43	.97	.00	2.33	1.32	.00
10	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
11	.00	.46	.00	1.45	.00	5.76	3.31	.93	.00	3.59	3.59	.00
12	4.08	5.82	1.40	2.91	.00	1.92	5.82	2.91	.00	5.82	5.82	.00
13	2.27	5.06	1.16	2.91	.00	1.92	5.82	2.86	.00	5.82	5.82	.00
14	2.27	3.93	.88	2.70	.00	3.26	5.23	2.34	.00	5.10	5.10	.00
15	2.49	3.22	.70	2.53	.00	4.03	4.80	2.07	.00	4.62	4.62	.00
16	3.40	4.19	.93	2.91	.00	4.22	5.82	2.56	.00	5.82	5.82	.00
17	3.17	3.63	.79	2.72	.00	4.60	5.46	2.33	.00	5.48	5.48	.00
18	2.72	2.09	.47	1.45	.00	1.92	2.91	1.28	.00	2.91	2.91	.00
19	2.27	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

Irr.	Allocation Unit No.											
No.	13	14	15	16	17	18	19	20	21	22	23	24
1	5.82	2.28	9.20	.00	8.73	8.73	5.51	.00	8.69	8.73	3.66	4.52
2	5.82	5.82	11.65	.00	4.88	6.47	5.73	.00	3.78	3.80	.00	.00
3	5.82	5.82	11.65	.48	8.73	8.73	5.82	.00	.00	8.73	1.92	2.37
4	5.82	3.23	9.28	.48	7.74	6.49	3.22	.00	.00	6.35	.00	.00
5	5.82	5.06	11.65	.40	6.51	8.71	5.82	.00	4.16	4.17	2.44	3.01
6	5.52	3.23	9.28	.40	3.05	4.04	3.22	.00	.00	5.16	.00	.00
7	5.82	.84	8.46	.40	3.95	1.36	.00	.00	.00	.00	.00	.00
8	5.79	.52	7.66	.00	2.47	.85	.00	.00	.00	.00	.00	.00
9	1.41	.52	2.17	.00	2.71	.93	.00	.00	.00	.00	.00	.00
10	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
11	3.59	4.29	8.74	.00	.00	.00	.00	.00	.00	.00	.00	.00
12	5.82	5.82	11.65	7.28	.00	.00	5.47	.00	.00	.00	.00	.00
13	5.82	5.42	10.78	.00	.00	.00	4.56	.00	.00	.00	.00	.00
14	5.10	4.96	9.90	4.04	.00	.00	3.47	.00	.00	.00	.00	.00
15	4.62	4.39	8.74	4.45	.00	.00	2.74	.00	.00	.00	.00	.00
16	5.82	5.82	11.65	6.47	.00	.00	3.65	.00	.00	.00	.00	.00
17	5.48	5.52	11.07	5.66	.00	.00	3.10	.00	.00	.00	.00	.00
18	2.91	2.91	5.82	4.45	.00	.00	1.82	.00	.00	.00	.00	.00
19	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

Irr.	Allocation Unit No.							
No.	25	26	27	28	29	30	31	32
1	.00	.00	.00	.00	.00	.00	.00	.00
2	.00	.00	.00	.00	.00	.00	.00	.00
3	.00	.00	.00	.00	.00	.00	.00	.00
4	.00	.00	.00	.00	.00	.00	.00	.00
5	.00	.00	.00	.00	.00	.00	.00	.00
6	.00	.00	.00	.00	.00	.00	.00	.00
7	.00	.00	.00	.00	.00	.00	.00	.00
8	.00	.00	.00	.00	.00	.00	.00	.00
9	.00	.00	.00	.00	.00	.00	.00	.00
10	.00	.00	.00	.00	.00	.00	.00	.00
11	.00	.00	.00	.00	.00	.00	.00	.00
12	.00	.00	.00	.00	.00	.00	.00	.00
13	.00	.00	.00	.00	.00	.00	.00	.00
14	.00	.00	.00	.00	.00	.00	.00	.00
15	.00	.00	.00	.00	.00	.00	.00	.00
16	.00	.00	.00	.00	.00	.00	.00	.00
17	.00	.00	.00	.00	.00	.00	.00	.00
18	.00	.00	.00	.00	.00	.00	.00	.00
19	.00	.00	.00	.00	.00	.00	.00	.00

Table 9.4 The storage in reservoir and inflow, losses and release of water from reservoir during each irrigation period for fixed cropping distribution with variable irrigation depth approach when irrigation interval is 14 days (best allocation plan)

Dead storage cacpacity of reservoir = .568400E+03 ha-m
Cariover storage = .000000E+00 ha-m

Irr. No.	Initial Storage (ha-m)	Final Storage (ha-m)	Inflow (ha-m)	Spilover (ha-m)
1	.223130E+04	.210458E+04	.000000E+00	.000000E+00
2	.210458E+04	.199112E+04	.000000E+00	.000000E+00
3	.199112E+04	.184546E+04	.126896E+00	.000000E+00
4	.184546E+04	.174797E+04	.000000E+00	.000000E+00
5	.174797E+04	.161892E+04	.000000E+00	.000000E+00
6	.161892E+04	.153450E+04	.000000E+00	.000000E+00
7	.153450E+04	.145254E+04	.000000E+00	.000000E+00
8	.145254E+04	.138291E+04	.000000E+00	.000000E+00
9	.138291E+04	.132612E+04	.000000E+00	.000000E+00
10	.132612E+04	.129025E+04	.000000E+00	.000000E+00
11	.129025E+04	.121235E+04	.000000E+00	.000000E+00
12	.121235E+04	.109165E+04	.000000E+00	.000000E+00
13	.109165E+04	.985262E+03	.000000E+00	.000000E+00
14	.985262E+03	.880662E+03	.000000E+00	.000000E+00
15	.880662E+03	.780854E+03	.000000E+00	.000000E+00
16	.780854E+03	.664458E+03	.000000E+00	.000000E+00
17	.664458E+03	.563360E+03	.780412E+01	.000000E+00
18	.563360E+03	.593072E+03	.103818E+03	.000000E+00
19	.593072E+03	.575098E+03	.117207E+01	.000000E+00
Total	.223130E+04	.575098E+03	.112921E+03	.000000E+00

Irr. No.	Release (Irrigation) (ha-m)	Release (other) (ha-m)	Seepage and other losses (ha-m)	Evaporation (ha-m)
1	.841393E+02	.160335E+02	.427910E+01	.222632E+02
2	.727610E+02	.160335E+02	.427910E+01	.203936E+02
3	.109610E+03	.160335E+02	.427910E+01	.158584E+02
4	.622796E+02	.160335E+02	.427910E+01	.148964E+02
5	.954333E+02	.160335E+02	.427910E+01	.133076E+02
6	.516765E+02	.160335E+02	.427910E+01	.124349E+02
7	.483268E+02	.160335E+02	.427910E+01	.133221E+02
8	.351583E+02	.160335E+02	.427910E+01	.141562E+02
9	.220789E+02	.160335E+02	.427910E+01	.144011E+02
10	.000000E+00	.160053E+02	.427910E+01	.155774E+02
11	.403418E+02	.158361E+02	.427910E+01	.174450E+02
12	.820224E+02	.158361E+02	.427910E+01	.185608E+02
13	.677676E+02	.158361E+02	.427910E+01	.185083E+02
14	.658146E+02	.158361E+02	.427910E+01	.186710E+02
15	.609137E+02	.158361E+02	.427910E+01	.187788E+02
16	.780523E+02	.158361E+02	.427910E+01	.182284E+02
17	.728308E+02	.158361E+02	.427910E+01	.159563E+02
18	.413138E+02	.158361E+02	.427910E+01	.126763E+02
19	.229777E+01	.791805E+01	.213955E+01	.679109E+01
Total	.109282E+04	.294914E+03	.791634E+02	.302227E+03

Water available = .139443E+04 ha-m Water consumed = .138773E+04 ha-m
(water av.=ini st-dead st-evp, seep & other losses-spill+inflow)
(water con=carriover for next yr+water for irr+other from res,canal&AU)

Table 9.5 The allocation of area to be irrigated (ha) to different crops in different allocation units (AU) for free cropping distribution with variable with variable depth irrigation approach, when irrigation interval is 21 days (best allocation plan)

AU No.	Crops					
	Gram	Sorghum	Onion	Wheat	Sunflower	Groundnut
1	.00	.00	39.00	.00	.00	.00
2	.00	.00	36.00	.00	.00	.00
3	.00	.00	8.00	.00	.00	.00
4	.00	.00	27.00	.00	.00	.00
5	.00	.00	42.77	.00	.00	.00
6	.00	.00	33.00	.00	.00	.00
7	.00	.00	59.00	.00	.00	.00
8	.00	.00	22.00	.00	.00	.00
9	.00	.00	200.36	.00	.00	.00
10	.00	.00	68.00	.00	.00	.00
11	.00	.00	62.00	.00	.00	.00
12	.00	.00	.00	.00	.00	.00
13	1.88	.00	125.12	.00	.00	.00
14	.00	.00	81.00	.00	.00	.00
15	.00	.00	217.00	.00	.00	.00
16	.00	.00	82.00	.00	.00	.00
17	.00	.00	145.00	.00	.00	.00
18	.00	.00	147.00	.00	.00	.00
19	.00	.00	118.00	.00	.00	.00
20	.00	.00	.00	.00	.00	.00
21	.00	.00	65.00	.00	.00	.00
22	.00	.00	156.00	.00	.00	.00
23	.00	.00	30.00	.00	.00	.00
24	.00	.00	37.00	.00	.00	.00
25	.00	.00	89.00	.00	.00	.00
26	.00	.00	93.00	.00	.00	.00
27	.00	.00	115.00	.00	.00	.00
28	.00	.00	30.00	.00	.00	.00
29	.00	.00	32.00	.00	.00	.00
30	.00	.00	87.00	.00	.00	.00
31	.00	.00	35.00	.00	.00	.00
32	.00	.00	90.00	.00	.00	.00
Total	1.88	0	2371.25	0	0	0

Table 9.6 The allocation of water (ha-m) to different crops in different allocation units for free cropping distribution with variable depth irrigation approach, when irrigation interval is 21 days

AU No.	Crops					
	Gram	Sorghum	Onion	Wheat	Sunflower	Groundnut
1	.00	.00	14.74	.00	.00	.00
2	.00	.00	13.60	.00	.00	.00
3	.00	.00	3.02	.00	.00	.00
4	.00	.00	10.20	.00	.00	.00
5	.00	.00	19.58	.00	.00	.00
6	.00	.00	12.28	.00	.00	.00
7	.00	.00	22.30	.00	.00	.00
8	.00	.00	8.31	.00	.00	.00
9	.00	.00	93.19	.00	.00	.00
10	.00	.00	25.70	.00	.00	.00
11	.00	.00	23.43	.00	.00	.00
12	.00	.00	.00	.00	.00	.00
13	.43	.00	46.56	.00	.00	.00
14	.00	.00	30.61	.00	.00	.00
15	.00	.00	82.01	.00	.00	.00
16	.00	.00	30.03	.00	.00	.00
17	.00	.00	53.11	.00	.00	.00
18	.00	.00	53.84	.00	.00	.00
19	.00	.00	44.40	.00	.00	.00
20	.00	.00	.00	.00	.00	.00
21	.00	.00	24.19	.00	.00	.00
22	.00	.00	58.05	.00	.00	.00
23	.00	.00	10.99	.00	.00	.00
24	.00	.00	13.55	.00	.00	.00
25	.00	.00	32.60	.00	.00	.00
26	.00	.00	34.06	.00	.00	.00
27	.00	.00	42.12	.00	.00	.00
28	.00	.00	10.99	.00	.00	.00
29	.00	.00	11.72	.00	.00	.00
30	.00	.00	31.87	.00	.00	.00
31	.00	.00	12.82	.00	.00	.00
32	.00	.00	32.97	.00	.00	.00
Total	43	.00	902.9	.00	.00	.00

Table 9.7 Water to be delivered (ha-m) to each allocation unit at each irrigation period for free cropping distribution with variable depth irrigation approach, when irrigation interval is 21 days (best allocation plan)

Irr.	Allocation Unit No.											
No.	1	2	3	4	5	6	7	8	9	10	11	12
1	2.27	2.30	.51	1.73	3.11	1.92	3.77	1.41	16.02	4.35	3.97	.00
2	2.27	2.09	.47	1.57	3.11	1.92	3.43	1.28	14.56	3.95	3.60	.00
3	2.27	2.09	.47	1.57	3.11	1.92	3.43	1.28	14.56	3.95	3.60	.00
4	2.49	2.30	.51	1.73	3.42	2.11	3.77	1.41	16.02	4.35	3.97	.00
5	2.72	2.72	.60	2.04	3.73	2.49	4.46	1.66	17.47	5.14	4.69	.00
6	2.72	2.09	.47	1.57	3.11	1.92	3.43	1.28	14.56	3.95	3.60	.00
7	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
8	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
9	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
10	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
11	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
12	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
13	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

Irr.	Allocation Unit No.											
No.	13	14	15	16	17	18	19	20	21	22	23	24
1	8.00	5.18	13.88	4.77	8.43	8.55	7.55	.00	3.78	9.07	1.74	2.15
2	7.27	4.71	12.62	4.77	8.43	8.55	6.86	.00	3.78	9.07	1.74	2.15
3	7.59	4.71	12.62	4.77	8.43	8.55	6.86	.00	3.78	9.07	1.74	2.15
4	8.11	5.18	13.88	5.24	9.27	9.40	7.55	.00	4.16	9.98	1.92	2.37
5	8.73	6.12	16.40	5.72	10.12	10.26	8.73	.00	4.91	11.79	2.09	2.58
6	7.27	4.71	12.62	4.77	8.43	8.55	6.86	.00	3.78	9.07	1.74	2.15
7	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
8	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
9	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
10	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
11	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
12	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
13	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

Irr.	Allocation Unit No.							
No.	25	26	27	28	29	30	31	32
1	5.17	5.41	6.69	1.74	1.86	5.06	2.03	5.23
2	5.17	5.41	6.69	1.74	1.86	5.06	2.03	5.23
3	5.17	5.41	6.69	1.74	1.86	5.06	2.03	5.23
4	5.69	5.95	7.35	1.92	2.05	5.56	2.24	5.76
5	6.21	6.49	8.02	2.09	2.23	6.07	2.44	6.28
6	5.17	5.41	6.69	1.74	1.86	5.06	2.03	5.23
7	.00	.00	.00	.00	.00	.00	.00	.00
8	.00	.00	.00	.00	.00	.00	.00	.00
9	.00	.00	.00	.00	.00	.00	.00	.00
10	.00	.00	.00	.00	.00	.00	.00	.00
11	.00	.00	.00	.00	.00	.00	.00	.00
12	.00	.00	.00	.00	.00	.00	.00	.00
13	.00	.00	.00	.00	.00	.00	.00	.00

Table 9.8 The storage in reservoir and inflow, losses and release of water from reservoir during each irrigation period for free cropping distribution with variable depth irrigation approach when irrigation interval is 21 days (best allocation plan)

Dead storage cacpacity of reservoir = .568400E+03 ha-m
Cariover storage = .000000E+00 ha-m

Irr. No.	Initial Storage (ha-m)	Final Storage (ha-m)	Inflow (ha-m)	Spilover (ha-m)
1	.223130E+04	.198943E+04	.000000E+00	.000000E+00
2	.198943E+04	.176332E+04	.126896E+00	.000000E+00
3	.176332E+04	.154058E+04	.000000E+00	.000000E+00
4	.154058E+04	.130430E+04	.000000E+00	.000000E+00
5	.130430E+04	.104505E+04	.000000E+00	.000000E+00
6	.104505E+04	.826087E+03	.000000E+00	.000000E+00
7	.826087E+03	.778243E+03	.000000E+00	.000000E+00
8	.778243E+03	.727580E+03	.000000E+00	.000000E+00
9	.727580E+03	.675273E+03	.000000E+00	.000000E+00
10	.675273E+03	.621229E+03	.000000E+00	.000000E+00
11	.621229E+03	.566922E+03	.317240E+00	.000000E+00
12	.566922E+03	.627468E+03	.111305E+03	.000000E+00
13	.627468E+03	.611567E+03	.117207E+01	.000000E+00
Total	.223130E+04	.611567E+03	.112921E+03	.000000E+00

Irr. No.	Release (Irrigation) (ha-m)	Release (other) (ha-m)	Seepage and other losses (ha-m)	Evaporation (ha-m)
1	.178412E+03	.240503E+02	.641865E+01	.329852E+02
2	.171265E+03	.240503E+02	.641865E+01	.245056E+02
3	.171631E+03	.240503E+02	.641865E+01	.206414E+02
4	.188518E+03	.240503E+02	.641865E+01	.172946E+02
5	.211786E+03	.240503E+02	.641865E+01	.169969E+02
6	.171725E+03	.240503E+02	.641865E+01	.167658E+02
7	.000000E+00	.239234E+02	.641865E+01	.175023E+02
8	.000000E+00	.237542E+02	.641865E+01	.204898E+02
9	.000000E+00	.237542E+02	.641865E+01	.221345E+02
10	.000000E+00	.237542E+02	.641865E+01	.238714E+02
11	.000000E+00	.237542E+02	.641865E+01	.244515E+02
12	.000000E+00	.237542E+02	.641865E+01	.205855E+02
13	.000000E+00	.791805E+01	.213955E+01	.701613E+01
Total	.109334E+04	.294914E+03	.791634E+02	.265241E+03

Water available = .143142E+04 ha-m Water consumed = .138825E+04 ha-m
(water av.=ini st-dead st-evp, seep & other losses-spill+inflow)
(water con=carriover for next yr+water for irr+other from res,canal&AU)

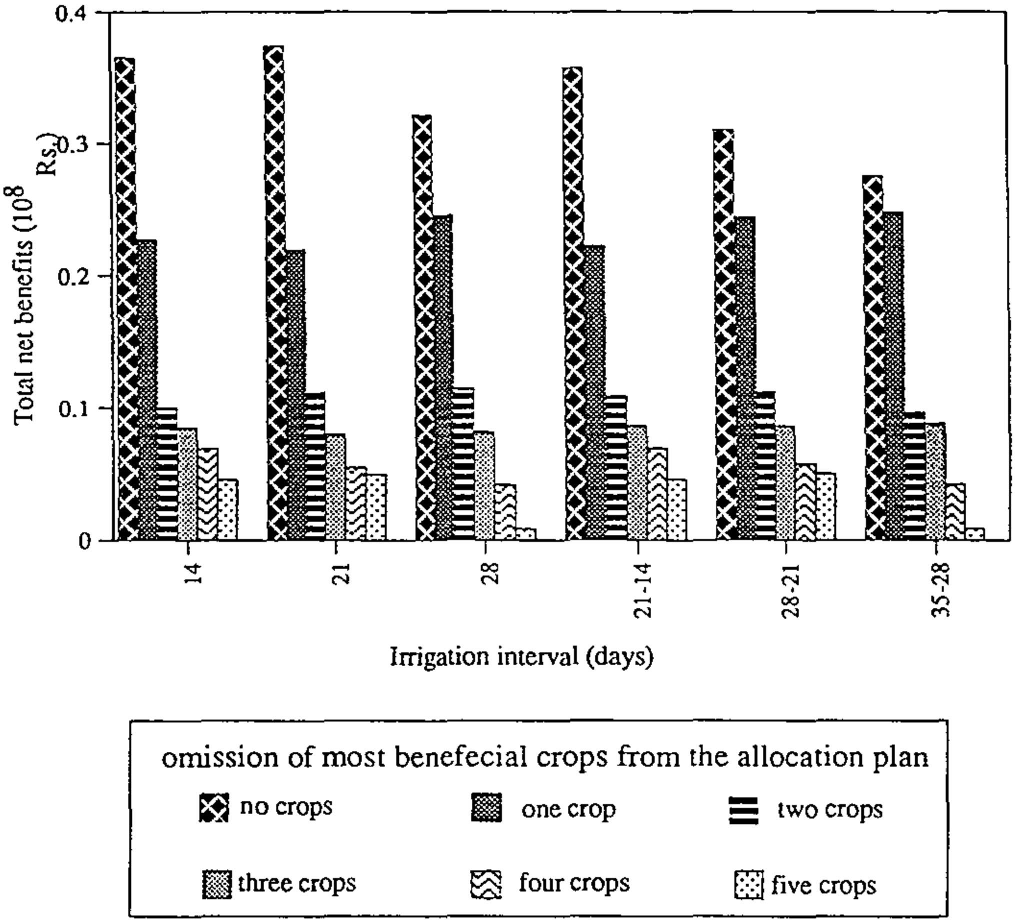


Figure 9.17 The total net benefits as influenced by the omission of the most benefecial crops from the allocation plan for different sets of irrigation interval

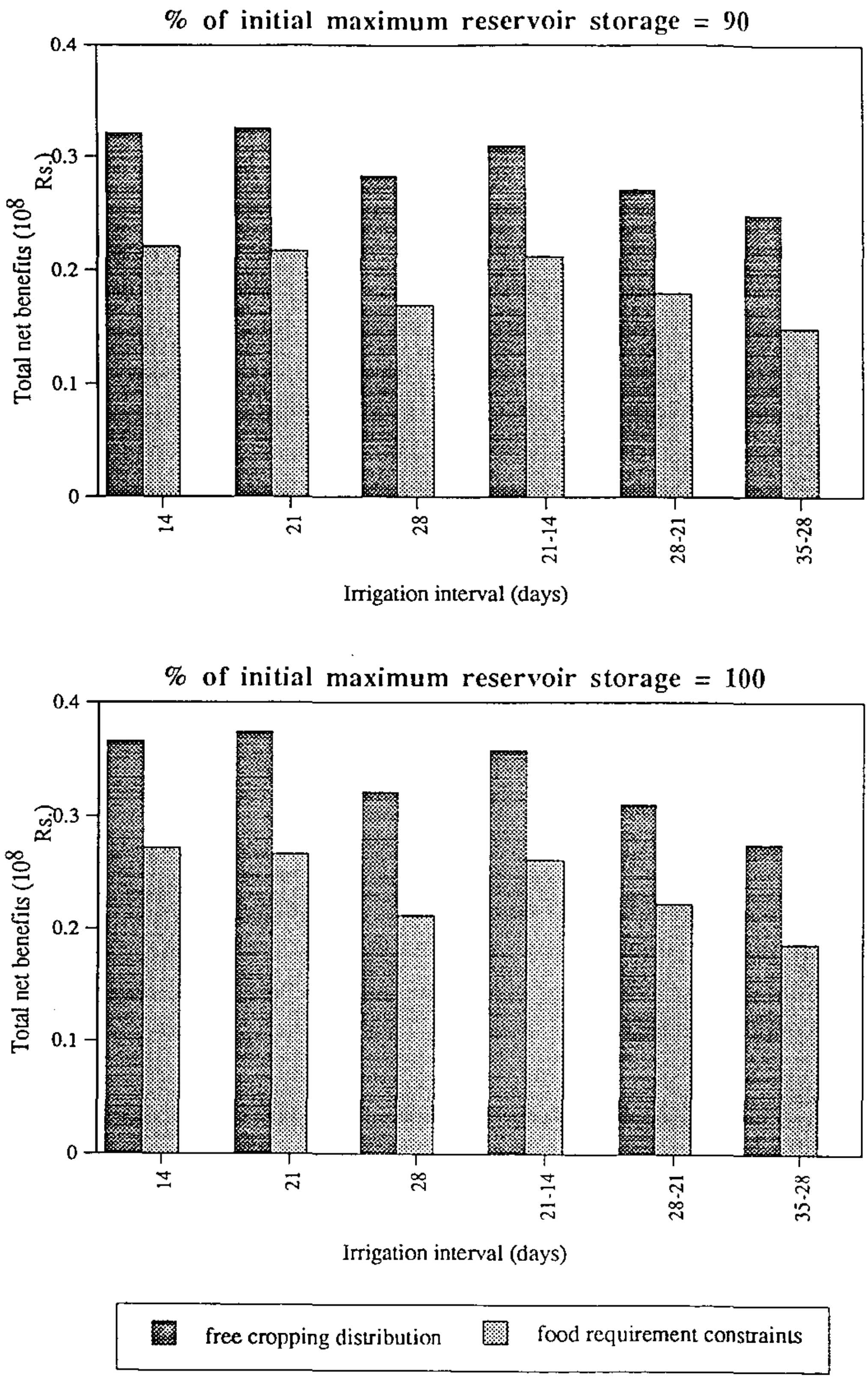


Figure 9.18 The comparison of total net benefits obtained with free cropping distribution and with food requirement constraints

particular case some allocation from onion and gram are transferred to sunflower and groundnut.

9.3.6 Efficiencies

As discussed in the preceding chapters, the water lost in the process of conveying it from the source to the crop root zone can be considerable and may vary with the soils, crop irrigated, irrigation method adopted, the condition of canals and the field channel net work in the tertiary units. Therefore the efficiency of water conveyance, distribution and application is important. In AWAM these efficiencies can be considered separately and made to vary with above mentioned factors. Thus the model attempts to consider the water losses in the system systematically if their values are known instead of assuming the single value of efficiency while obtaining the allocation plans. In the VDI approach, as the irrigations can be skipped and the water is delivered in the variable depths, the separate and detailed consideration of efficiencies is helpful to obtain the realistic estimation of water requirement and corresponding crop yield for different irrigation strategies.

In the present analysis the values of efficiencies for different CSR units (application efficiency) and AUs (distribution efficiency) could not be known. Therefore these are assumed the same for corresponding units and as available from the irrigation scheme (Section 9.2.6). In this section the influence of variation of these efficiencies on the total net benefits is presented. The variation of the total net benefits with application efficiency for fixed cropping distribution and VDI approach is shown in Figure 9.19 and with distribution and conveyance efficiencies is shown in Figure 9.20. As expected the total net benefits increased with the improved irrigation efficiencies. However such type of analysis is helpful in studying the trade off between the expenses incurred on improving the efficiencies and the increase in the total net benefits obtained.

The improved efficiencies influenced the allocation to different allocation units also. For example, improving distribution efficiency from 76% to 96% extended the allocations from 22nd AU to 25th AU. Improving the conveyance efficiency from 96% per 1000m to 99% per 1000m extended the allocation from 19th AU to 26th AU. The allocations to the AU towards the tail of the system also increased due to the lower conveyance losses and more suitable soils.

9.3.7 Canal and Outlet Capacities

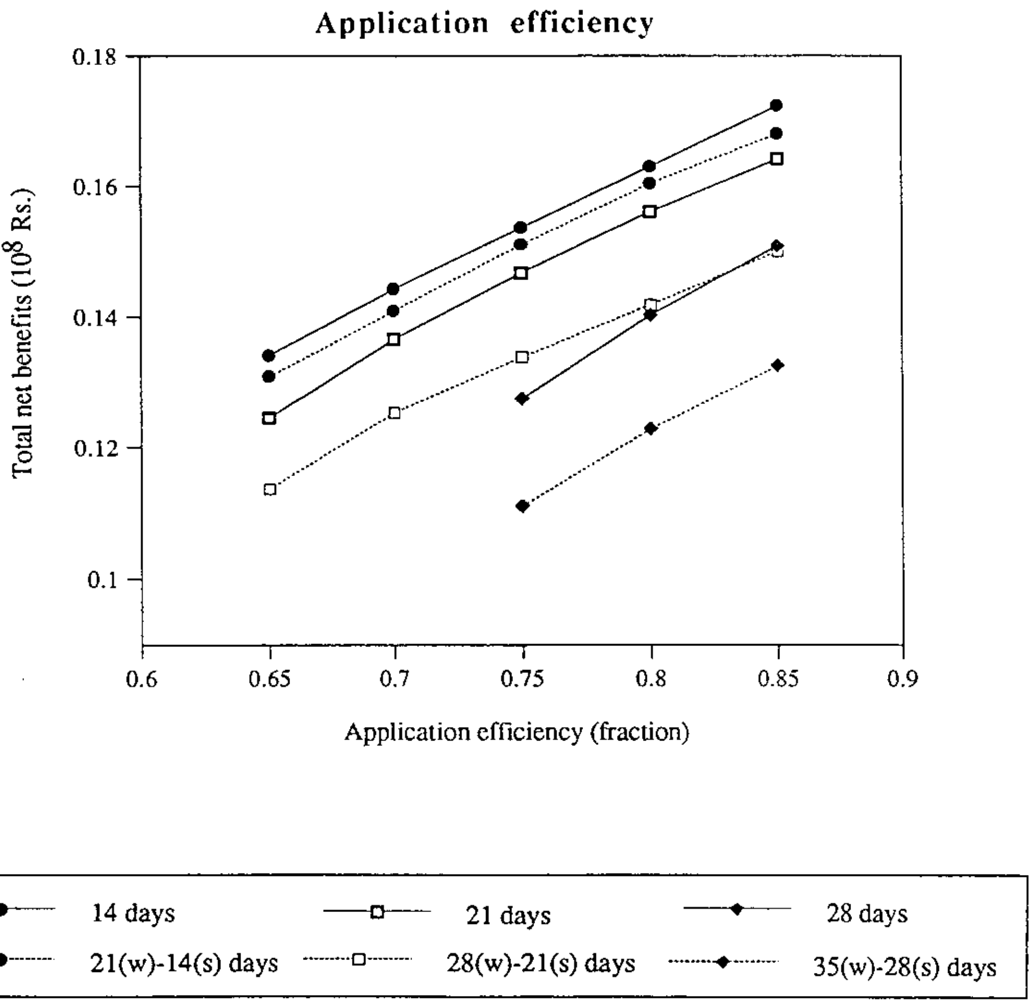


Figure 9.19 The total net benefits influenced by the variation in application efficiency for fixed cropping distribution

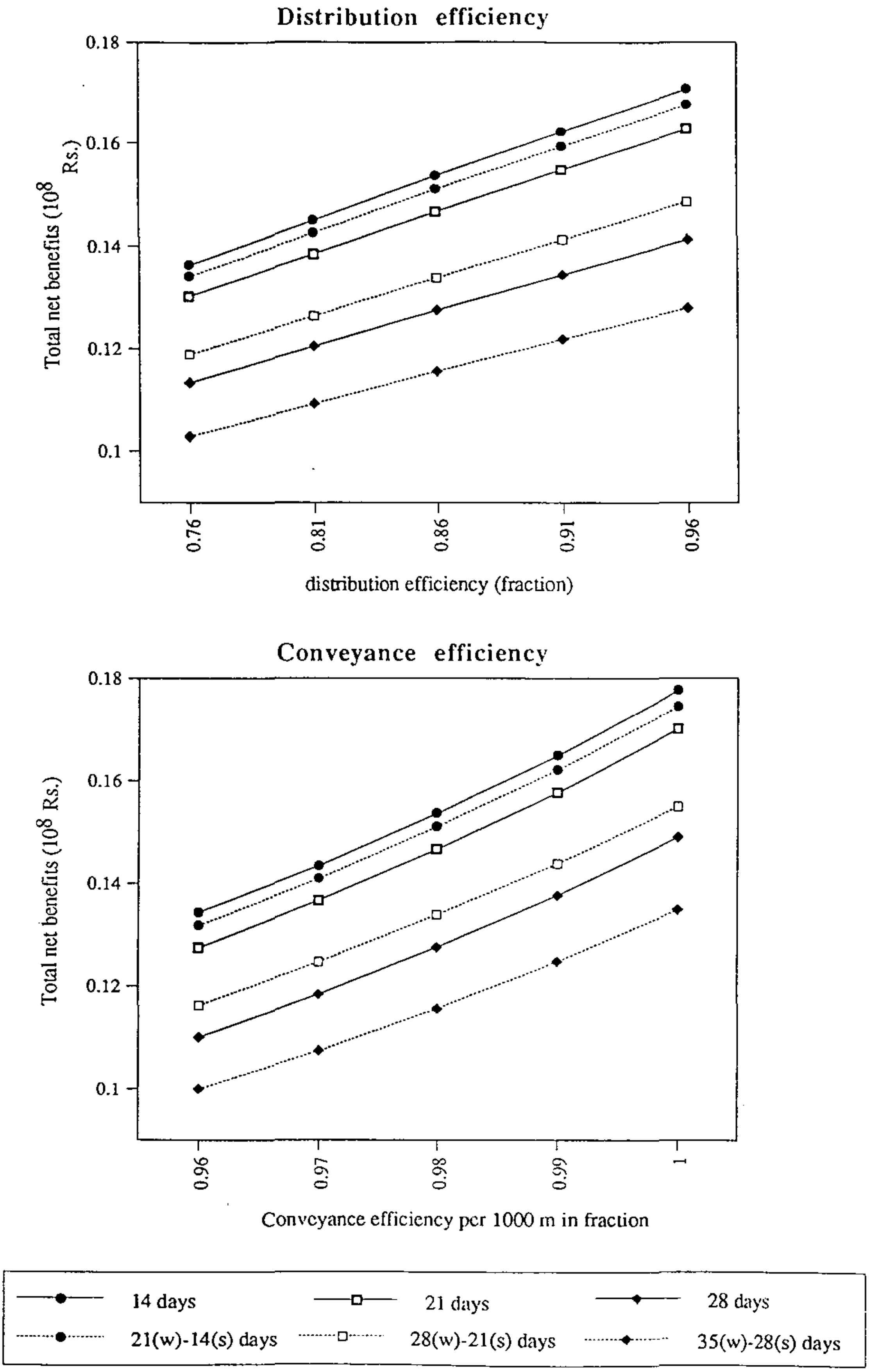


Figure 9.20 The total net benefits influenced by the variation in distribution and conveyance efficiencies for fixed cropping distribution

When the allocation is done at scheme level, the considerations of the capacity of the canal net work and outlets are not required, except for the restrictions on the capacity of the main canal. AWAM allocates the resources at lower levels also, and in these cases it is important to consider the carrying capacity of the canal network and outlets. The results obtained above (allocation plans) for the different parameters are with inclusion of constraints which take care not to release water through the canal network and outlets beyond their prescribed capacity (Section 6.3.3.2).

The results (allocation plans) were also obtained without considering the canal and outlet capacity constraints for the same sets of parameters (all the approaches, initial reservoir storage volumes, irrigation interval and cropping distributions). It was found that the total net benefits decreased very little (less than 0.75%) by considering these restrictions. However the allocations to some of the AUs were affected. Thus it is appropriate to consider the carrying capacity of the canal network for VDI approach also, though the network is designed for fixed depth irrigation approach. The capacity of some of the outlets is relatively low. Increasing the capacity of these outlets is already under consideration. With the increase in irrigation interval and decrease in reservoir storage capacity, the influence of these restrictions on the total net benefits was negligible. The similar results are obtained for all irrigation depth approaches.

9.4 CONCLUSIONS

The concept of deficit irrigation was included in the computer model through variable depth irrigation approach for the allocation of the resources at planning and during operation of the irrigation scheme. This forms the Hypothesis 3. However the verification of this hypothesis is not complete without testing it for actual application. Therefore the specific aim of this chapter was to apply the model to the case study to obtain the allocation plans with the incorporation of deficit irrigation and in the process to compare the output obtained from the variable depth irrigation approach (in which the concept of deficit irrigation as outlined under Hypothesis 1 is included) with the traditional fixed depth irrigation and full depth irrigation approaches.

The allocation plans were obtained for different parameters which were included in the model such as crops, soils, irrigation interval, initial reservoir storage volumes, efficiencies and the outlet and canal efficiencies. The total net benefits were compared for the different magnitude or considerations of these parameters. The summary of the allocation plans for the two cases which are the best allocation plan in terms of maximum total net benefits for fixed cropping distribution and free cropping dsitribution is presented in this chapter, and the details of the allocation plan for fixed cropping distribution are given in the Appendix C. Thus the part of the Hypothesis 3 (allocation plans at the planning stage) is verified in this chapter. The total net benefits obtained with the VDI approach introduced in the model were found to be higher than those obtained with FXDI and FLDI approaches. The results of this chapter are thus indicative of the benefits of deficit irrigation and its application in the irrigation scheme while obtaining the allocation plans through the use of the model AWAM, developed during this research.

CHAPTER X

PRODUCTIVITY AND EQUITY AND OTHER PERFORMANCE PARAMETERS

Summary. In this chapter performance parameters of an irrigation scheme in relation to management options are discussed. The inclusion of two performance parameters viz. productivity and equity while obtaining the allocation plans with AWAM, and measurement of these parameters for the generated allocation plan, are described. The productivity and equity of allocation plans produced for different management options, obtained from the combinations of different irrigation depth approaches and sets of irrigation interval, are compared. This constitutes part of Hypothesis 4. This is followed by the verification of Hypothesis 5, by studying the relationship between productivity and equity. The other two performance parameters viz. stability and sustainability in relation to AWAM are also discussed. The allocation of the resources during intraseasonal operation of the irrigation scheme to include deficit irrigation and productivity and equity aspects (part of Hypotheses 3 and 4) is also summarised at the end of this chapter.

10.1 PERFORMANCE OF IRRIGATION SCHEME

The objective of the irrigation scheme may vary over the period of time and with the interest of persons or organisations involved in the scheme. To quote Steiner (1991:6):

"Viewed from an international level the purpose of the system may be to contribute to structural adjustment and the balance of payments or merely to provide a tangible example of donor agency expenditure. On the national level, the purpose of a system may be framed in terms of famine relief, refugee resettlement, or food security. Underlying irrigation development may be socio-political reasons, such as the exercise of influence on a political constituency and, in some cases, the introduction into a given irrigation region of ethnic groups more favourable to the government."

Notwithstanding the several possible purposes of an irrigation scheme, the overall objective of the type of irrigation scheme considered in this thesis is usually to contribute to the well being of the people directly or less directly involved in the scheme (Chambers, 1988). As a huge amount is invested in the irrigation scheme and the well being of several thousands of the people depends on its success, it is important to know how the scheme has performed to achieve the declared objectives or goals. Several researchers (Biswas, 1984; Chambers, 1988; Abernethy, 1989 and Burton, 1992) discussed the performance assessment of the irrigation scheme. According to Abernethy (1989:2) the performance of the irrigation scheme is represented by

"its measured levels of achievement in terms of one, or several, parameters which are chosen as indicators of the system's goals."

Abernethy (1986) considered production, equity, regularity and reliability and durability as the set of parameters representing the performance of the irrigation scheme. Abernethy (1989) later redefined five major goals as: productivity, equity, profitability, sustainability and quality of life. According to Chambers (1988), the criteria of good performance vary depending on the type of person involved in the management of the scheme. For example, for an agricultural economist 'high and stable farm production and incomes' may be the performance criteria and on the other hand the goal of a landless labourer may be 'increased labour demand, days of working and wages'. However he summarised the three criteria of productivity, equity and stability. Citing Uphoff (1988), Steiner (1991) grouped the performance goals into five major headings : productivity, equity, harmony, environmental sustainability and economic sustainability or cost effectiveness. The purpose of the present study is not to argue over "what the performance goals should be?" But for the purpose of describing the performance parameters and the utility of proposed method to achieve the performance goals, these are grouped in to four and described briefly in the following sections. The detailed discussion is presented by Chambers (1988), Steiner (1991) and Abernethy (1989).

10.1.1 Productivity

The productivity is related to output from the system in response to the input added to the system and there are several indicators of productivity. The principle output of the scheme is the crop produce or its economic equivalence and area irrigated. The productivity can be indicated by measuring these outputs in gross term or relative to input utilised. The inputs of interest in irrigation are land and water and finance. The productivity is relevant when the outputs are measured in terms of the input which is scarce. Lenton (1986), Chambers (1988), Abernethy (1989), Steiner (1991), Burton (1992) and Hales (1994) listed various indicators of productivity. All these can be summarised as total production, total net benefits and total area irrigated in gross terms and total production or benefits or area irrigated per unit of water utilised or area available. The water utilised is measured at various levels in the irrigation scheme i.e. from the headworks to the root zone of the crop. The productivity indicators are easy to quantify and included in all studies related to performance of an irrigation scheme.

10.1.2 Equity

Equity is the complex issue. It implies equality, fairness and even handed dealing (Chambers, 1988). The performance criteria of equity is the source of debate and is complex because equity depends on one's concept of what is fair, and in what way it is fair, and this may vary greatly in the irrigation scheme. Another reason, as Abernethy (1989) pointed out, is that equity is multidimensional, which takes into account varying circumstances of farmers such as size of land holding, soil type or value of land, its closeness to headworks and many more. The equity according to one parameter (say land holding) may be in fact inequity with respect to another parameter (say family size). Depending on the circumstances existing in the irrigation scheme, both equity or inequity in certain ways might be desirable.

Here the objective is not "in what way equity should be achieved?" but "how to achieve the equity or inequity in a prescribed way". Therefore the possible causes of inequity are discussed in this section.

All the studies related to equity are aimed at equity or inequity in water distribution. Chambers (1988) discussed 'two doctrines' in water distribution existing in irrigation schemes throughout the world. One is of prior appropriation meaning whoever first exploits resources establishes a right to continue to do so. The other doctrine is of proportional equality, generally in proportion of land surface area. He argued the first doctrine leads to inequity as the topenders regard the use of water as a right and the second doctrine, though it appears to be equity in water distribution, may add to the already existing inequality of land holding. This view was supported by Steiner (1991). In parts of Maharashtra state of India, the practice followed is to reduce allocation of water as land holding is increased (Chambers, 1988). Full water is allocated to the first 2 hectares and then less per hectare above two hectares. In such cases, however, there are other factors which may not justify the water allocation to be truly dependant on area. Some times the person with a small land holding may have other sources of income, and the large farmer is truly dependant on farming for survival. Another view not supporting equity in distribution was discussed by Mary Tiffen (Abernethy, 1986). According to her in the irrigation scheme with inequitable water distribution, the land at the top end of the scheme will have a higher price and land at the tail end may be cheap. So a farmer at the top end might have invested more per unit of land and bought less land though his family size is more. He might have assumed that he is able to support his family from more production per unit land area. However if area proportionate equity is enforced in such scheme, the farmer at the top end will be adversely affected and farmer at the tail end with more land bought at cheap rate may enjoy the unequal benefits of equal distribution.

The value of land or the soil type may be the cause of inequity. If some farmers have sandy soil, the area proportionate water allocation to them will not achieve equity as another farmer with clay-loam soil may produce more with the same water on the same area. Similar is true when the two farms, one near the head of the system and another at the tail of the system are compared. The other views are to allocate the water proportionately to the family size (Malhotra, 1982) because of the greater needs of a large family. The availability of water to the farmers in different crop growth stages also influences the equity. The delivery of water in critical crop development stages is more important than in other stages. Thus even if there is equity in water distribution two farms of same characteristics but receiving water in two different stages may cause inequity.

The above discussion indicates that achieving equity in water distribution may or may not be justified and several other parameters play a role in the allocation of water to different users. The local conditions better describe the type of allocation. Therefore there is a need to include not only equity in the distribution of water but also desired inequity (such as farmers with small land holding getting more water than proportional to their land holding) while formulating any allocation plan.

10.1.2.1 Measures of equity

Though there are different views on consideration of equity, there are a number of methods to measure equity of water distribution. Abernethy (1986) studied Christianson Coefficient (Christianson, 1942 and Till and Bos, 1985), Gini coefficient, inter-quartile ratio, modified inter-quartile ratio and coefficient of variation and found on the basis of standard error that Gini coefficient, Christianson coefficient and modified inter-quartile ratio were acceptable. Sampath (1988) recommended Theil's information theoretic measure (Theil, 1967). Steiner (1991) considered relative mean deviation, coefficient of variation, inter-quartile comparison and Gini coefficient as the measures of equity.

10.1.3 Stability

Stability refers to the variability of productivity and equity over time. This variability is mainly due to variation of weather conditions over different years. It is quite important that management of an irrigation scheme should result in steady output over the period of time for creating the sense of security among the water users. Stability can be measured by comparing the productivity and equity over the time.

10.1.4 Sustainability

Sustainability can be described as environmental sustainability and economic sustainability. These are described by Abernethy (1986), Chambers (1988) and Steiner (1991). Environmental sustainability refers to the management of irrigation scheme in such a way that its effective life span is not reduced. It includes the prevention of adverse physical changes such as waterlogging, salinity, leaching of nutrients from soil, silting of reservoir and canal network, growth of weeds, erosion, mining of ground water. In relation to land and water allocation, waterlogging and salinity are important. Economic sustainability refers to the productive capacity of the scheme. It includes labour use and payment from water users. According to Abernethy (1986) sustainability is easy to say but not easy to measure and to some extent this can be assessed by monitoring rates of change of key variables, in order to assess whether there is deterioration. For example monitoring the rate of change in salinity levels and water table levels, weed concentration, reservoir levels and level of maintenance and repair of structures in the scheme. However Abernethy further commented that the rates of changes may be subject to greater errors than measurement of the primary variables.

10.2 MANAGEMENT POLICIES AND OPTIONS

The various organisations and people involved in the scheme agree that the irrigation scheme should perform in the best possible way. But what causes the scheme to vary its performance? The availability and adoption of different management policies change the scheme performance. As discussed in Chapter I, these can be classified as hardware related management policies and software related management policies. Hardware related management policies may range from increasing the capacity of the reservoir, reducing the conveyance losses in the canal network to the development of on farm structures. However software related management policies include allocation of resources in the scheme, adoption a water supply system to create awareness among the farmers about water use, and formation of water users organisations in the scheme. As discussed in Chapter I, these are complementary to each other. It is possible that some management policies do not directly influence certain performance parameters. For example increasing the size of reservoir may not affect the salinity levels (unless the increased supply of water is meant for leaching of the salt and not for irrigating more land or for increasing crop yield through improved water supply).

There may be several options with each management policy. For example, increasing the capacity of the reservoir can be achieved by desilting the reservoir, increasing the height of the dam or if reservoir capacity is sufficient, the water availability can be improved by developing the catchment area. There may be several options of the magnitude of increase in size depending on the trade off between increased reservoir size and changed performance. All these options are called management options.

In the present study the management policy is software related and is the optimum allocation of land and water resources to various crops grown in different allocation units. The management options are discussed in Section 10.6.1.

Performance of the irrigation scheme against a particular management policy can be evaluated before the beginning of a particular time span, during the span and after the time span. It is possible that performance expected in the beginning may change during and after the chosen time span. This may happen due to changed conditions during the time span and changes in other management policies during the span. For example, land and water allocation plan can be designed for certain performance in the beginning of the chosen time span. However its performance may be altered during or after the time span due to changed climatic conditions during the time span or changes in the management of water delivery to the farms.

10.3 PERFORMANCE OF IRRIGATION SCHEMES IN IRRIGATION WATER MANAGEMENT MODELS

In Chapter II, irrigation water management models are classified in to: allocation models and evaluation models. In all these models some performance criteria are included while producing or testing allocation policies. The allocation models discussed in Chapter II produce a land and water allocation plan before the start of the irrigation season. These models considered the productivity and stability while developing the allocation plans. Only in two cases the equal distribution of water to the command areas of different canals or regions in the scheme was considered while maximising the productivity (Shyam et al., 1994 and Onta et al., 1995). The stability was considered in those models which mainly produced water allocation plans (Dudley et al., 1971[a]; Palmer-Jones, 1977; Bras and Cordova, 1981; Rhenals and Bras, 1981; Rees and Hamlin, 1983; Loftis and Houghtalen, 1987 and Vedula and Mujumdar, 1992) and in some cases only land allocation plans (Maji and Heady, 1978 and Afshar et al., 1991). This was incorporated by assuming certain weather parameters as stochastic. However evaluation models which test the chosen water allocation policy were able to test the equity in water distribution among the different users (Burton, 1992 and Hales, 1994). The evaluation model could not give consideration to the stability. There is no mention about sustainability while developing the allocation plans. The main difficulty as pointed out earlier is to quantify and measure the sustainability. However underlying considerations while deciding or assuming the water allocation policy can throw some light on the sustainability. In water allocation models, some land and water allocation models and evaluation models, the amounts of water delivered to different crops or units are adjusted to fill the soil root zone to an appropriate level, and thus may not be the cause of increased salinity or water logging (unless other management policy does not perform well, such as distribution of allocated water in practice which is related to on and off farm water management in the scheme). Land allocation models, however, do not tend to supply water to the correct requirement as mostly the underlying water allocation policy is full irrigation. This may cause the supply of water which is not necessary.

10.4 PERFORMANCE PARAMETERS IN AWAM

It is possible to compute productivity and equity in an irrigation scheme by certain allocation plans developed by irrigation water management models (allocation models). In such cases both productivity and equity are guided by the criterion of objective function, and computing productivity and equity is equivalent to analysing the objective function criteria for these performance parameters. Achieving a certain performance by the management policy through the development of an allocation plan for the irrigation scheme, however, remained unnoticed. Though the objective function criterion of the allocation models relate to maximising productivity, the review of different irrigation management models presented in Chapter II reveals that the productivity is included in the models for developing the allocation plans either in the form of total crop production (single crop model), or of total net benefits. The productivity in other forms and the equity parameter of performance are mostly neglected in development of allocation plans by allocation models. The productivity and equity in different forms are appropriately considered in the allocation plans by evaluation model, by defining those goals in water allocation policy for which allocation plans were prepared. But as discussed earlier the water allocation policy chosen may not be the optimum one and is directed by some considerations. In such cases, the global optimum solution in respect of an allocation plan is not possible. Therefore there is a need to incorporate productivity and equity in various forms while developing allocation plans by the allocation model, so that the specific needs or objectives in the irrigation scheme can be satisfied. Similarly the deficit irrigation approach suggested in this study (variable depth irrigation) should also be able to produce allocation plans with productivity and equity in consideration. With this view the Hypothesis 4 was formulated. This is again given below.

> The resources can be allocated at planning and operation stages of a heterogeneous irrigation scheme to include the productivity and equity aspect (the fair allocation of the resources to different users while optimising the output from the irrigation scheme). The deficit irrigation can be coupled with productivity and equity aspects and the entire scenario can be combined in a computer model.

The attempts were made while formulating the AWAM to incorporate the productivity and equity in various forms with different irrigation depth approaches including variable irrigation depth approach. The formulation in this regard is explained in Chapter VI (Section 6.3). In this section these are summarised below. The consideration of stability and sustainability in AWAM is discussed in Section 10.8.

10.4.1 Productivity

The productivity is included in AWAM through the objective function of RA (Resource Allocation) in the following forms

a) Gross terms

These are included through quantitative type of objective function (Section 6.3.2.1)

1. Total net benefits (equation 6.18)
2. Total area irrigated (equation 6.19)
3. Total crop production for the single crop case (equation 6.20)

b)Efficiency terms

These are included through qualitative type of objective function (Section 6.3.2.2)

1. Net benefits per unit area irrigated
2. Crop production per unit of area irrigated for single crop
3. Crop production per unit water used for single crop
4. Net benefits per unit water used
5. Maximum irrigated area per unit of culturable command area

10.4.2 Equity and Inequity

It is important to include both equity and inequity in distribution in the irrigation water management models which lead to development of allocation plans. In AWAM equity or inequity is included through the formulations of constraints in RA model. These are described in Section 6.3.3.3 under equity constraints. Thus AWAM tries to achieve prescribed equity or inequity while optimising productivity

10.4.2.1 Equity

As discussed in Section 10.2.2, the equity may be needed based on area possessed by the farmer, soil type of the farm, family size and there may be many more factors. All these are the 'base of equity'. In AWAM the provision is made to allocate the resources based on the area of land holding (base of equity-area) and the soil type through water requirement (base of equity-water requirement). The allocation with equity based on other factors can be obtained by AWAM but the corresponding proportion (λd_a) has to be computed externally and be given to AWAM as input.

10.4.2.2 Inequity

The inequity may be required in any form and base. AWAM can produce the allocation plans with prescribed inequity if the values of proportion (λd_a) corresponding to the prescribed distribution are given as input for each AU.

10.4.2.3 Means of equity

All the studies and discussion so far presented were intended towards the equal or unequal distribution of water. Some causes of conflict arise when equity in water distribution is considered due to soil type, the position of the allocation unit in the irrigation scheme, crops grown and water delivery in different crop growth stages. The point always argued is that due to these factors equity in water distribution may cause the inequity in output generated. For example as discussed, the area based equal allocation of water to AUs with different soils may produce proportionally more output for AU with silty clay soil than AU with sandy soil, or the water requirement based equal allocation of water may tend to allocate water excessively to AU with sandy soil and thus result in area proportionate inequity in outputs generated. If the equity in water distribution can cause the inequity in income generated and when it is not desirable, then why not allocate the resources to achieve equity in the benefits? In AWAM, therefore, the provision is made to obtain the allocation plan for equity in output generated. The output considered is net benefits or crop production (in the single crop case). The equity in area irrigated is also included while obtaining allocation plans in AWAM. In variable depth irrigation approach, equity in area irrigated may not be appropriate, but it is useful in fixed depth irrigation, full depth irrigation and variable depth irrigation with minimum stress approaches. In full depth irrigation approach or variable depth irrigation approach with minimum stress, equity in area allocation for irrigation may be helpful to offset the effect of soil type. Thus the following are the four means of equity included in AWAM while obtaining the allocation plan.

1. Area irrigated (equation 6.61)
2. Water distributed (equation 6.62, 6.63, 6.64)
4. Crop production obtained (single crop case, equation 6.65)
3. Benefits generated (equation 6.66)

While developing the allocation plan for equity in water distribution, the equity in water distribution with or without conveyance and/or distribution losses are also included. This is to integrate the entire scenario while trying to achieve the equity in water distribution. The desired inequities in all these described means can be incorporated in AWAM.

10.5 MEASUREMENT OF PRODUCTIVITY AND EQUITY IN AWAM

10.5.1 Productivity

Productivity in AWAM is measured by all those forms through which it can be included while obtaining the allocation plans i.e. total net benefits, total area irrigated, total crop production for the single crop case, net benefits per unit area irrigated, crop production per unit of area irrigated for a single crop, crop production per unit water used for a single crop, net benefits per unit water used, maximum irrigated area per unit of culturable command area. The productivity can be measured directly by these terms or by reference to certain standards, for example productivity with no limitations on water, or productivity of that management option which gives maximum productivity. The productivity measured by reference to a certain standard is useful to compare the productivity of two different irrigation schemes for a certain management policy.

10.5.2 Equity

Like equity consideration while obtaining the allocation plan, equity measurement is also multidimensional. Different possibilities were considered while measuring the equity in AWAM through following.

1. Parameter by which equity is measured
2. Parameter to which equity should be proportional and
3. Formula for equity measurement

As discussed above, equity can be included in AWAM for area, water, crop production and net benefits. Similarly equity can be measured for area, water, crop production and net benefits. In AWAM, the equity can be included to be proportional to area, water requirement or other aspects (such as family size) while obtaining the allocation plans. In the same way, equity can be measured in AWAM proportional to area, water requirement or other aspects. However for other aspects data of proportionality needs to be given separately to AWAM. In AWAM equity can be measured by following six formulae.

1. Christianson Coefficient
2. Inter-quartile ratio
3. Modified inter-quartile ratio
4. Coefficient of variation
5. Theil's Index
6. Gini Coefficient

Christianson Coefficient, inter-quartile ratio, modified inter-quartile ratio and the coefficient of variation are the measure of equity and therefore their values equivalent to 1 indicate equity. However Theils index and Gini Coefficient are the measure of inequity and therefore their values equivalent to zero indicate the equity.

The inclusion of equity or measurement of equity in relation to 'water' can be effected at various points in the irrigation scheme. In AWAM various points considered are haedworks, outlet of allocation unit and farm.

10.5.2.1 Computation

The equity in AWAM is not measured directly by the quantity of the parameter (area irrigated, water delivered or benefits generated from each AU) by which equity is to be measured, because the characteristics of each AU or the value of the parameter to which equity should be proportional for each AU is different. For example, CCA of each AU is different. To even this effect, the contribution of the parameter by which equity is measured towards each AU is computed with reference to the contribution of the parameter to which equity should be proportional for the corresponding AU. This is called the allocation ratio and is computed as the ratio of the actual allocation proportion and the desired allocation proportion given by equation 10.1.

$$Ra_a = \frac{\lambda a_a}{\lambda d_a} \tag{10.1}$$

where

Ra_a = allocation ratio of a^{th} allocation unit

λa_a = actual allocation proportion for a^{th} allocation unit

λd_a = desired allocation proportion for a^{th} allocation unit

$$\lambda d_a = \frac{\xi d_a}{\sum_{a=1}^{na} \xi d_a} \tag{10.2}$$

where

ξd_a = the value of the parameter to which equity should be proportional, assigned to a^{th} allocation unit.

ξd_a can be equal to $Aamax_a$, the CCA of a^{th} allocation unit (ha). In this case

$$\sum_{a=1}^{na} \xi d_a = TA$$

where TA is CCA of irrigation scheme.

$$\lambda a_a = \frac{\xi a_a}{\sum_{a=1}^{na} \xi a_a} \tag{10.3}$$

where

ξa_a = value of parameter by which equity is measured, computed for a^{th} allocation unit

The value of the parameter by which equity is measured can be area allocated, water allocated (at various levels) or crop production or benefits generated. Thus

$$\xi a_a = \sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} A_{pcsa}$$ (area allocated)

$$\xi a_a = \sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} SWD_{pcsa} A_{pcsa}$$ (water allocated at headworks)

$$\xi a_a = \sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}\sum_{i=1}^{I} \frac{WD_{ipcsa}}{\eta ca_{ia}} A_{pcsa}$$ (water allocated at AU)

$$\xi a_a = \sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}}\sum_{i=1}^{I} \frac{WD_{ipcsa}}{\eta ca_{ia}\eta da_{ia}} A_{pcsa}$$ (water allocated in AU)

$$\xi a_a = \sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} Ya_{pcsa} A_{pcsa}$$ (crop production obtained-single crop case)

$$\xi a_a = \sum_{s=1}^{ns_a}\sum_{c=1}^{nc_{sa}}\sum_{p=1}^{np_{csa}} NB_{pcsa} A_{pcsa}$$ (Net benefits generated)

Once the allocation ratio for each allocation unit is determined equity is computed by one of the six formulae in AWAM. These are described below. The allocation ratios of each AU are arranged in descending order and divided into the required number of groups (generally quarters)

1. Christianson Coefficient

$$Ecc = \frac{\overline{Ra^{ql}}}{\overline{Ra}} \tag{10.4}$$

where

Ecc	=	Christianson Coefficient
$\overline{Ra}$	=	the average of allocation ratios of all AUs
$\overline{Ra^{ql}}$	=	the average of allocation ratios of all AUs in last division or quarter

2. Inter-quartile ratio

$$Eil = \frac{Ra^{qlf}}{Ra^{qfl}} \tag{10.5}$$

where

Eil	=	inter-quartile ratio
Ra^{qfl}	=	the allocation ratio of the last AU of first division or quarter
Ra^{qlf}	=	the allocation ratio of the first AU of last division or quarter

3. Modified inter-quartile ratio

$$Ei2 = \frac{\overline{Ra^{ql}}}{\overline{Ra^{qf}}} \tag{10.6}$$

where

Ei2	=	modified inter-quartile ratio
$\overline{Ra^{qf}}$	=	the average of allocation ratios of all AUs in first division or quarter
$\overline{Ra^{ql}}$	=	the average of allocation ratios of all AUs in last division or quarter

4. Coefficient of variation

$$Ecv = \frac{1}{\overline{Ra}} \sum_{a=1}^{na} \sqrt{\frac{\left(Ra_a - \overline{Ra}\right)^2}{na}} \tag{10.7}$$

where

Ecv = coefficient of variation

5. Theil's Index

$$Eti = \sum_{a=1}^{na} \log\left(\frac{1}{Ra_a}\right) \tag{10.8}$$

where

Eti = Theil's index

6. Gini Coefficient

$$Egc = \frac{\frac{1}{na(na-1)} \sum_{i=1}^{na} \sum_{j=1}^{na} \left|Ra_i - Ra_j\right|}{\overline{Ra}} \tag{10.9}$$

where

Egc = Gini coefficient

10.6 ALLOCATION PLANS WITH PRODUCTIVITY AND EQUITY BY AWAM

Hypothesis 4 states that the productivity and equity can be incorporated for obtaining allocation plans by an irrigation water management model. Sections 6.3 and 10.4 explains about the formulation of the model to include productivity and equity to obtain allocation plans. In this section the actual allocation plans are obtained with productivity and equity with the help of AWAM for Nazare Medium Irrigation Project in Maharashtra State of India. As explained in Sections 10.4 and 10.5, productivity and equity (or inequity) can be included and measured in several ways depending on the specific needs. However in this section for verifying the Hypothesis 4, few cases of productivity and equity are considered. The main objective is to show that the optimum allocation plans can be obtained with inclusion of productivity and equity in irrigation water management model for different situations. While accomplishing this objective, different management options and equity cases are inter compared (See Section 10.6.1).

10.6.1 Management Options and Consideration of Productivity and Equity

The management policy is the optimum allocation of land and water resources. The different options considered under this management policy are the combinations of different irrigation depth approaches (variable depth irrigation, VDI, fixed depth irrigation, FXDI and full depth irrigation, FLDI) and different sets of irrigation interval (14, 21, 28, 21-14, 28-21 and 35-28 days). The allocation plans are obtained for with no equity and achieving equity in area allocation, water allocation and benefits generated from each allocation unit while maximising the productivity. The water allocation is considered at AU. The equity in allocation is considered proportional with the culturable command area of each allocation unit.

The productivity is measured in terms of the total net benefits obtained from the irrigation scheme and represented with reference to the productivity of the management option with the highest productivity. Thus the productivity of the management option with the highest productivity would be one. The allocation plans of different sets of irrigation interval, irrigation depth approaches and equity scenarios for particular cropping distribution are considered together while computing productivity. However different cropping distributions are treated separately for computing productivity. The equities in allocation of area, water and benefits generated are measured in proportion to area of each allocation unit. Christianson Coefficient is used for the measurement.

The allocation plans are obtained for three different situations. These are free cropping distribution, crop production restriction at scheme level and crop production restrictions at allocation unit level. The free cropping distribution is introduced in Section 9.2.4. Crop production restriction at scheme level restricts the production to be obtained from different crops from the scheme within certain range. The minimum of the range for all crops is given in Section 9.2.5 and maximum of the range is free. Crop production restrictions at allocation unit level put the limits on production to be obtained from each crop from each allocation unit. The minimum limit for each crop at allocation unit level is considered as equivalent to area (CCA) proportionate minimum limit of each crop at scheme level (Section 9.2.5). The maximum limit is considered as free.

First the allocation plans are obtained without giving consideration to equity in distribution, and then allocation plans with equity in area and water allocation and benefits generated are obtained.

In the following discussion of productivity and equity in relation to several management options and cropping distribution, the term 'more suitable soil' is used for the soil with higher water holding capacity. Thus the soils, SG-2, SG-3 and SG-4 are more suitable soils and SG-1 is less suitable soil. 'More productive AU' are used for those AUs which can make the efficient use of water delivered from the headworks. These are the AUs with more close to headworks, less distribution losses and more suitable soils. Different AUs, their relative position in the scheme and soil types are shown in Figure 7.8. The AU-1, AU-5 and AU-16 are with less suitable soil. AU-5, AU-9, AU-12 and AU-20 are with higher distribution losses.

10.6.2 No Consideration to Equity in Allocation

This is the case which was discussed in Chapter IX. In this chapter the equities in allocation are computed when equity is not considered in the allocation. This case does not direct allocation to specific AU by any criteria but the resources are allocated to those AUs which satisfy the optimality criteria of the objective function. The allocation is thus influenced by soil type, conveyance and distribution losses, capacity of canal network, crops and their evapotranspiration requirement etc.

If two AUs with different soils and the same other characteristics, exist at the same location in irrigation scheme, the AU with more suitable soil gets allocation over AU with less suitable soil. However if an AU with less suitable soil exists relatively close to the headworks, there will be a trade-off between conveyance losses and productivity of soil of AU for deciding the allocation. Similarly AU with more suitable soil but more distribution losses may not get allocation over AU with less suitable soil and less distribution losses. In the same way other factors and combinations of these factors act. The limitation to canal and outlet capacity can also restrict the allocation to the most productive AUs.

The productivity and equities in allocation of area, water (at AU) and generation of benefits for different sets of irrigation interval and irrigation depth approaches (management options) are shown in Figure 10.1. As explained earlier, in free cropping distribution only those crops which contribute to optimisation of criteria in the objective function appear in the allocation plan. In this particular case onion proved to be more beneficial than other crops in obtaining maximum total net benefits from the irrigation scheme. The maximum productivity is obtained with I=21 days and the variable irrigation depth approach. Productivity decreases with increasing and decreasing irrigation interval from I=21 days. The equities in allocation vary from 0 to 0.7. It is seen that in most cases equities are more than 0.5 (especially with VDI approach). The equity above 0.5 can not be considered as low. The relatively higher values of equity without consideration of equity are due to relatively high benefits attributed to onion. Due to this water tends to be allocated to less productive AUs than being allocated to more water consumptive crop on more productive AUs or less beneficial crops in an other season on more productive AUs. The allocation, therefore, is spread over more AUs resulting in more equity. Zero equity associated with I=14 days for fixed and full depth irrigation approaches is due to more frequent irrigations and application of minimum possible irrigation depth every time (for onion minimum possible irrigation depth with smaller irrigation interval is more than the application requirement). This caused more water to be applied to more productive AUs and thus restricting allocation to less productive AUs. The productivity is not drastically decreased mainly because of crop yield obtained close to maximum crop yield. In VDI as the irrigations can be skipped, the water loss due to applying minimum irrigation depth was, therefore, compensated. Equities in allocation of area, water (AU) and benefits are nearly the same, mainly because of only one crop appearing in the allocation plan.

The allocation ratio for area, water (at AU and headworks) and net benefits for each allocation unit for VDI, FXDI and FLDI approaches and for the irrigation interval with the best productivity (I=21 for all irrigation depth approaches) corresponding to each approach are shown in Figure 10.2. It is seen that the allocation is wide spread over the AUs. The effect of soil type and losses in conveyance and distribution is reflected in the figure. AU-1, though with less suitable soil got the allocation over other AUs with more

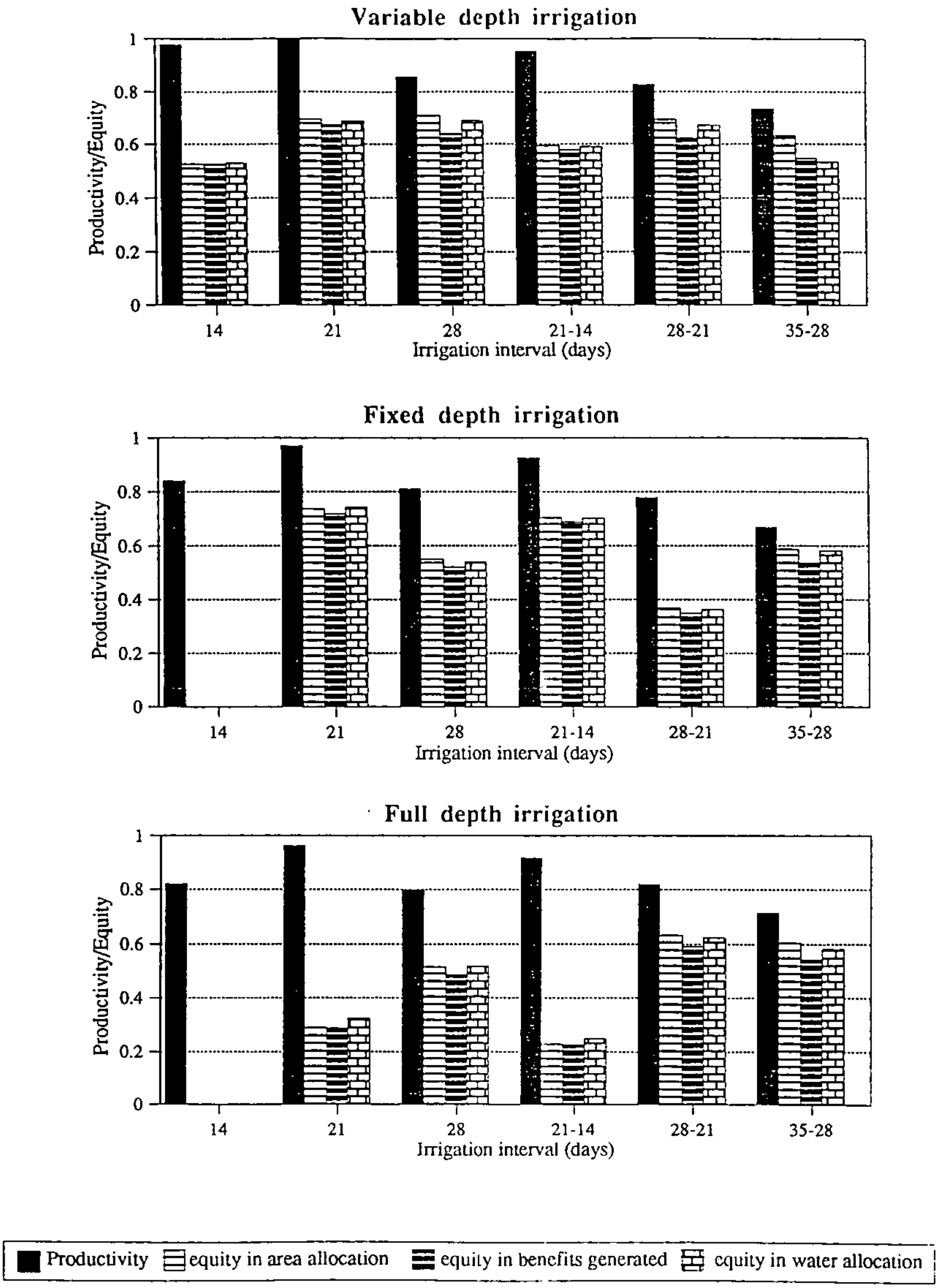


Figure 10.1 The measures of productivity and equities in area and water allocation (at AU) and net benefits generated for free cropping disitribution when equity in allocation is not considered

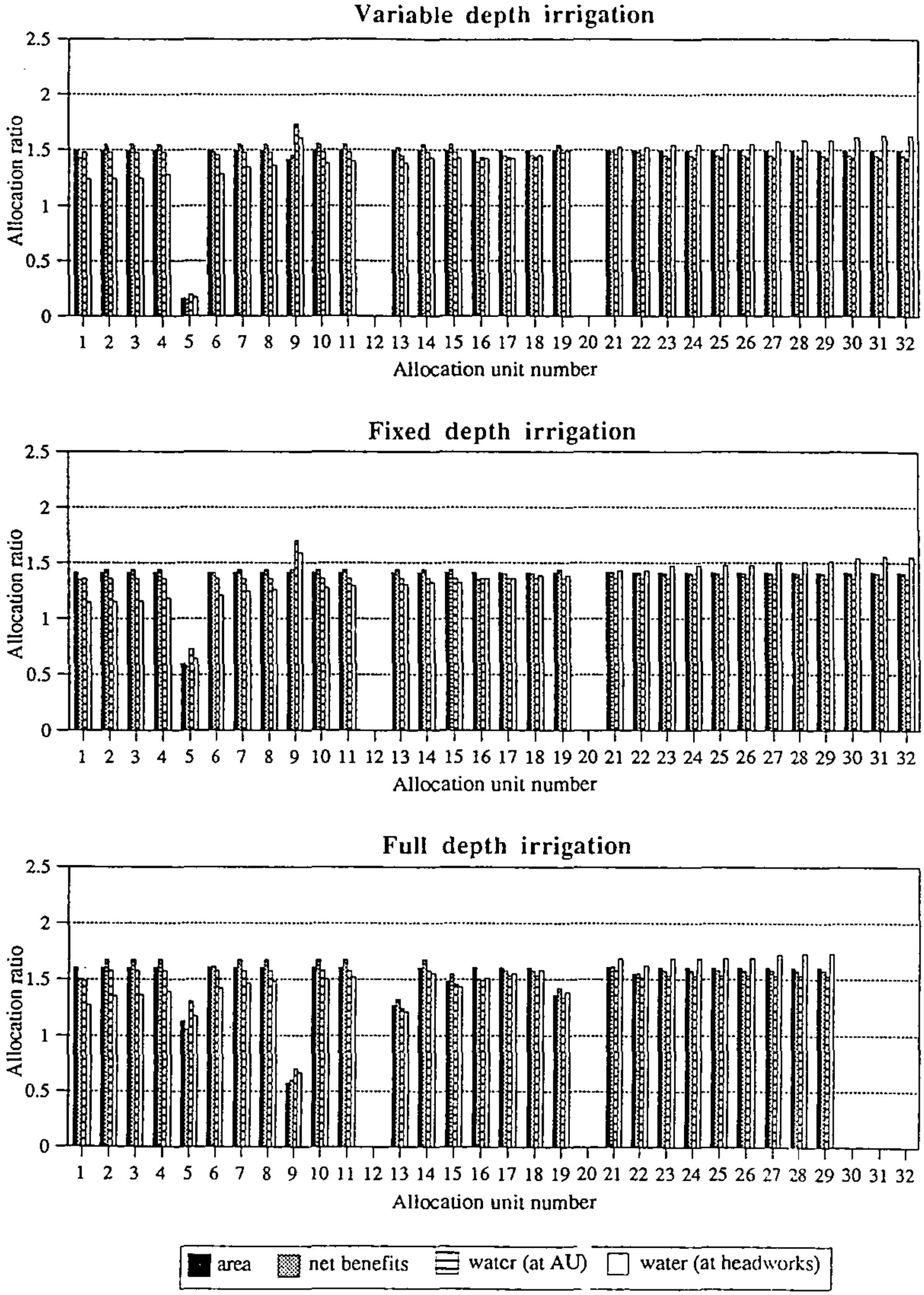


Figure 10.2 The allocation ratios for area allocated, water allocated (at AU and headworks) and net benefits generated for free cropping distribution when equity in allocation is not considered

suitable soil due to less conveyance losses. It should be pointed out here that though SG-1 is with relatively less water holding capacity but was found suitable for the most beneficial crop i.e. onion. Therefore though AU-16 which is also with less suitable soil but in middle reach also got allocation over AUs with more suitable soil, less conveyance losses but with more distribution losses (all approaches) or AUs with more suitable soil, less distribution losses and more conveyance losses (FLDI approach). AU-12 and AU-20 though with more suitable soil, did not get allocation due to more distribution losses within the allocation unit. AU-5 which is with more distribution losses got some allocation due to its closeness to the headworks. In FLDI the AUs at the tail end of the scheme, though with more suitable soil did not get allocation due to more conveyance losses. The AWAM, thus, appropriately evaluates all the process in the system and allocates the resources to crops and allocation units to satisfy the objective function and different restrictions.

The values of productivity and equities in allocation of area, water (AU) and generation of benefits are shown in Figure 10.3 when the restrictions are put on the production to be obtained from the different crops at the scheme level. The maximum productivity is obtained with VDI approach and I=14 days. It is observed that equities have now drastically dropped. In FXDI and FLDI approaches, the equities are zero with all sets of irrigation interval. Equities in VDI approach with higher irrigation interval are also zero. The allocation ratios for different allocation units for the best sets of irrigation interval for each irrigation depth approach shown in Figure 10.4 also indicate this fact. It is seen from Figure 10.4 that the allocation is spread over more AUs with variable depth irrigation approach than with fixed depth and full depth irrigation approaches. This was due to forced introduction of all crops in allocation plan. This made the allocation to be transferred to other crops from onion. The allocations transferred to the crops in other season (sunflower and groundnut in summer season) are utilised in the more productive AUs. Similarly the introduction of more water consumptive crop reduced the area to be irrigated. This caused the allocation to the less productive AUs to reduce, thus decreasing the equities. Equities in FXDI and FLDI approaches are zero due to less efficient use of water than in VDI approach. It is also observed that various equities differ. Equity in area allocation is usually higher followed by equity in water distribution. This indicates that the allocation to lesser productive unit was mainly done for less water consumptive crops and less beneficial crops. It is reflected in the allocation ratios for different allocation units for the best sets of irrigation interval for each irrigation depth approach shown in Figure 10.4 (I=14, 21-14 and 21 for VDI, FXDI and FLDI, respectively). The allocation to different AUs are found to be related to distribution and conveyance losses and suitability of soil in the allocation unit.

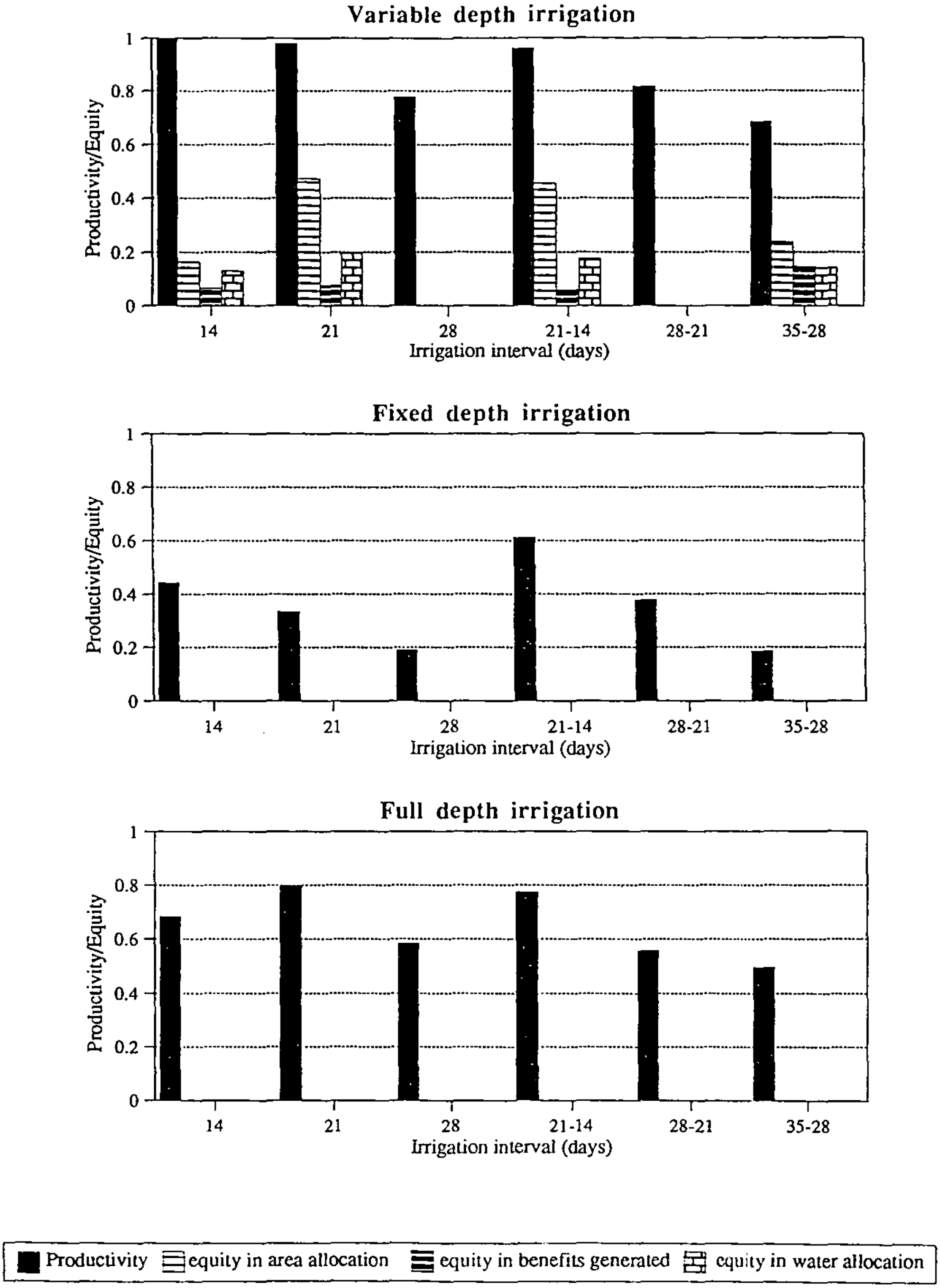


Figure 10.3 The measures of productivity and equties in area and water allocation (at AU) and net benefits generated for crop production restrictions at scheme level when equity in allocation is not considered

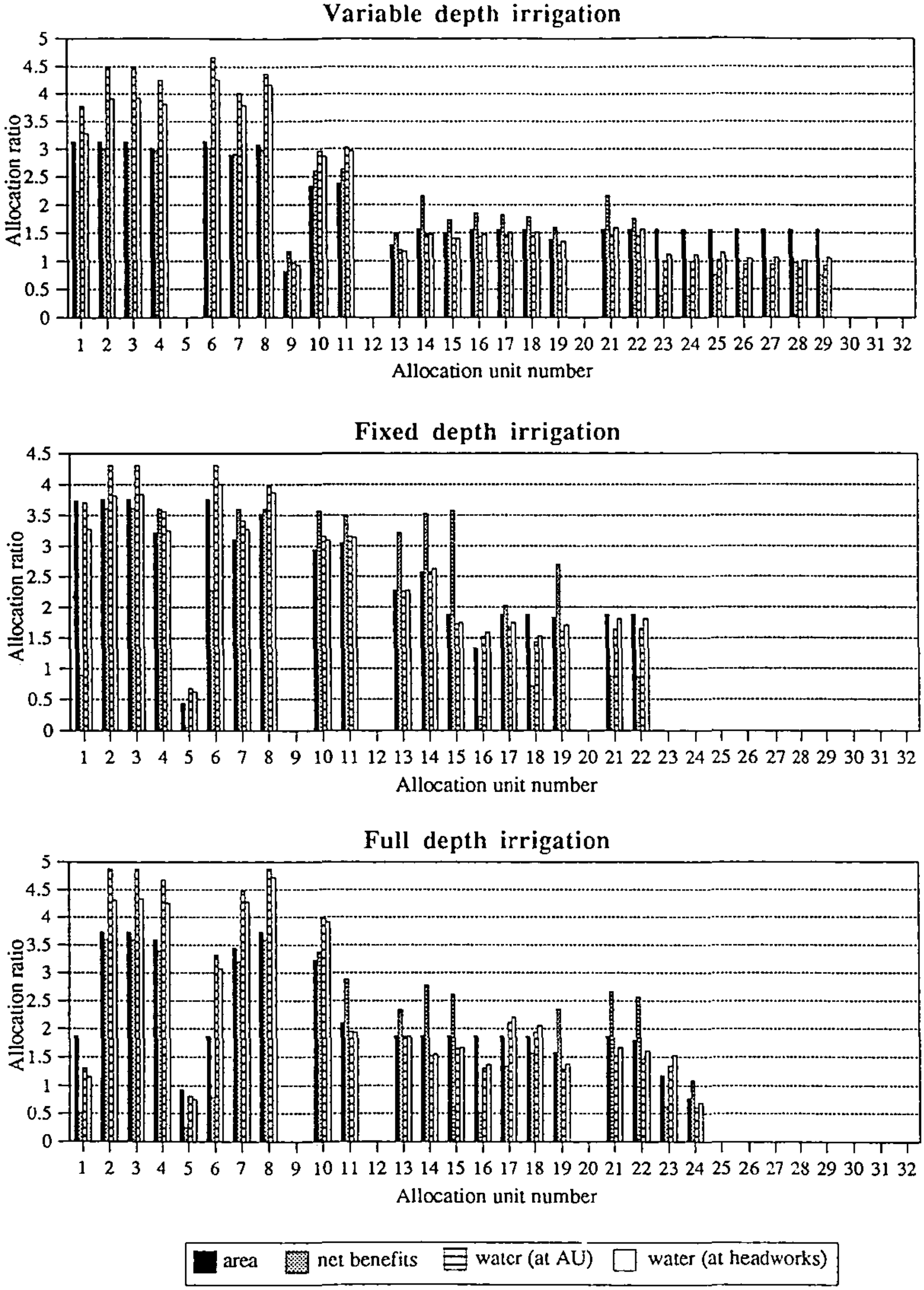


Figure 10.4 The allocation ratios for area allocated, water allocated (at AU and headworks) and net benefits generated for crop production restrictions at scheme level when equity in allocation is not considered

Productivity and equities, when the restrictions are put on the production to be obtained with different crops at AU level, are shown in Figure 10.5 for VDI, FXDI and FLDI approaches. The productivity is highest in the VDI approach with I=14 days. As expected, the equities are neither close to zero nor to one. The equities are not zero due to forced allocation to all AU due to restriction on production to be obtained from each AU from each crop. The equities are not close to one because of all surplus allocation going to the most productive AUs. This is indicated in the allocation ratios presented for the best sets of irrigation interval (same as with crop production restrictions at scheme level) in Figure 10.6. The less equity in benefits indicates that due to forced allocation to all crops in all AUs, area and water are allocated to all AUs but surplus water is allocated to those crops which produce maximum net benefits.

The allocation ratios for water allocated at AU and at headworks indicate that with the conveyance losses, allocation ratio for water allocated at AU decreases and allocation ratio for water allocated at headworks increases relative to each other. This is due to the greater amount of water lost in the process of conveyance for the AUs at farther end contributing to the water allocated to those AUs.

The productivity and equities with the best irrigation interval for VDI, FXDI and FLDI approaches for FRCD, CPR(S) and CPR(AU) are shown in Figure 10.7. It is seen that in the free cropping distribution, VDI, FXDI and FLDI are almost comparable. But when all the crops are forced on to the allocation plan, the performance of FXDI and FLDI dropped down drastically.

10.6.3 Equity in Area Allocation

In this case the land area which should be brought under irrigation is distributed proportional to the prescribed parameter (in this case proportional to culturable command area of AU) to each AU. This helps to achieve equity in distribution of area irrigated, but the distribution of water allocated to different AUs depends on the VDI, FXDI and FLDI approaches. In variable depth irrigation, the proportionate area will be allocated to all AUs but not water. Allocation of water is guided by the criteria in the objective function. In this case less productive AUs may get the minimum possible water allocation to irrigate the prescribed proportional area. This makes the equity in water distribution less and equity in benefits generated still less due to lower productivity of those AUs. In full depth irrigation approach the AUs with light soil get the comparatively less water than AUs with heavy soil on the prescribed proportional

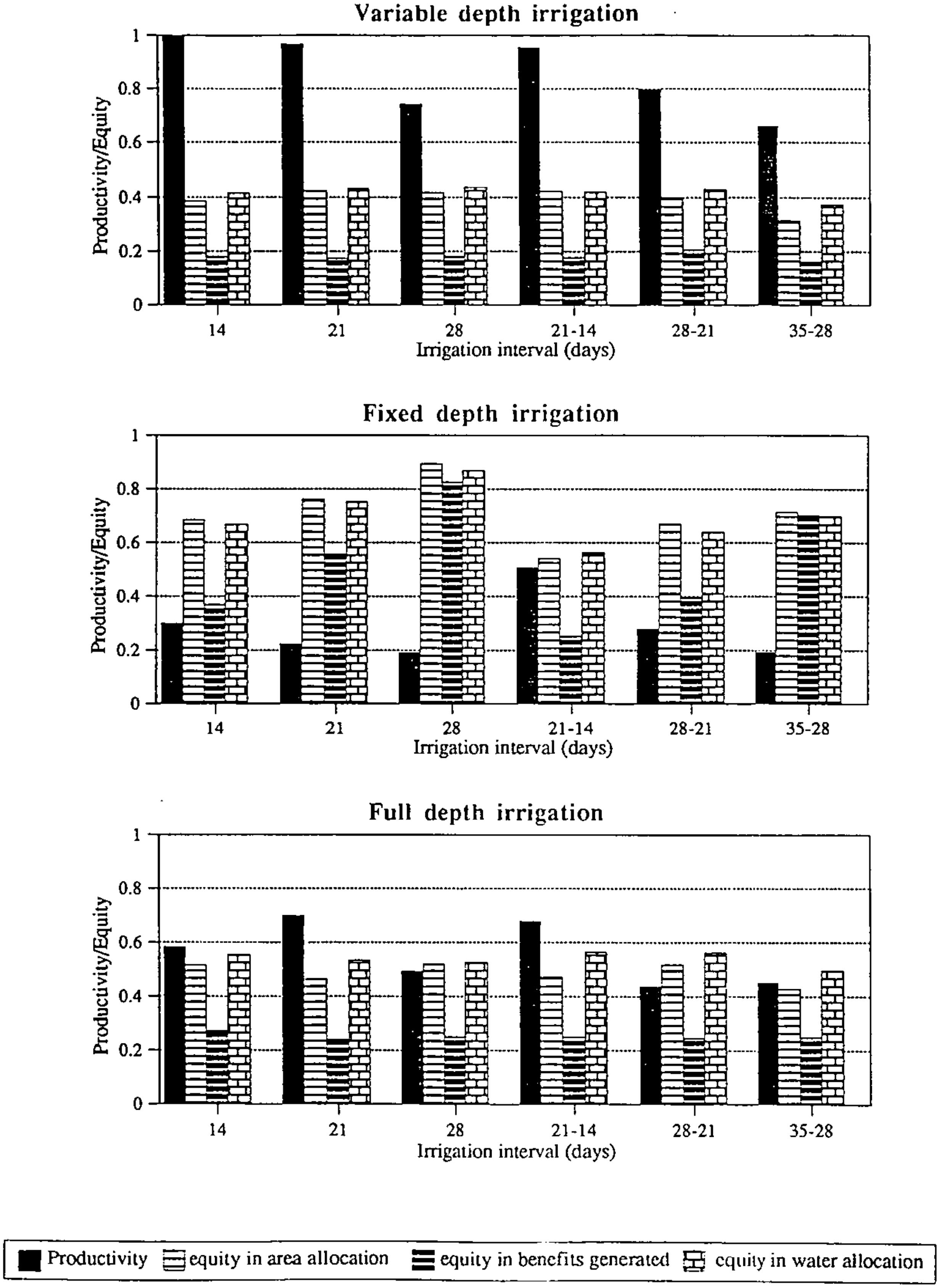


Figure 10.5 The measures of productivities and equties in area and water allocation (at AU) and net benefits generated for crop production restrictions at allocation unit level when equity in allocation is not considered

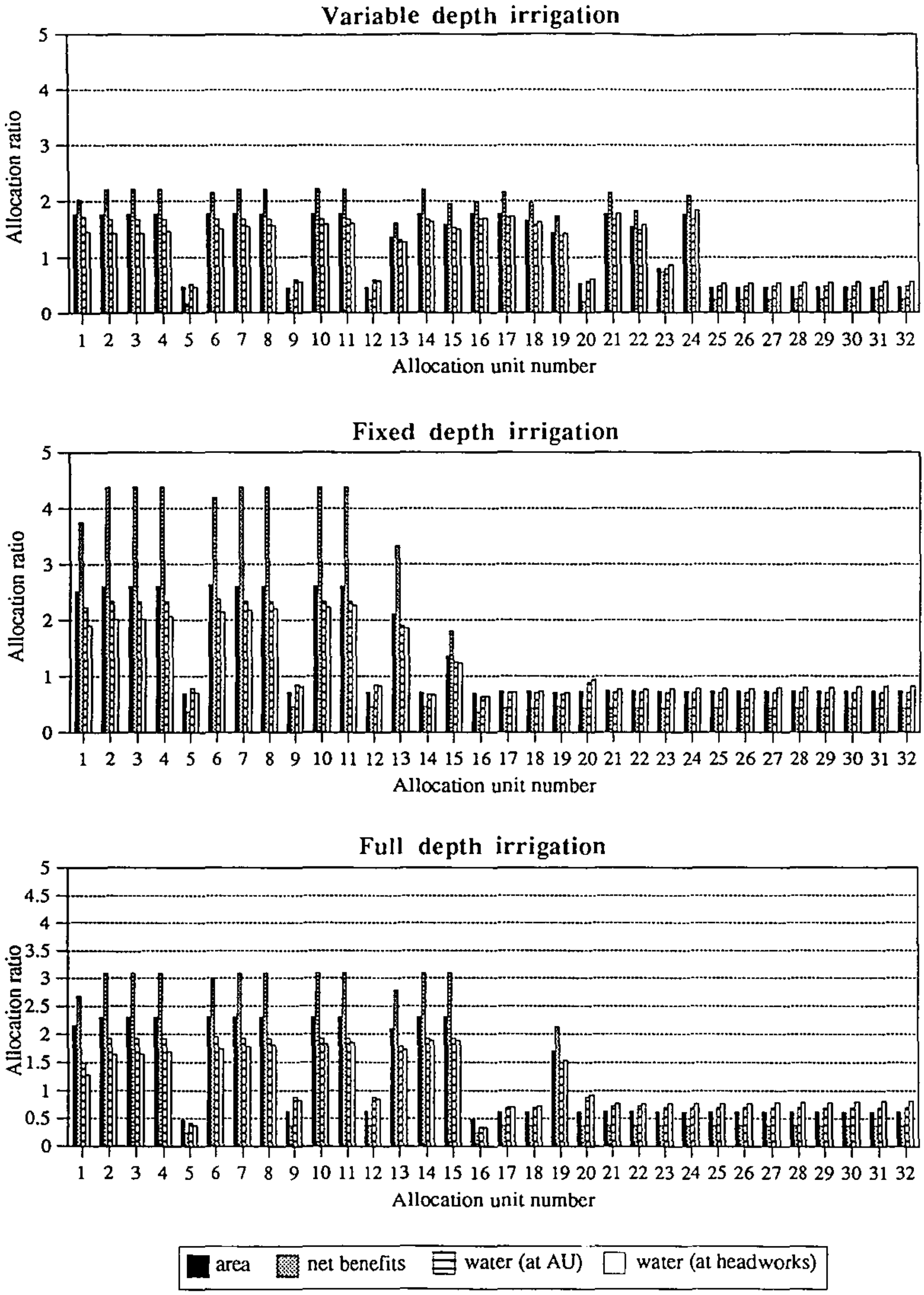


Figure 10.6 The allocation ratios for area allocated, water allocated (at AU and headworks) and net benefits generated for crop production restrictions at allocation unit level when equity in allocation is not considered

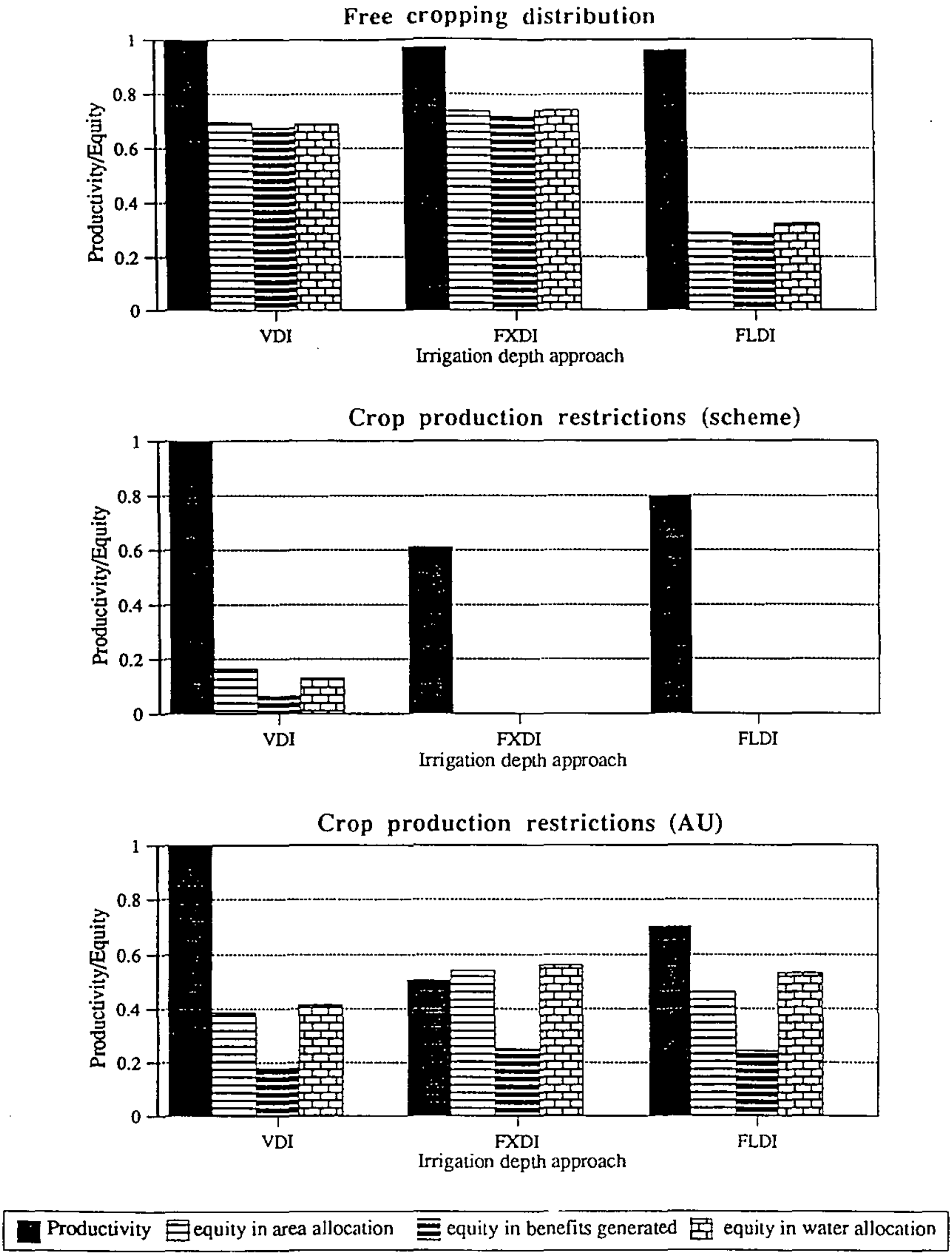


Figure 10.7 The measures of productivity and equities in allocation for the best set of irrigation intervals of each irrigation depth approach when equity in allocation is not considered

area, and thus equity in water distribution will be less than area distribution. The AUs with less suitable soil generate lower benefits than AUs with more suitable soil even if full irrigations are applied to all these AUs. Therefore equity in benefits generated is also less than equity in area distribution. However in fixed depth irrigation, as the fixed depth is applied to all AUs, if equity in area allocation is achieved, equity in water allocation should also be achieved (the deviation in these equities may vary depending on the points in the irrigation scheme from where the fixed depth is delivered and the equity in water allocation is measured). But equity in benefits generated will not be observed due to the difference in productivity of different AUs. These distributions will also be influenced by losses in conveyance, distribution and capacity of canal network and outlets.

The productivity and equities in area and water allocation and the benefits generated observed for VDI, FXDI and FLDI for free cropping distribution are shown in Figure 10.8. The maximum productivity is found in VDI approach with I=21 days. In free cropping distribution equities in water allocation and benefits generated are not markedly lower than equity in area distribution. The causes for this are attributed to the selection of one crop in the solution due to its greater profitability over other crops. This is also reflected in the allocation ratios for the best set irrigation intervals (I=21 days for all irrigation depth approaches) in each case of VDI, FXDI, and FLDI approaches (Figure 10.9).

In the case of crop production restricted at scheme level (Figure 10.10), the equities in water allocation and benefits generated are notably reduced in VDI and FLDI. However in FXDI equities in area and water allocation are comparable, but equity in benefits generated is reduced. This is also indicated in the allocation ratios presented in Figure 10.11 for the best set of irrigation intervals for each of VDI, FXDI and FLDI approaches (I=14, 21-14 and 21, respectively). The maximum productivity is seen with VDI with I=14 days. The productivity with FXDI and FLDI are considerably reduced.

The productivity and equities obtained for crop production restrictions at AU level for VDI, FXDI and FLDI approaches are shown in Figure 10.12. The maximum productivity is obtained with VDI when I=14 days. The productivity in FXDI and FLDI are less than productivity in VDI. The equities in water distribution and benefits generated are less then equity in area but the difference is not like that observed with crop production restrictions at scheme level. This is mainly due to forced introduction of all crops to all AUs. The feasible solutions could not be obtained with FXDI at higher irrigation intervals. This mean that the required levels of crop production for each AU

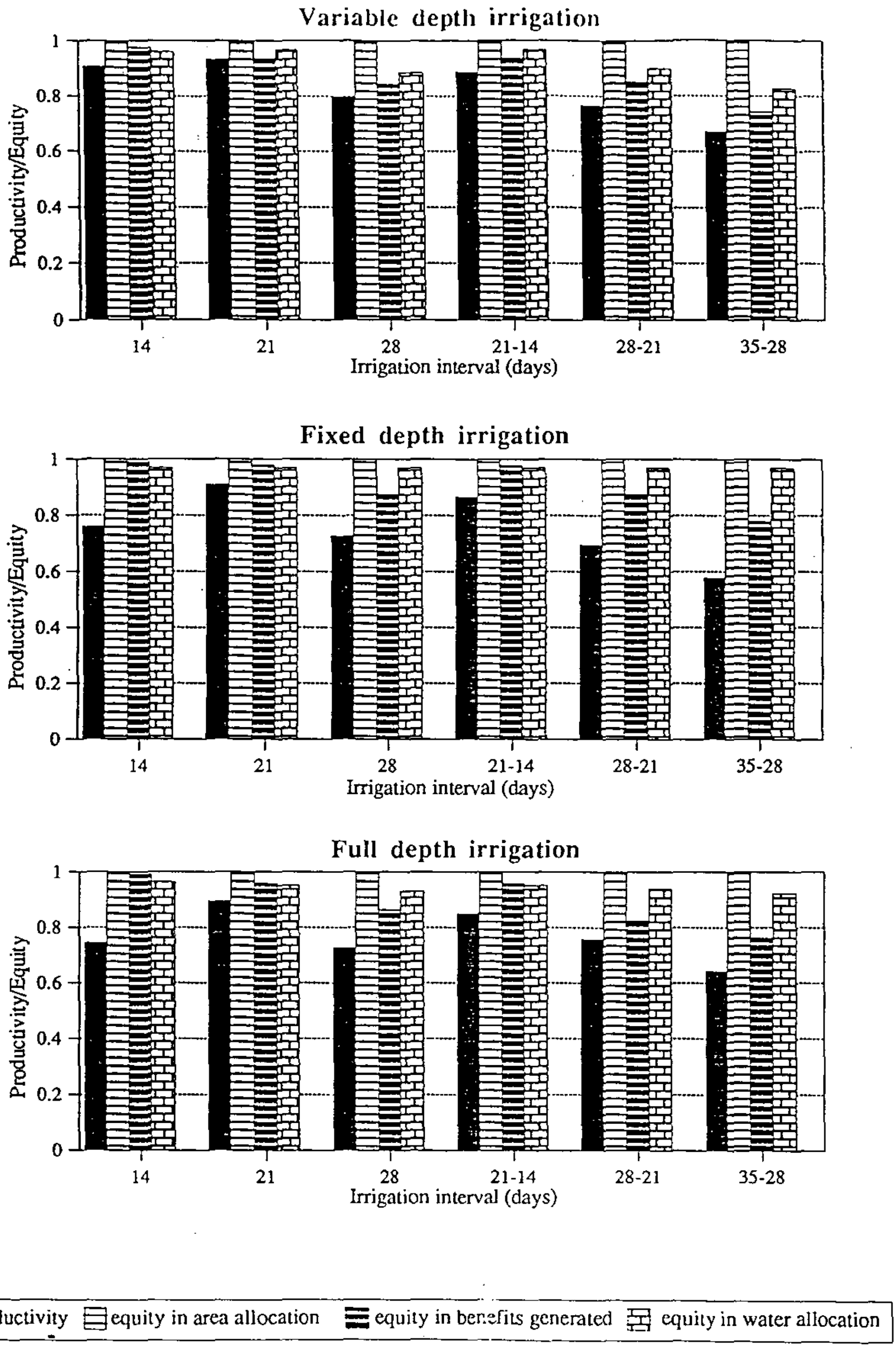


Figure 10.8 The measures of productivity and equties in area and water allocation (at AU) and net benefits generated for free cropping distribution when allocation plans are obtained with equity in area allocation

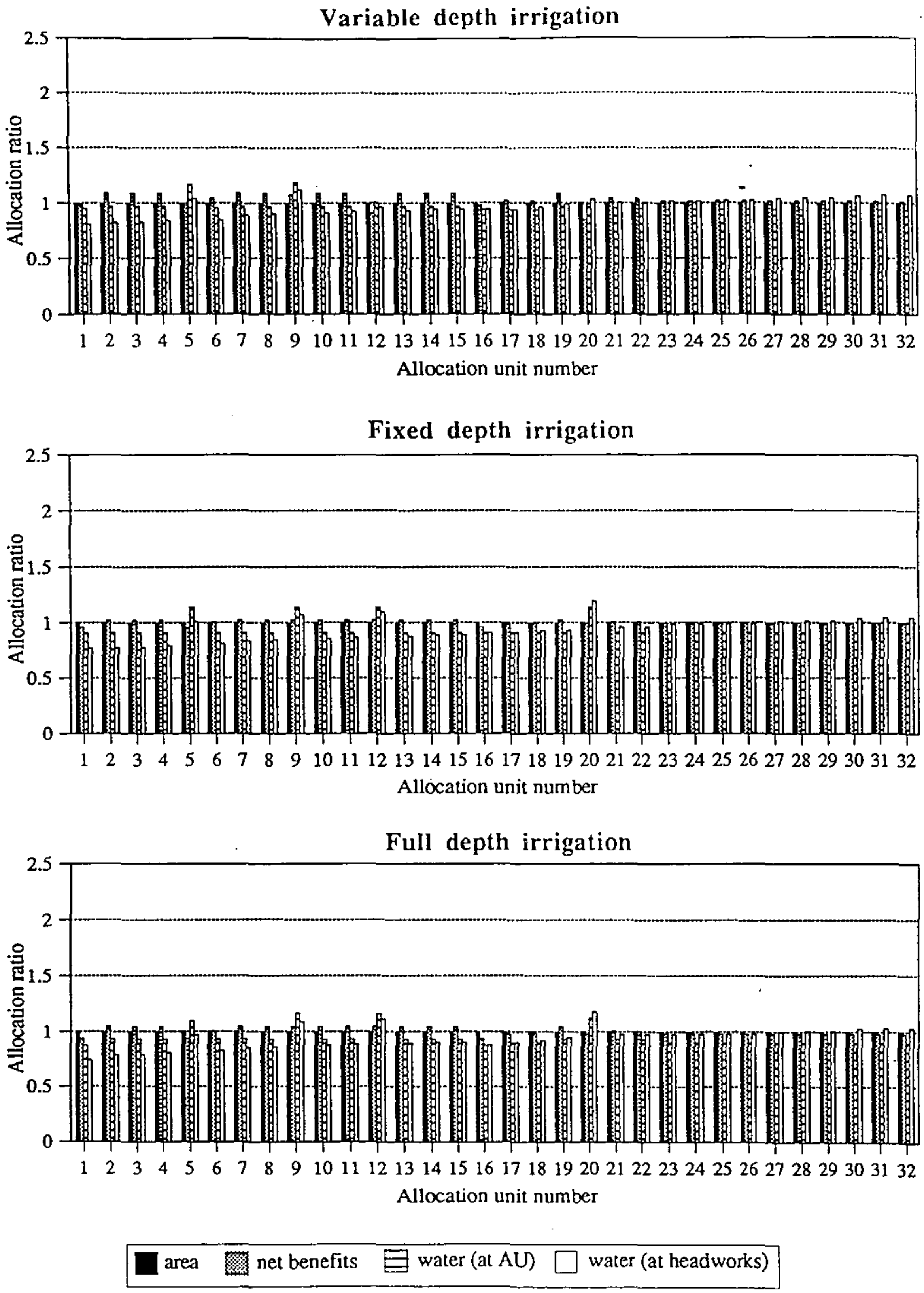


Figure 10.9 The allocation ratios for area allocated, water allocated (at AU and headworks) and net benefits generated for free cropping distribution when allocation plans are obtained with equity in area allocation

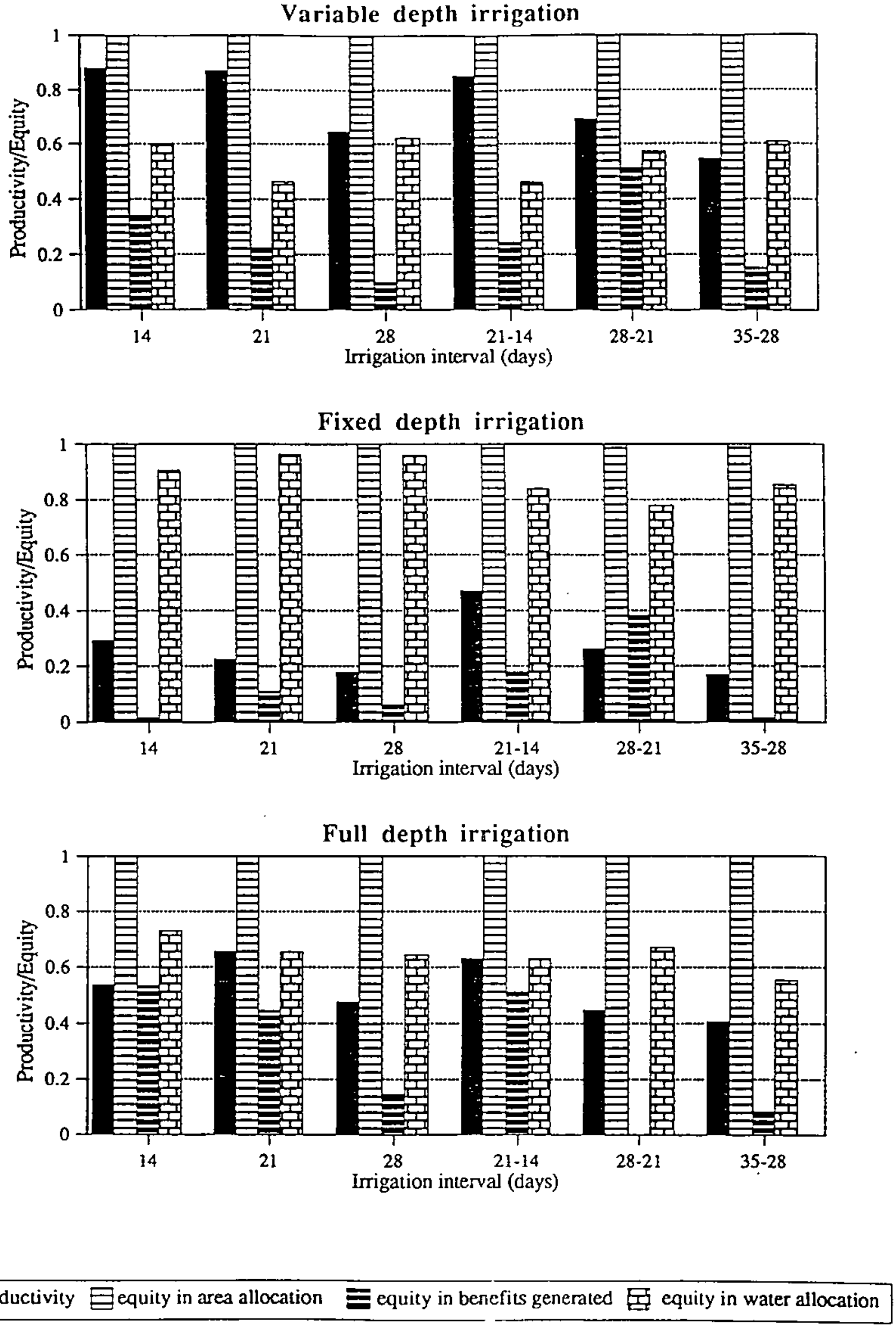


Figure 10.10 The measures of productivity and equities in area and water allocation (at AU) and net benefits generated for crop production restrictions at scheme level when allocation plans are obtained with equity in area allocation

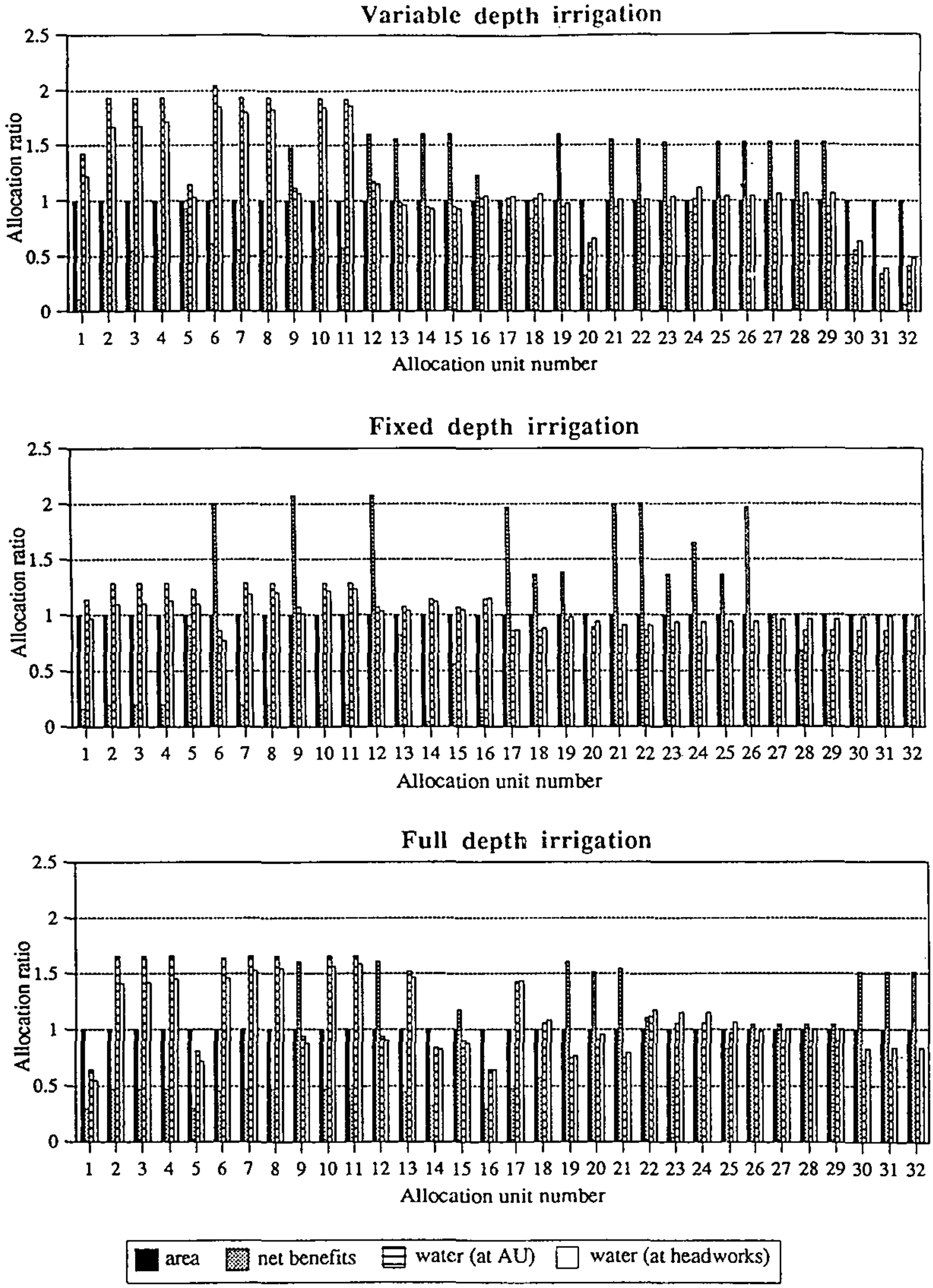


Figure 10.11 The allocation ratios for area allocated, water allocated (at AU and headworks) and net benefits generated for crop production restrictions at scheme level when allocation plans are obtained with equity in area allocation

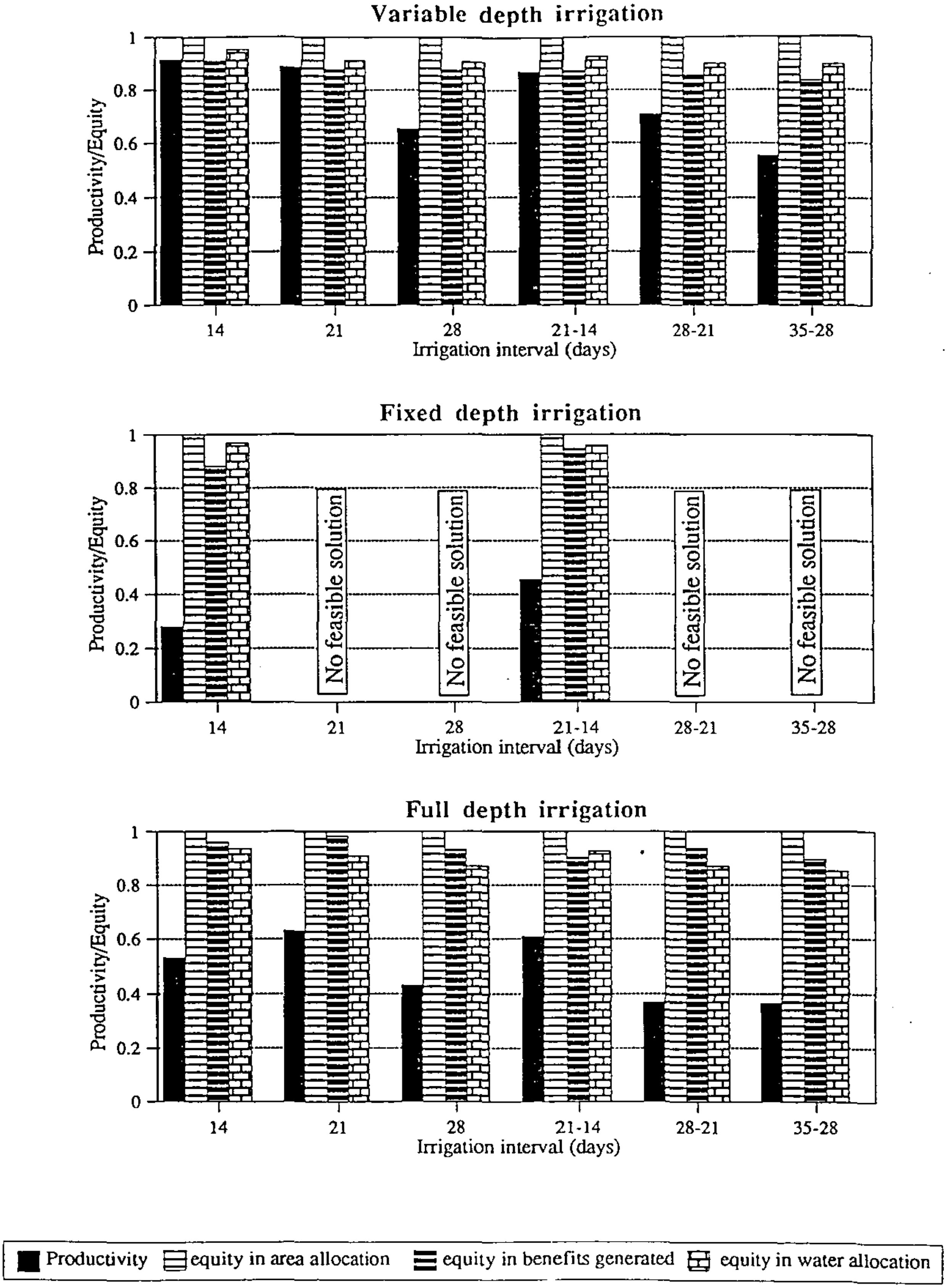


Figure 10.12 The measures of productivity and equities in area and water allocation (at AU) and net benefits generated for crop production restrictions at allocation unit level when allocation plans are obtained with equity in area allocation

could not be satisfied if the equity in area allocation is to be achieved for the available amount of water for irrigation in fixed depth irrigation approach. The allocation ratios for the best set irrigation intervals in each case of VDI, FXDI, and FLDI approaches are shown in Figure 10.13 (same as in case with CPR at scheme level).

When the best sets of irrigation interval of VDI, FXDI and FLDI are compared for each cropping distribution (Figure 10.14), it is seen that the in free cropping distribution there is not marked difference in the performance of all these three approaches. However with crop production restrictions at scheme or AU level, the VDI approach faired better over other approaches.

10.6.4 Equity in Water Allocation

In this case water is distributed proportional to a certain prescribed parameter (here, CCA of AU) to each AU. Therefore equity in water allocation can be achieved in allocation plan. The issue is more complicated than equity in area allocation or benefits generation due to several possibilities of achieving equity in water allocation depending on the different views. For example, equity in water allocation can be considered with reference to water delivered from headworks, different points in the canal network, at the allocation unit, within the allocation unit. In AWAM, as discussed earlier, three possibilities are considered. These are achieving equity in water allocation when water is delivered from headworks (variation in conveyance and distribution losses with allocation unit are not considered), when water is delivered at allocation unit (variation in distribution losses are not considered) and when water is delivered within the allocation unit i.e. to farm gate (variation in conveyance and distribution losses considered). In the present study the equity in water allocation for distributing water at the AU is considered. However equities in water allocation to different AUs from headworks are also computed.

Though this case achieves the equity in water allocation, the distribution of benefits generated depends on other factors such as soil type, losses which are not considered etc. The less productive AUs will generate proportionally less benefits. The influence of losses can be minimised if the allocation of water is considered close to the AU or farm.

The productivity and equities in area and water allocation (at the AU and headworks) and the benefits generated found for VDI, FXDI and FLDI for free cropping distribution are shown in Figure 10.15. The maximum productivity is observed in VDI with I=21 days. The equities in area allocation and benefits generated do not much differ from

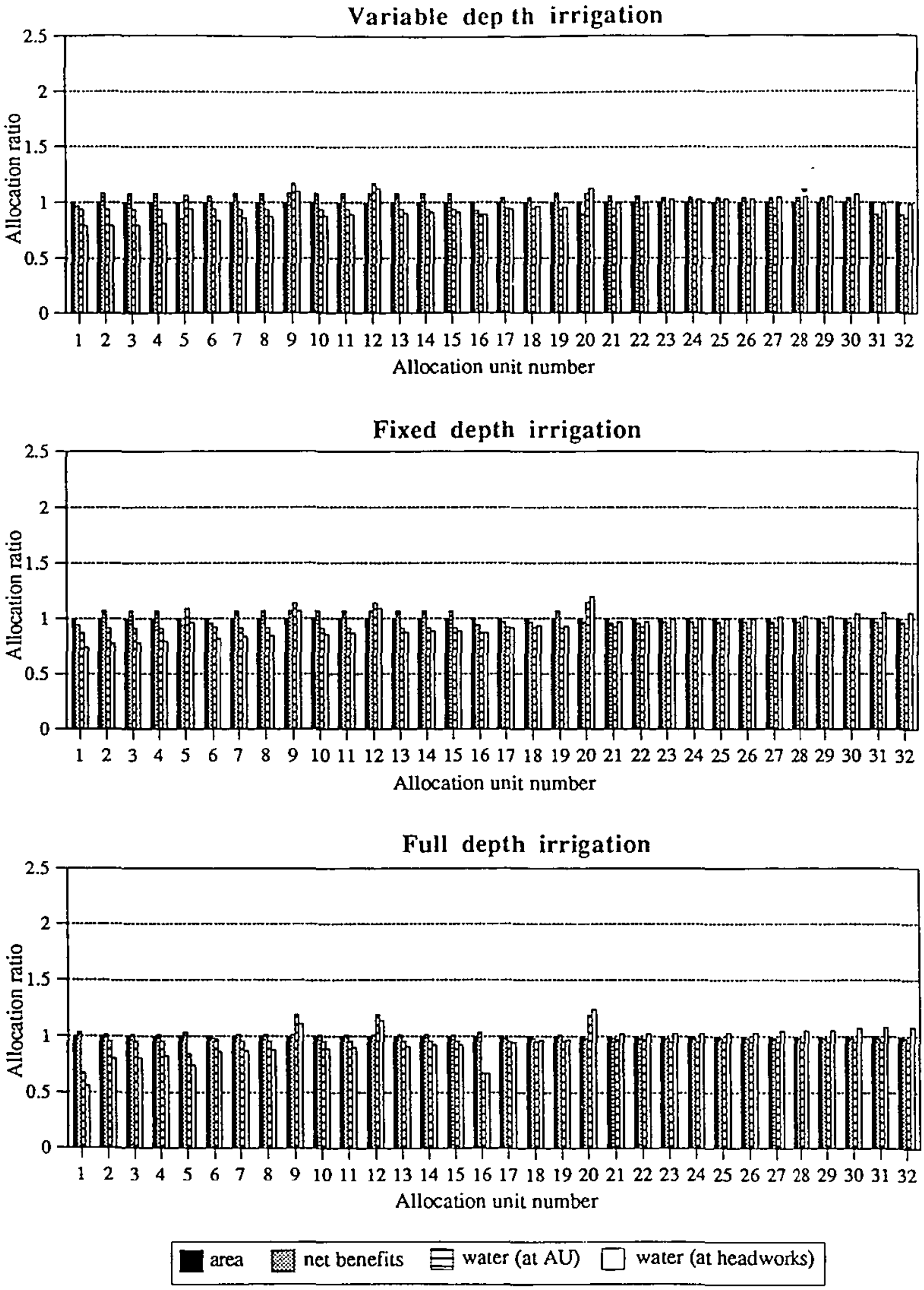


Figure 10.13 The allocation ratios for area allocated, water allocated (at AU and headworks) and net benefits generated for crop production restrictions at allocation unit level when allocation plans are obtained with equity in area allocation

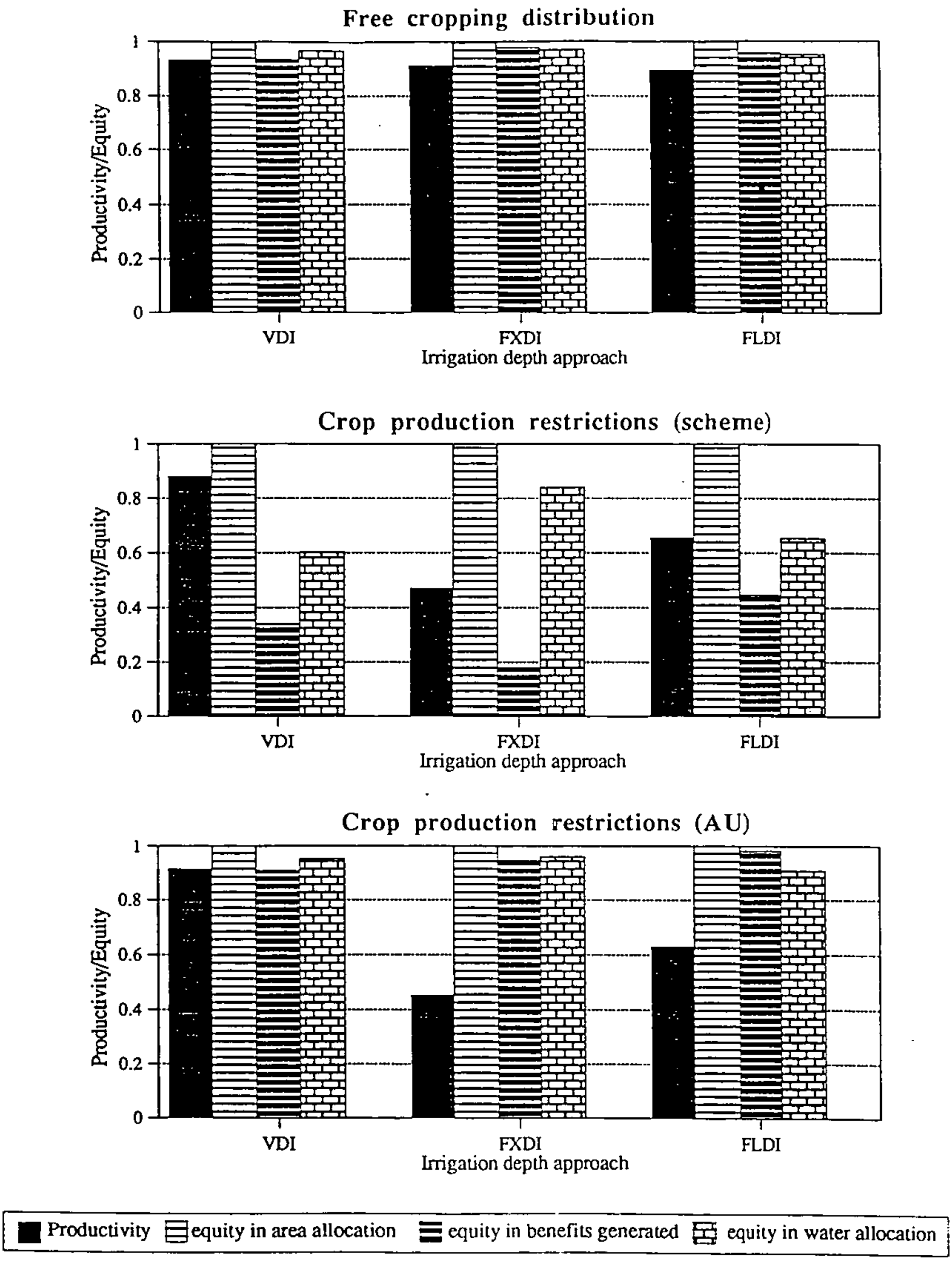


Figure 10.14 The measures of productivity and equities in allocation for the best set of irrigation intervals for each irrigation depth apporach when allocation plans are obtained with equity in area allocation

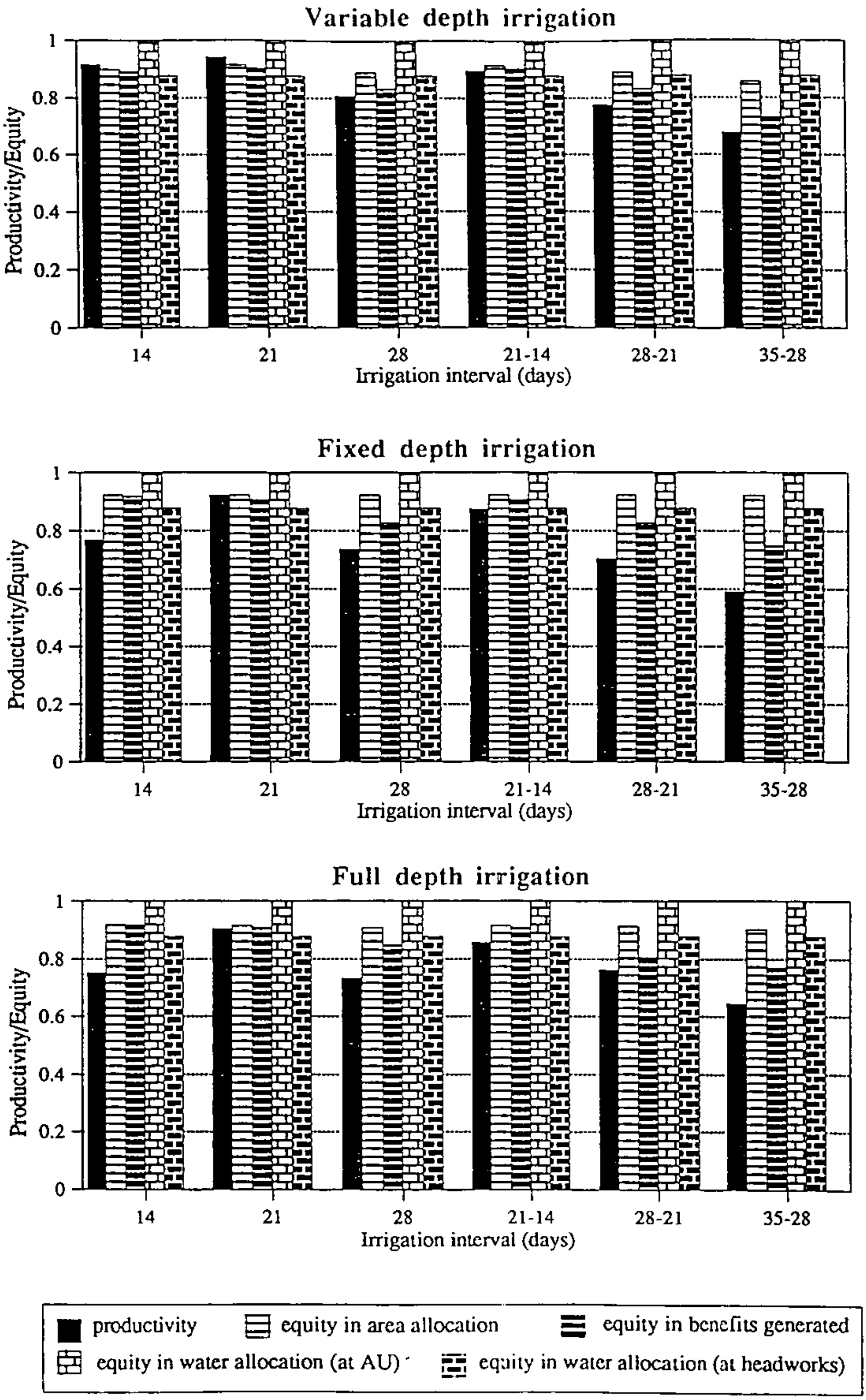


Figure 10.15 The measures of productivity and equities in area and water allocation (at AU and headworks) and net benefits generated for free cropping distribution when allocation plans are obtained with equity in water allocation (at AU)

equity in water allocated for the reason explained in Section 10.6.2. The allocation ratios corresponding to each allocation unit for the best set of irrigation interval for each approach are shown in Figure 10.16 (I=21 days for all irrigation depth approaches).

The productivity and different equities for crop production restriction at scheme level for different irrigation depth approaches are shown in Figure 10.17. The maximum productivity is obtained in VDI approach when I=14 days. The productivity is reduced in FXDI and FLDI. The equities in area allocation and benefits generation are lower, but equity in benefits generation is much lower than equity in water allocation. The benefits generated from the less productive AUs (AUs with less suitable soil and more distribution losses) are lower than other AUs as seen from the allocation ratios for the best sets of irrigation interval (I=14, 21 and 21-14 days for VDI, FXDI and FLDI approaches, respectively) in Figure 10.18. Thus equity in water allocation may not necessarily bring equity in income generation.

When the crop production restrictions are put at allocation unit level, the equities do not differ much (Figure 10.19). The maximum productivity is obtained in VDI with I=14 days. In FXDI, feasible solutions are obtained with small irrigation intervals, and in FLDI, no feasible solutions are obtained at higher irrigation intervals. This indicates that with the water available for irrigation FXDI and FLDI failed to achieve equity in water allocation while satisfying crop production restrictions at allocation unit level, in the cases where VDI could produce results. The allocation ratios for the best sets of irrigation interval for each of the three irrigation depth approaches are shown in Figure 10.20 (I=14, 21 and 21-14 days for VDI, FXDI and FLDI approaches, respectively).

The comparison of the three approaches for free cropping distribution and crop production restrictions at scheme and allocation unit level (Figure 10.21) shows the similar trend as observed when equity is not considered and equity in area allocation is considered. Though the equity in water allocation at AU level is one, equity in water allocation at headworks is less. This is reflected in the allocation ratios (Figures 10.16, 10.18 and 10.20), wherein the allocation ratios for water allocation at headworks gradually increase with the distance of AU from the headworks. This is to make equity in water allocation at AU unity by compensating for conveyance losses.

When allocation plans are obtained with equity in water allocation at various levels in the irrigation scheme, it is found that in most cases the productivity increases close to the headworks but equity in income generation decreases. This is evident from the fact that when equity in water allocation close to the farm is considered the less productive

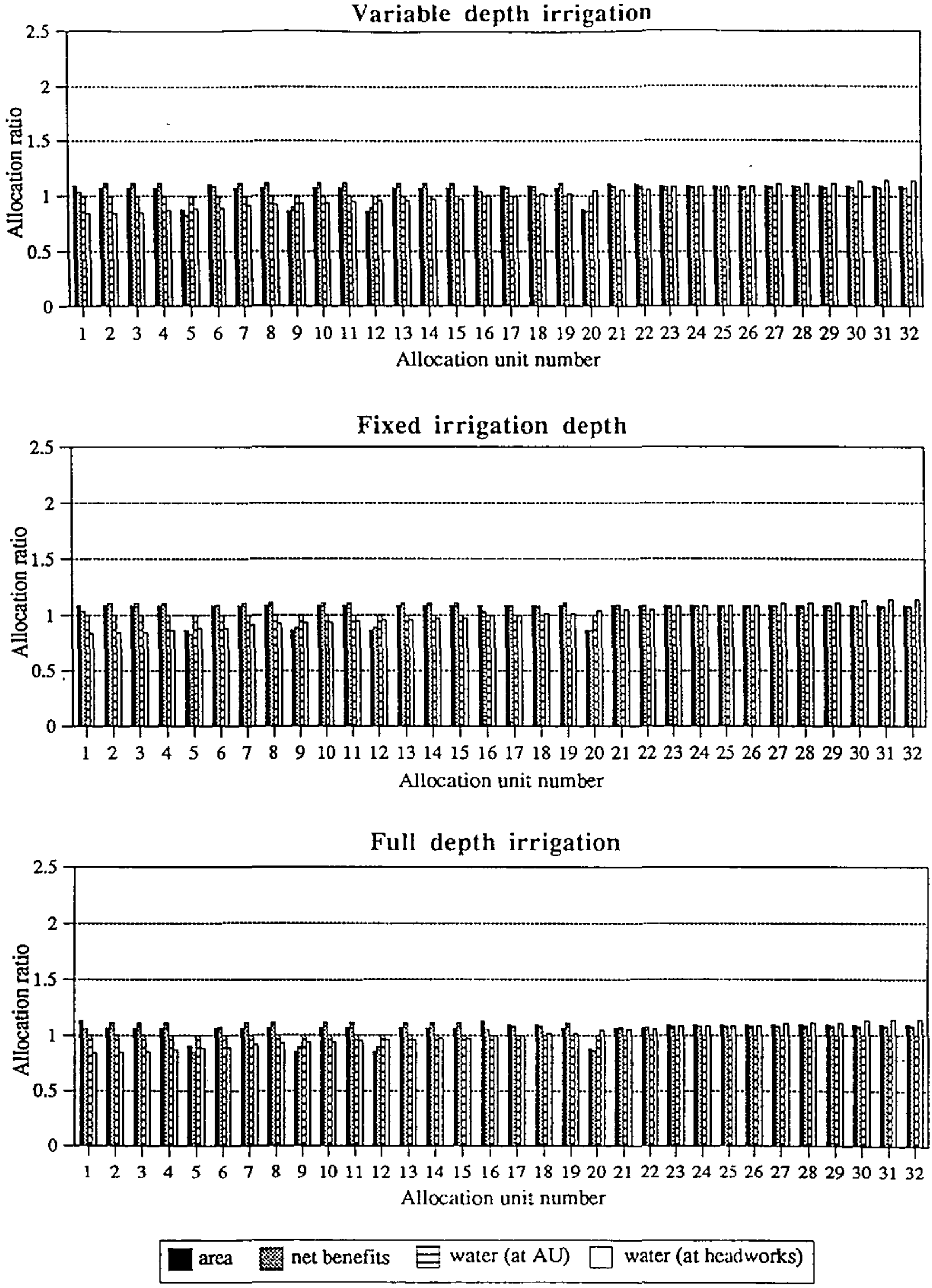


Figure 10.16 The allocation ratios for area allocated, water allocated (at AU and headworks) and net benefits generated for free cropping distribution when allocation plans are obtained with equity in water allocation (at AU)

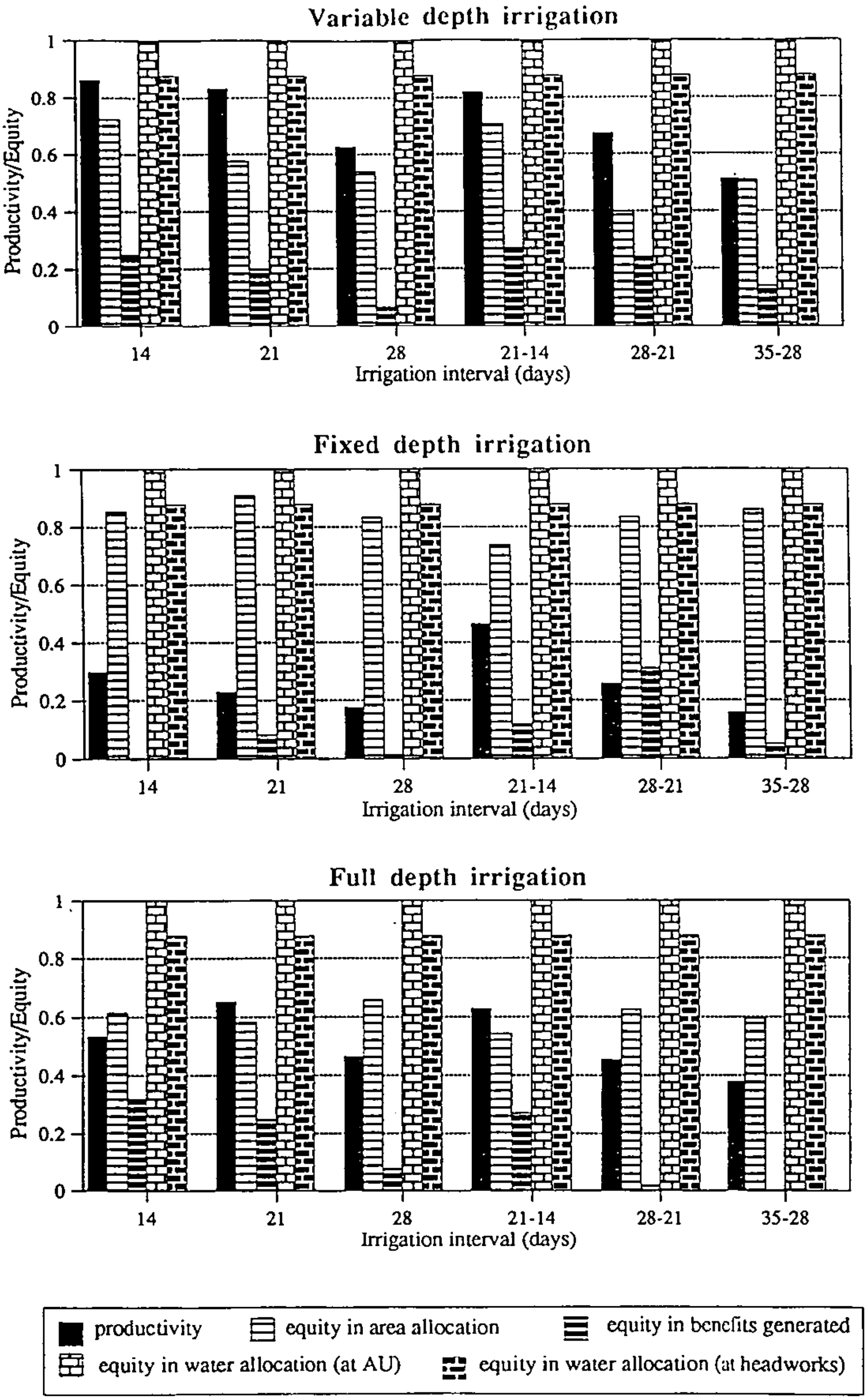


Figure 10.17 The measures of productivity and equities in area and water allocation (at AU and headworks) and net benefits generated for crop production restrictions at scheme level when allocation plans are obtained with equity in water allocation (at AU)

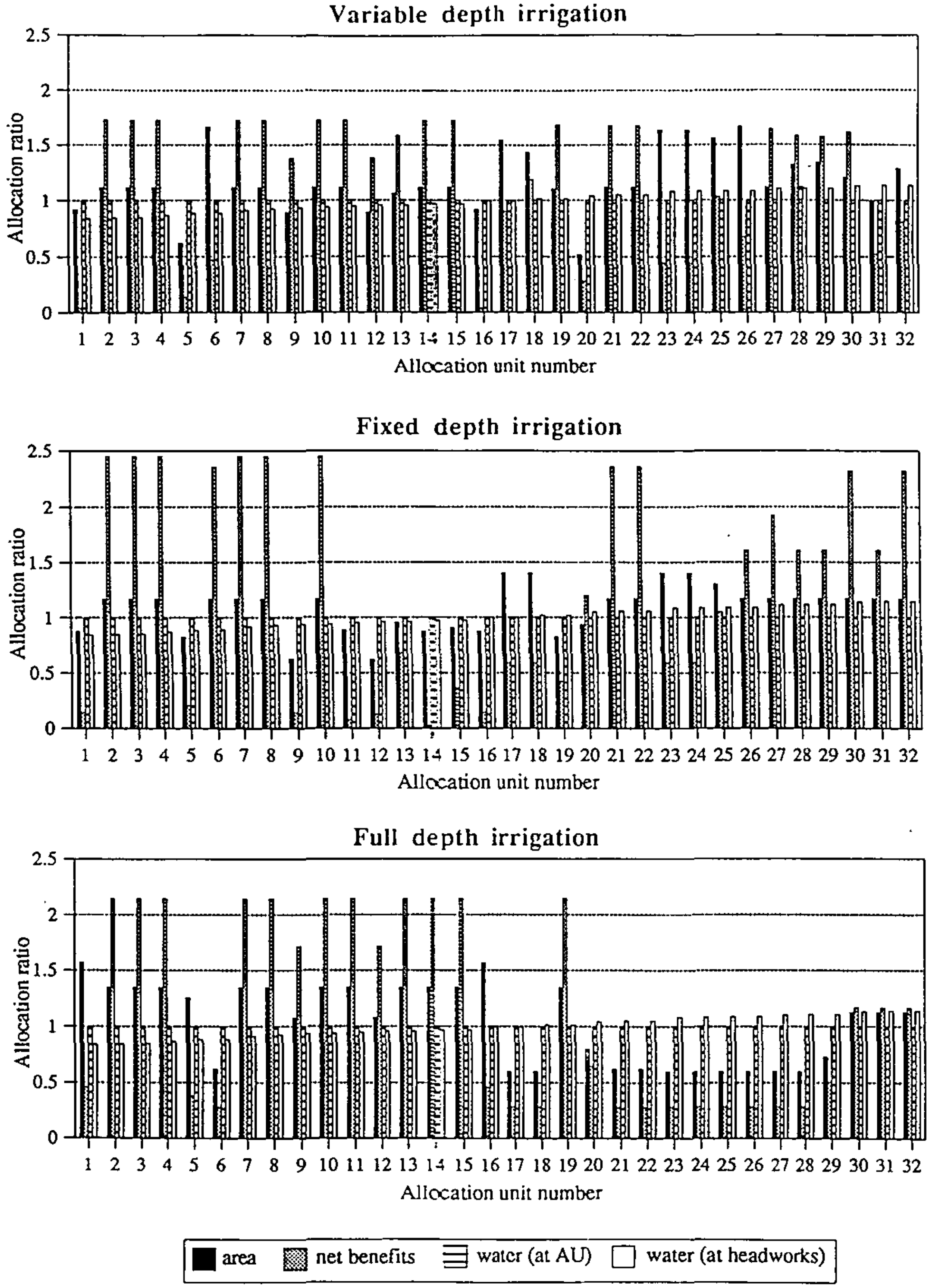


Figure 10.18 The allocation ratios for area allocated, water allocated (at AU and headworks) and net benefits generated for crop production restrictions at scheme level when allocation plans are obtained with equity in water allocation (at AU)

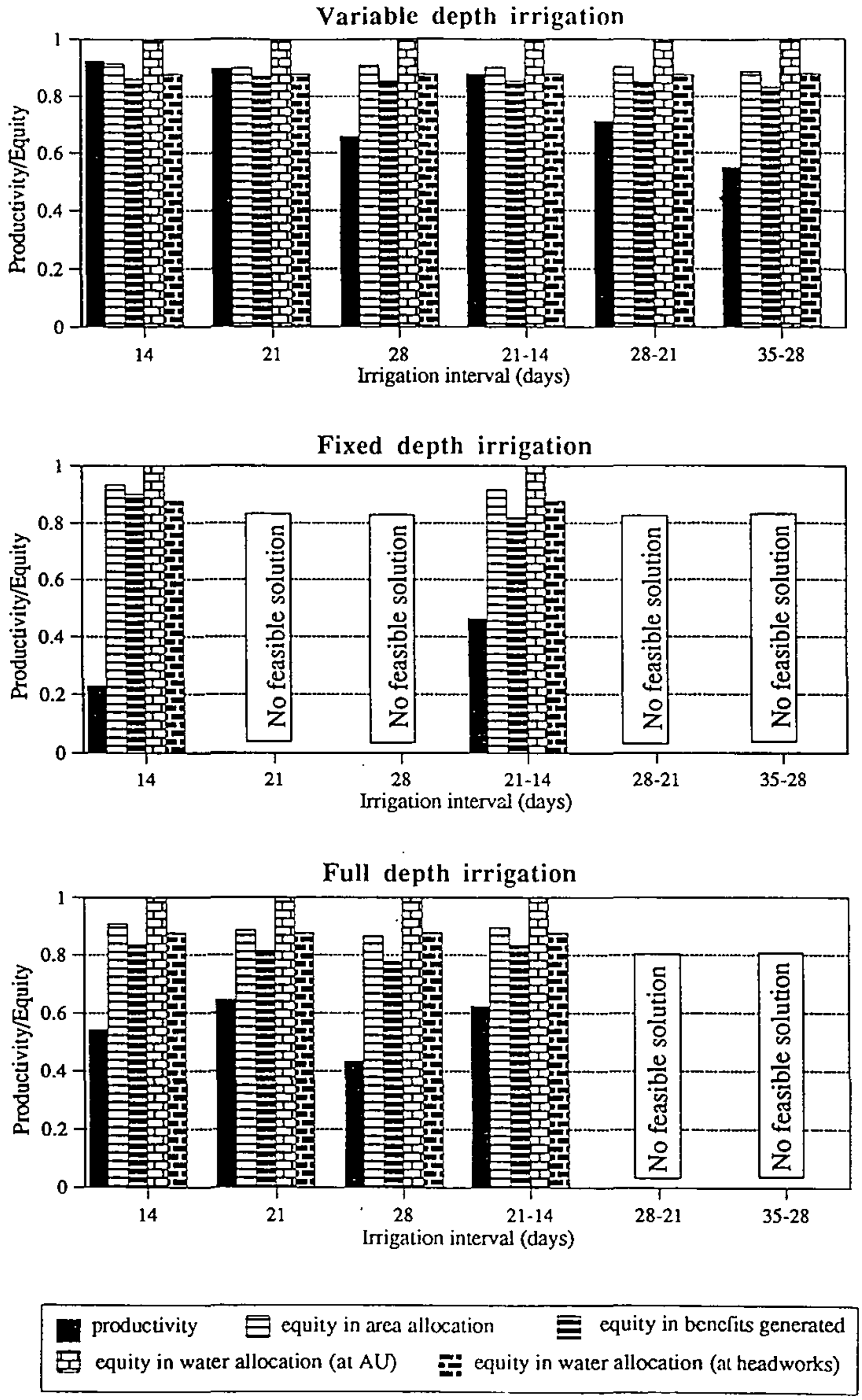


Figure 10.19 The measures of productivity and equities in area and water allocation (at AU and headworks) and net benefits generated for crop production restrictions at allocation unit level when allocation plans are obtained with equity in water allocation (at AU)

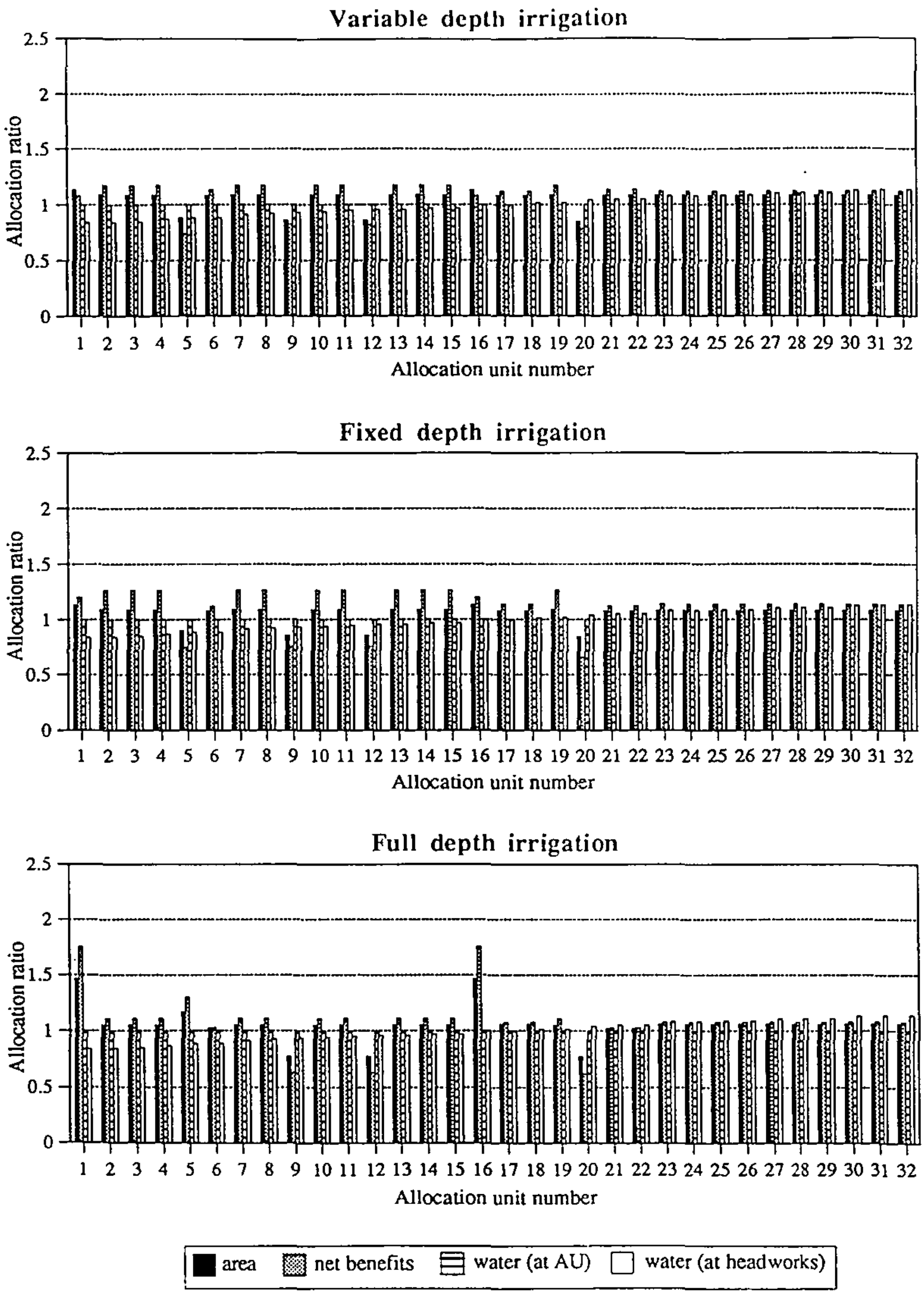


Figure 10.20 The allocation ratios for area allocated, water allocated (at AU and headworks) and net benefits generated for crop production restrictions at allocation unit level when allocation plans are obtained with equity in water allocation (at AU)

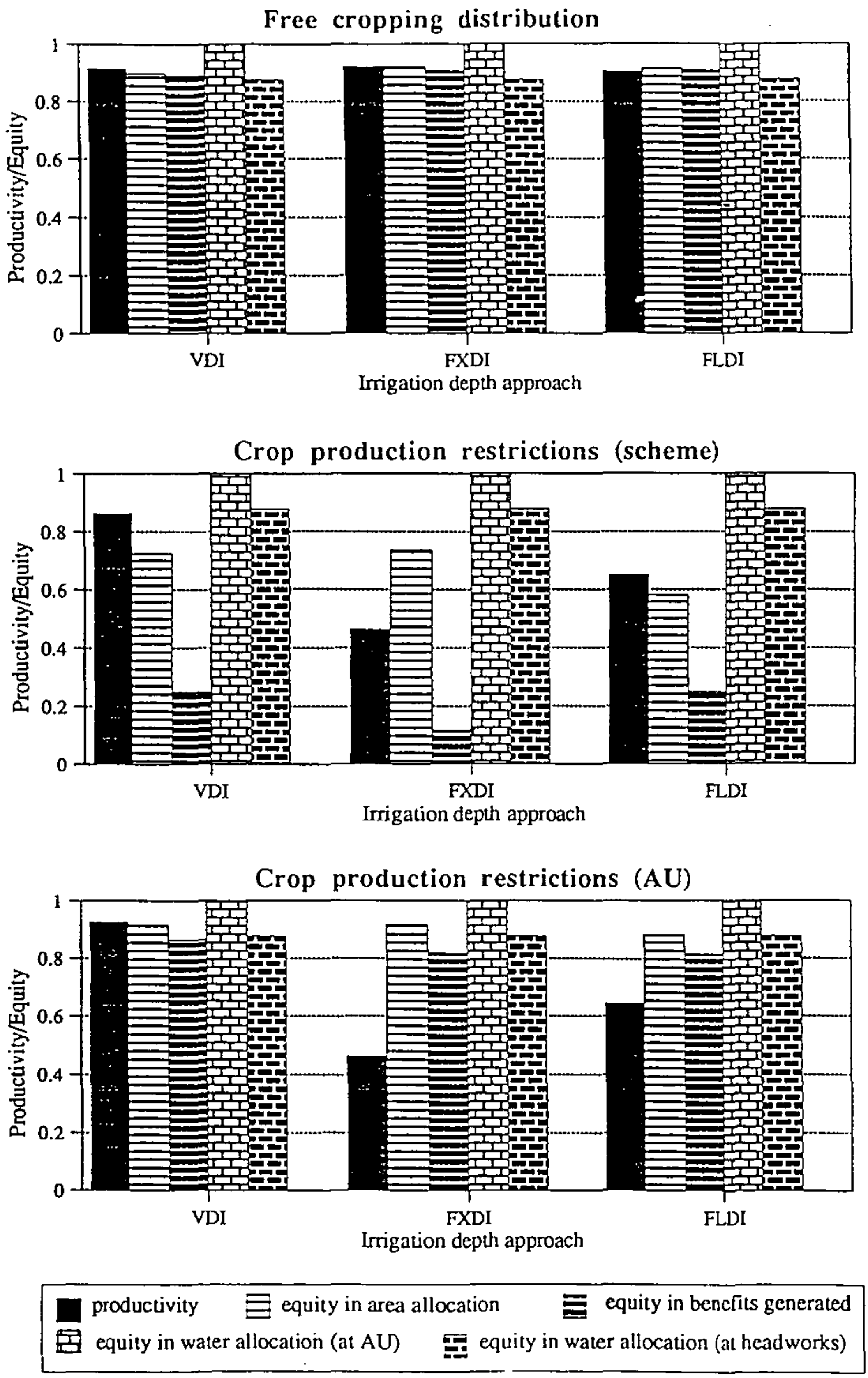


Figure 10.21 The measures of productivity and equities in allocation for the best set of irrigation intervals for each irrigation depth approach when allocation plans are obtained with equity in water allocation

AUs tend to get more water, causing less water allocation to more productive AUs compared to when equity in water allocation close to the headworks is considered. This reduces the total output from the scheme but evening its distribution over the allocation units. This is apparent from comparison of productivity and equities when allocation of water is performed at headworks, at AU and within AU (Figure 10.22) and allocation ratios (Figure 10.23) for the best sets of irrigation interval in VDI approach with CPR at scheme level.

10.6.5 Equity in Benefits Generation

In this case area and water are allocated to each AU so that proportionally the same benefits are obtained from each AU. If the cropping pattern of each AU is similar, more water should be allocated to less productive AUs to produce the same proportionality in benefit generation.

The allocation plans for equity in benefits generation over all the allocation units are obtained for free cropping distribution, and the corresponding productivity and equities in area and water allocation and benefits generation for all the three irrigation depth approaches are shown in Figure 10.24. The results shows the similar trend to those obtained with no equity and equity in area and water allocation. The lower values of area and water allocation are due to greater area and water allocation to the less productive AUs to obtain comparable benefits (Figure 10.25).

The productivity and equities in area and water allocation and benefits generation for CPR at scheme level are shown in Figure 10.26. The maximum productivity is obtained in VDI when I=14 days. The productivity in FXDI and FLDI are lower. The equities in area and water allocation are considerably lower than one. This is explicit from Figure 10.27, wherein the allocation ratios for the best sets of irrigation interval for each of the irrigation depth approaches are shown (I=14, 21 AND 21-14 for VDI, FXDI and FLDI, respectively). However in this case more area and water are not allocated to the less productive AUs as in case of free cropping distribution. The investigation of the detailed allocation plans showed that the crops with comparatively more water consumption and less benefits (for example, sunflower over onion) were preferred in AUs with less conveyance losses. As there is no restriction on the crops to be grown in each AU, the AUs with more conveyance losses got allocation for those crops which need less water and generate more benefits, so that overall productivity is increased by reducing the conveyance losses.

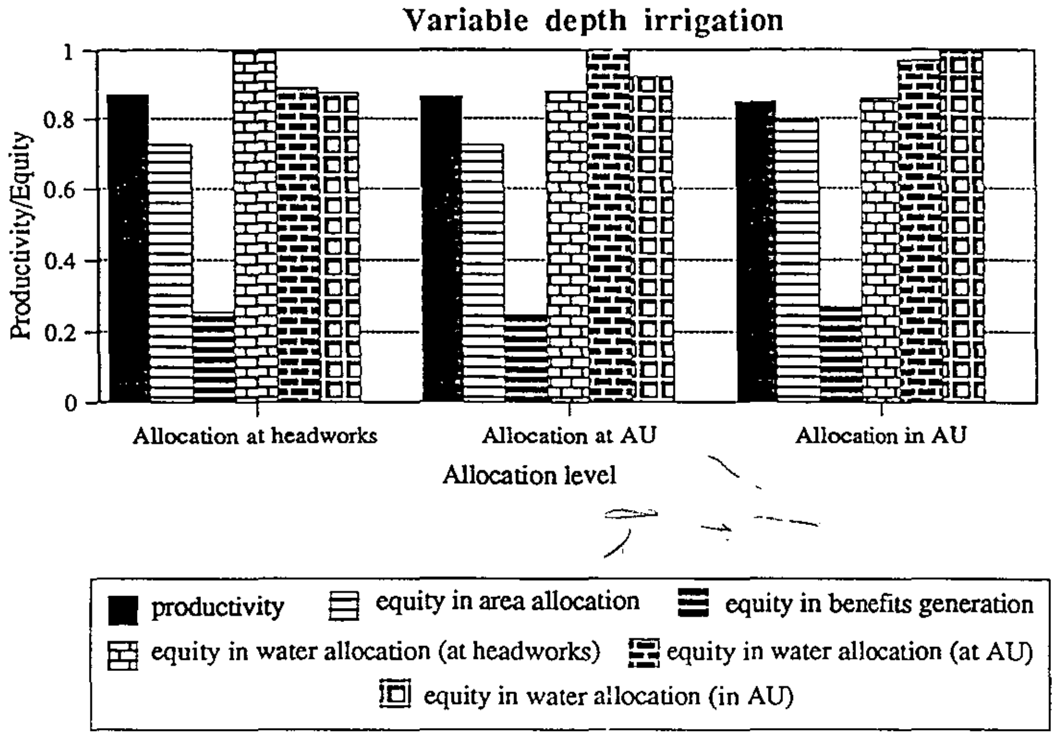


Figure 10.22 Productivity and equities in area and water allocation (at headworks, AU and in AU) and net benefits generated for crop production restrictions at scheme level in variable depth irrigation approach when allocation plans are obtained with equity in water allocation at headworks, AU and in AU

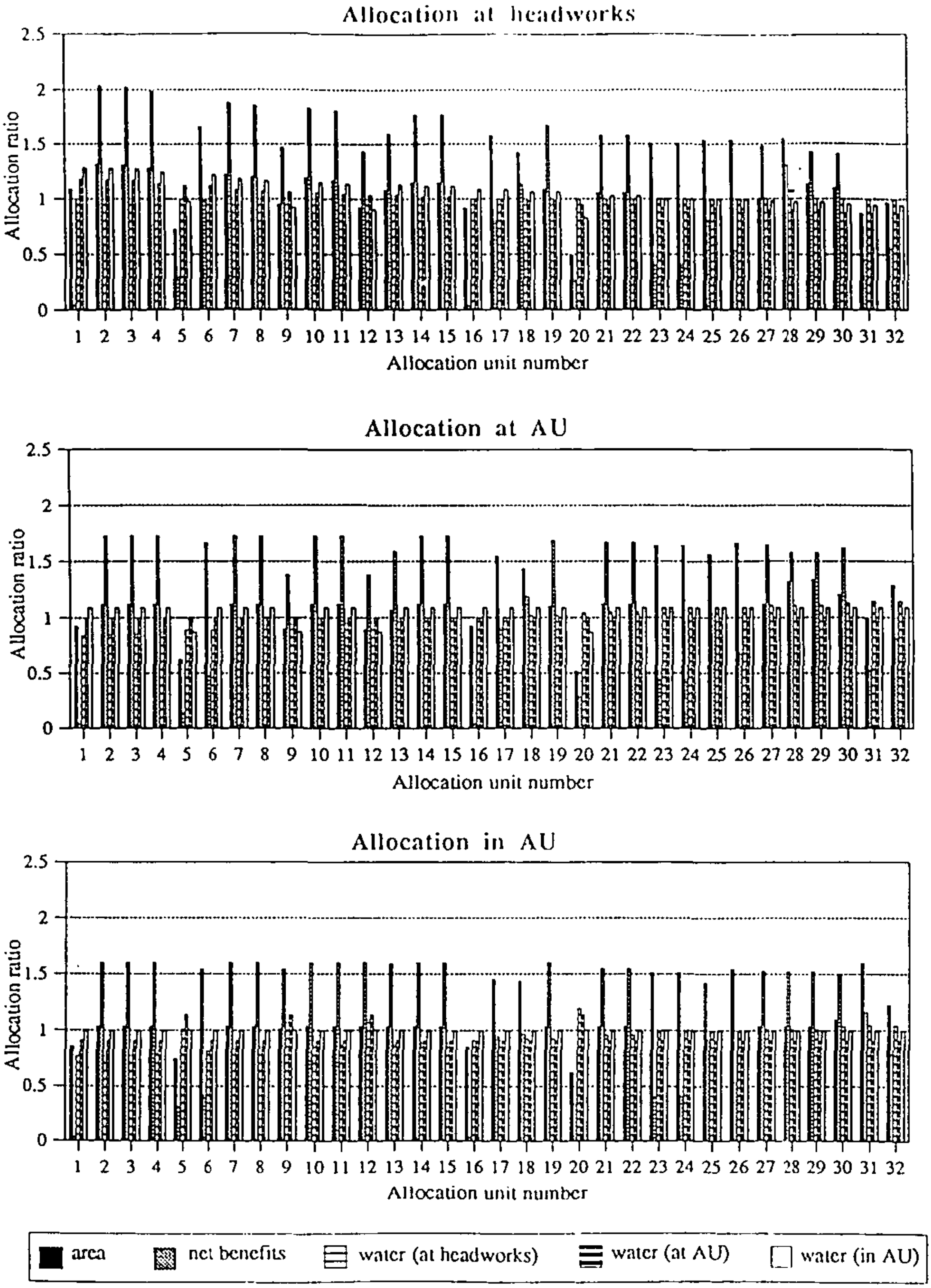


Figure 10.23 The allocation ratios for area irrigated, water allocated (at headworks, AU and in AU) and net benefits generated for crop production restrictions at scheme level in variable depth irrigation approach when allocation plans are obtained with equity in water allocation at headworks, at AU and in AU)

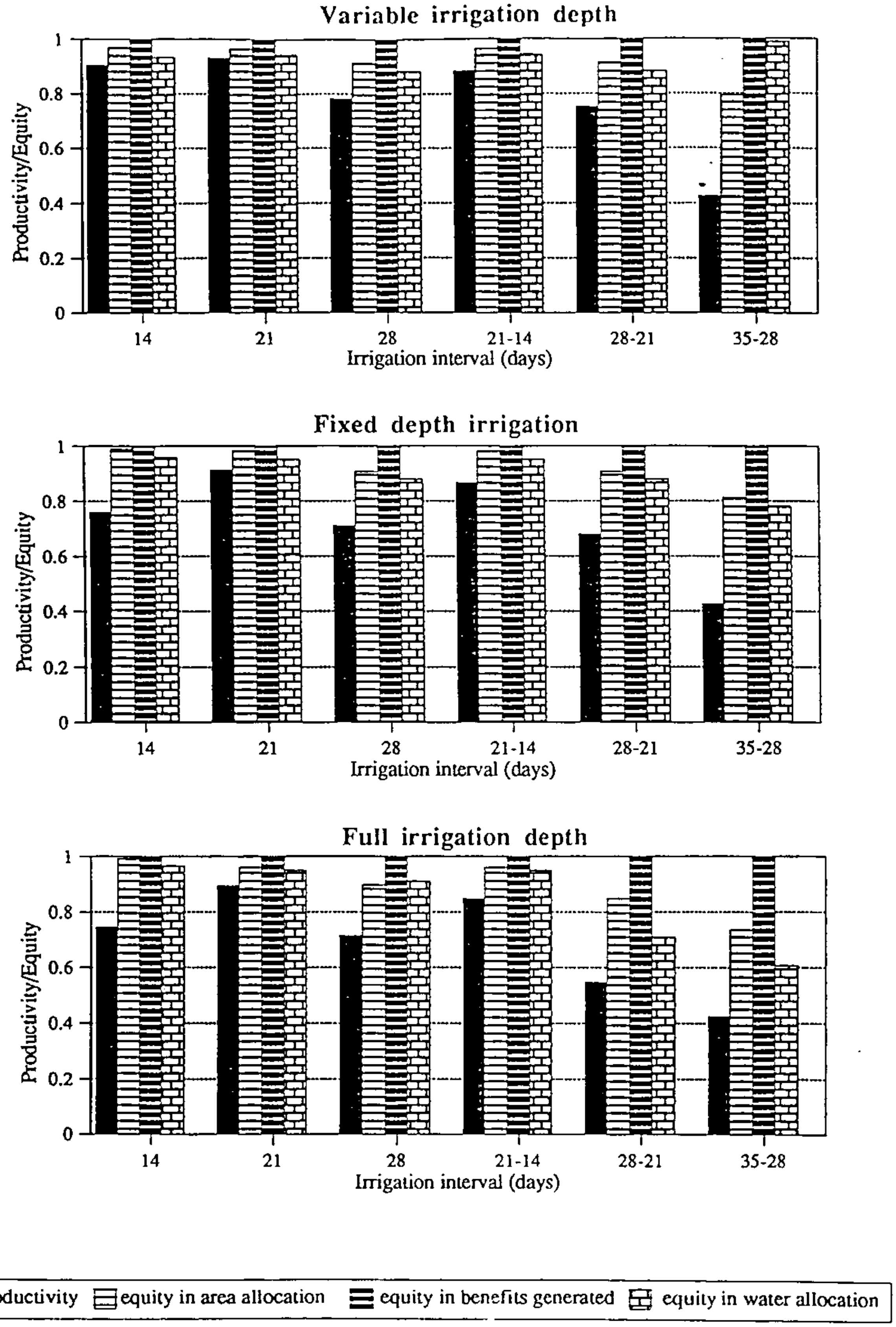


Figure 10.24 The measures of productivity and equities in area and water allocation (at AU) and net benefits generated for free cropping distribution when allocation plans are obtained with equity in benefits generation

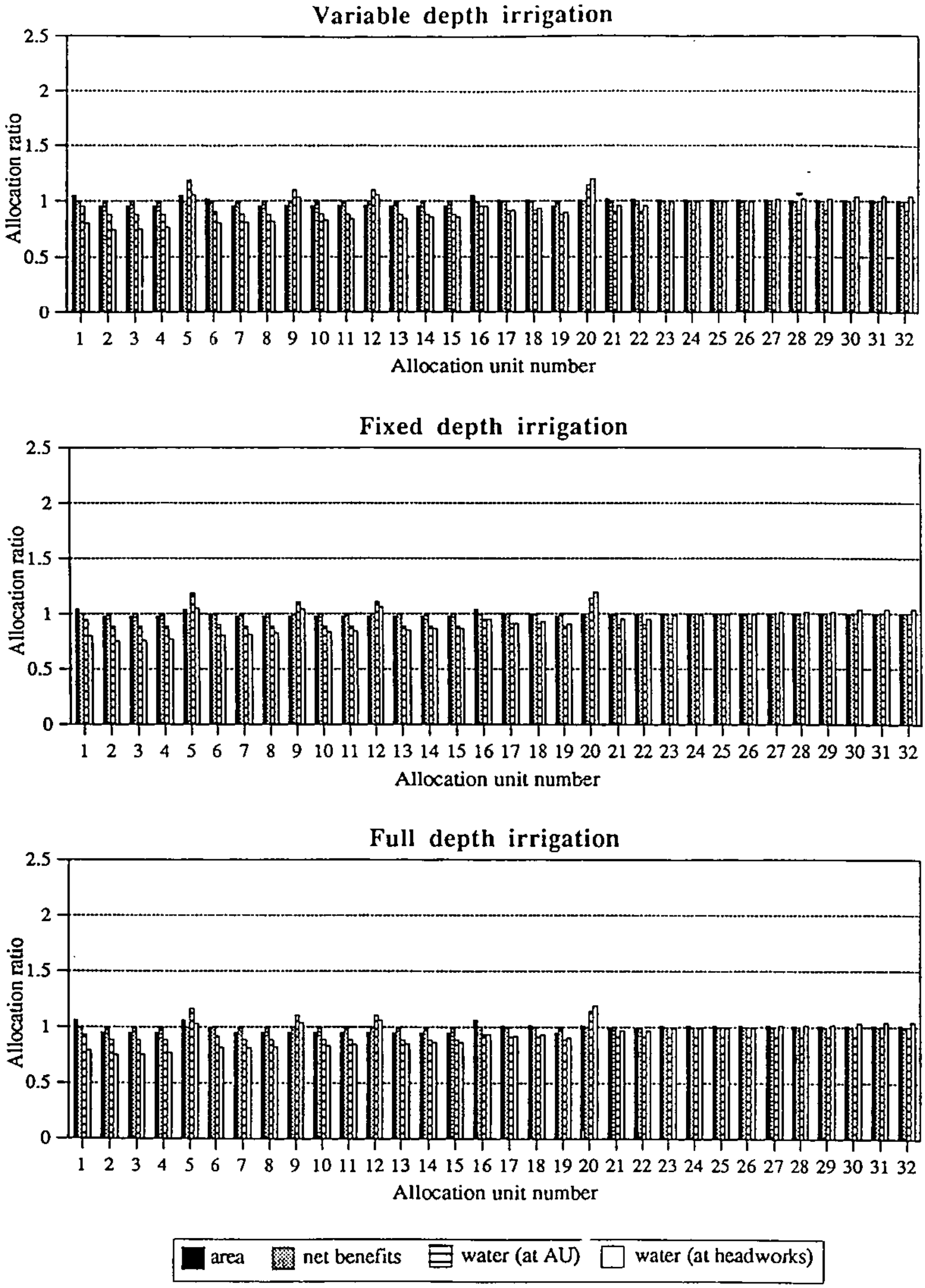


Figure 10.25 The allocation ratios for area allocated, water allocated (at AU and headworks) and net benefits generated for free cropping distribution when allocation plans are obtained with equity in benefits generation

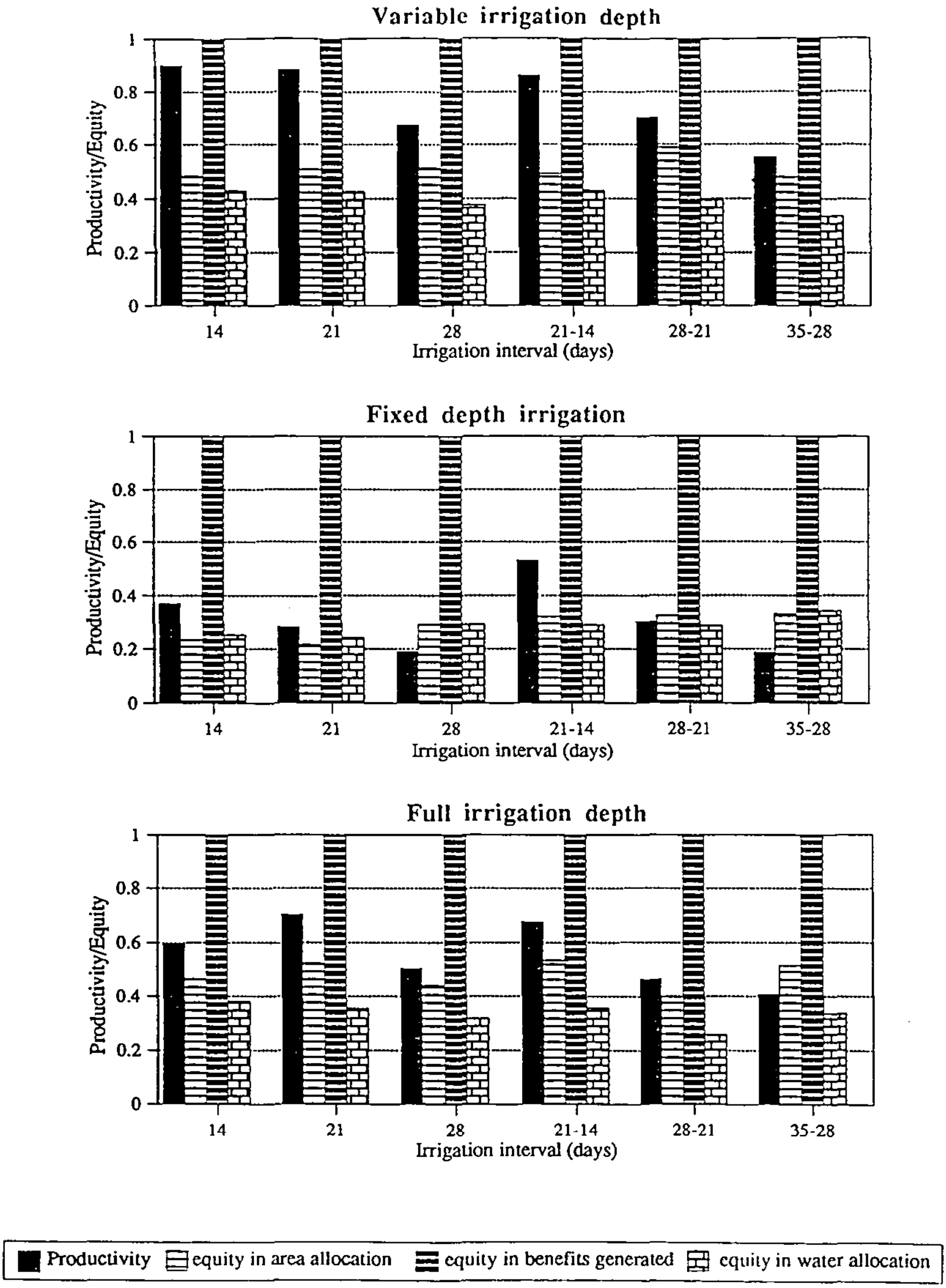


Figure 10.26 The measures of productivities and equities in area and water allocation (at AU) and net benefits generated for crop production restrictions at scheme level when allocation plans are obtained with equity in benefits generation

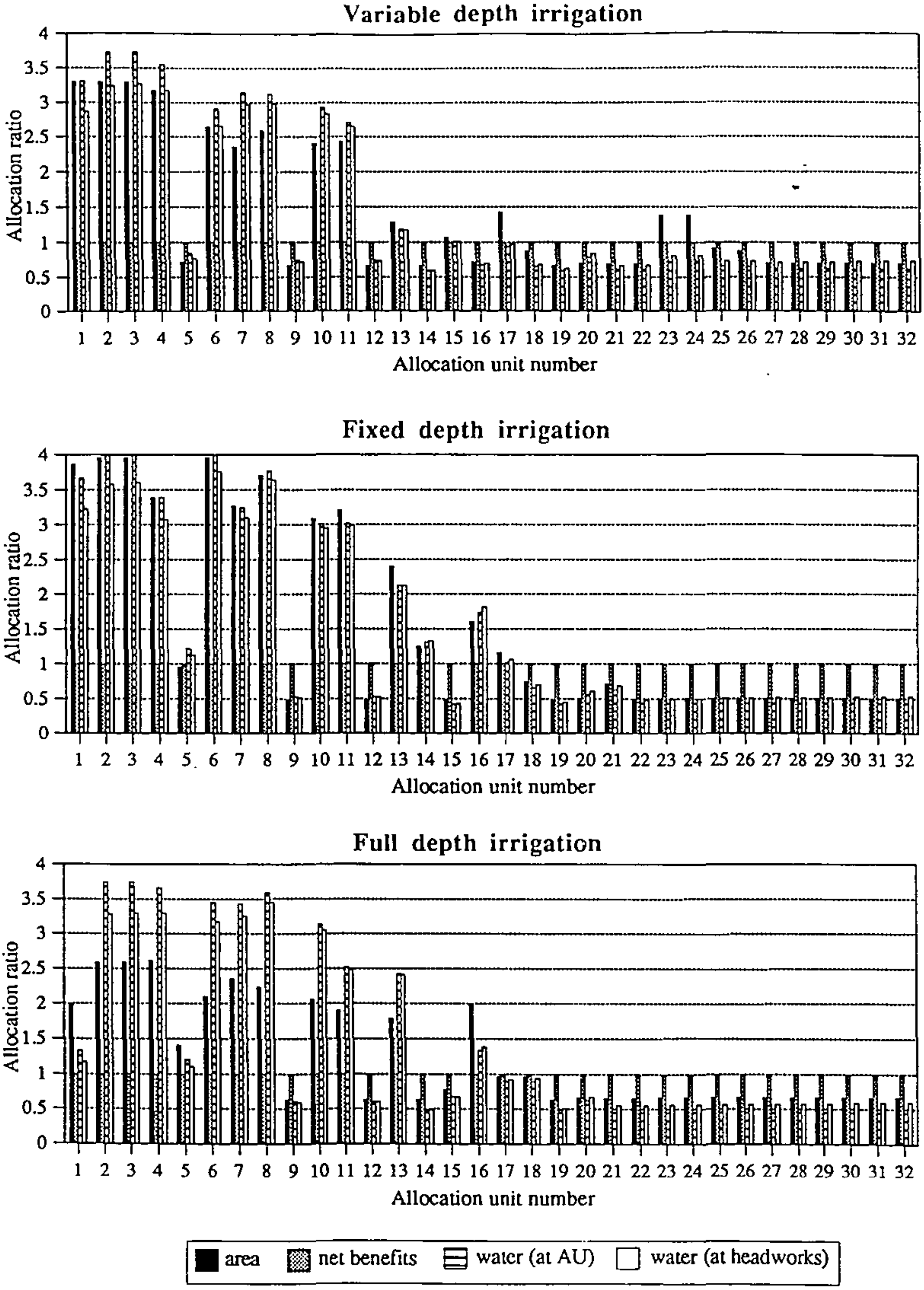


Figure 10.27 The allocation ratios for area allocated, water allocated (at AU and headworks) and net benefits generated for crop production restrictions at scheme level when allocation plans are obtained with equity in benefits generation

When the restrictions on crop production are put on each allocation unit, the equities in area and water allocation are found to be comparatively close to equity in benefits generation (Figure 10.28). The maximum productivity is found in VDI with I=14 days. The reduced productivity is found in FXDI and FLDI. Fixed depth irrigation approach could not produce a feasible solution at higher irrigation intervals. The allocation ratios for the best sets of irrigation interval for each irrigation depth approach (I=14, 21-14 and 21 for VDI, FXDI and FLDI, respectively) in Figure 10.29 indicates that less productive AUs get more area and water allocation to make their generation of benefits comparable to other allocation units. The different kind of allocation ratios in crop production restrictions at scheme level and at AU level are due to the forced inclusion of all crops to each AU.

The comparison of performance results of each irrigation depth approach for all the three cropping distribution (Figure 10.30) indicates the similarity with the results obtained with the other cases (no equity, equity in area and water allocation).

10.6.6 Comparing Productivity and Equities of Different Equity Cases

The productivity of different equity cases indicates that in free cropping distribution and crop production restrictions at AU level, the productivity is higher when equity in water allocation is observed, followed by equity in area allocation and equity in benefits generation. However in case of crop production restriction at scheme level, the reverse trend was found. The productivity by equity in benefits generation is higher followed by equity in area allocation and water allocation. Common to the free cropping distribution and crop production restrictions at AU level was the cropping pattern which was same for all allocation units. Whereas with crop production restriction at scheme level the cropping pattern was different in different AUs, and guided by the objective function. This indicates that the resources are not efficiently utilised for the prescribed cropping pattern at AU level, when equal distribution of income is to be followed over equal distribution of water. This is due to proportionally more water being allocated to less productive AUs to make benefits proportionally equal. But when the cropping pattern is flexible among different AUs, the crops to be grown in different AUs and the water allocation to different AUs are also flexible and therefore adjusted to obtain maximum net benefits.

It was found that equities in free cropping distribution and crop production restriction at AU level do not differ much. This is again due to similar cropping pattern for each AU. But with crop production restriction at scheme level, the equities in allocation are

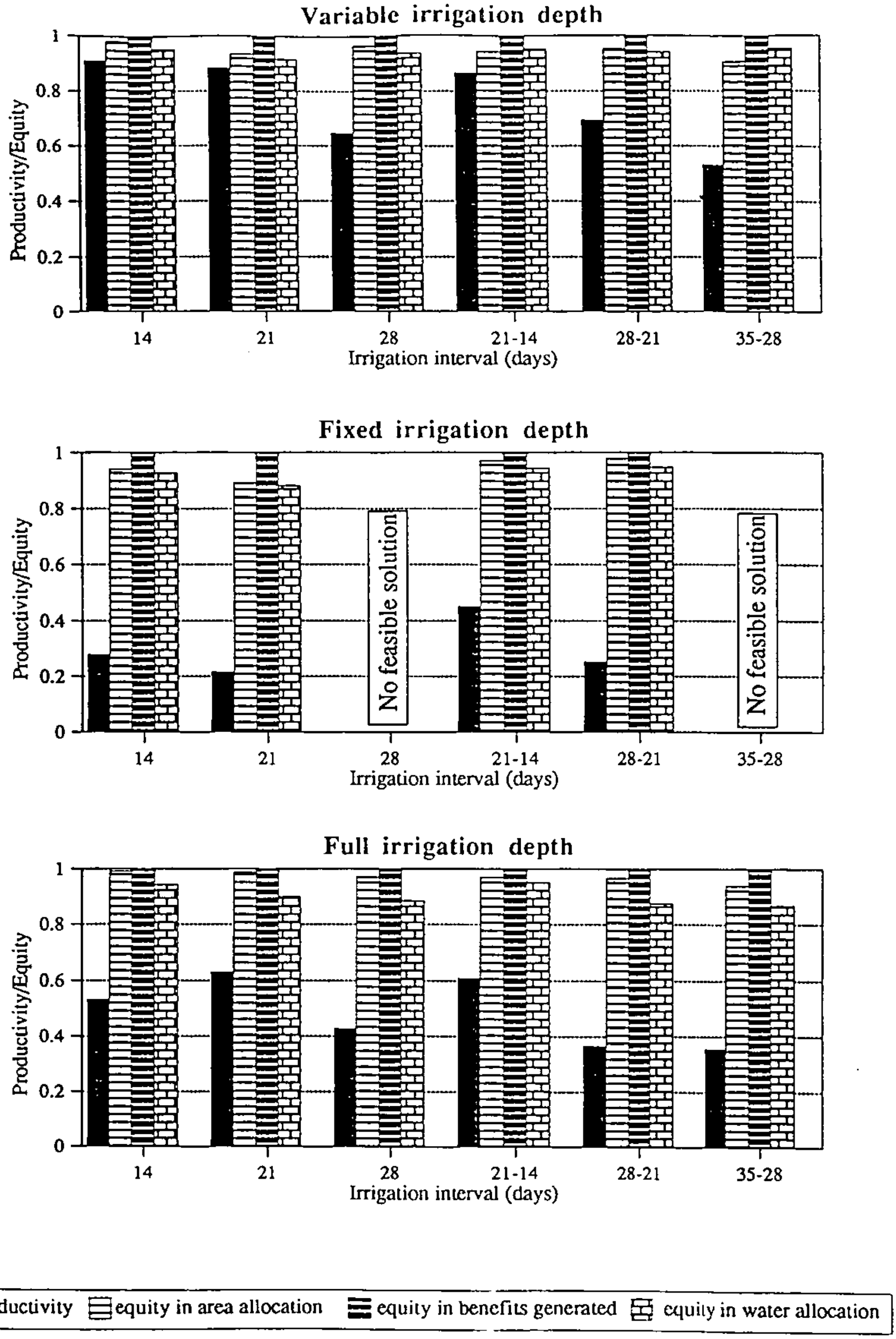


Figure 10.28 The measures of productivity and equities in area and water allocation (at AU) and net benefits generated for crop production restrictions at allocation unit level when allocation plans are obtained with equity in benefits generation

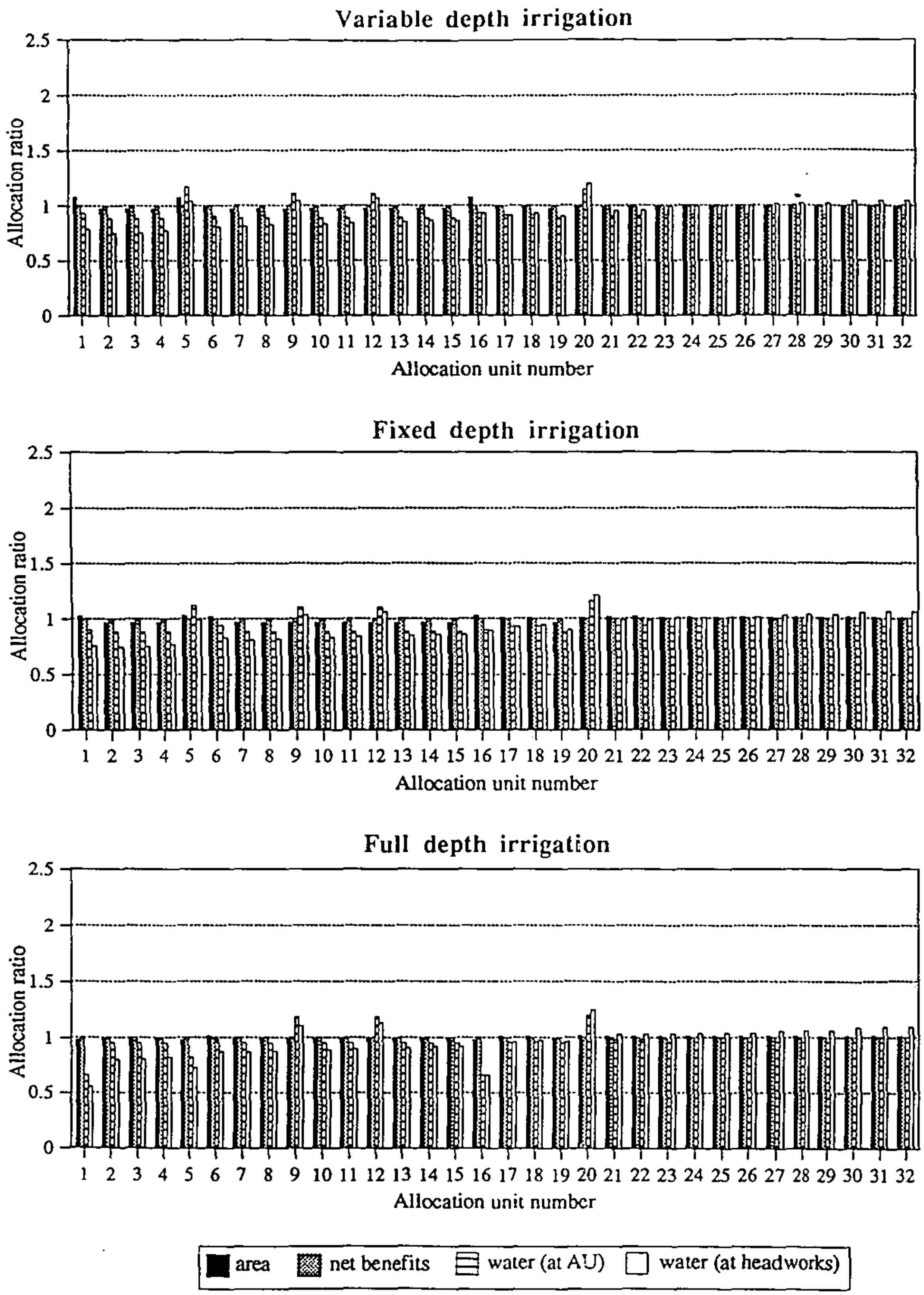


Figure 10.29 The allocation ratios for area allocated, water allocated (at AU and headworks) and net benefits generated for crop production restrictions at allocation unit level when allocation plans are obtained with equity in benefits generation

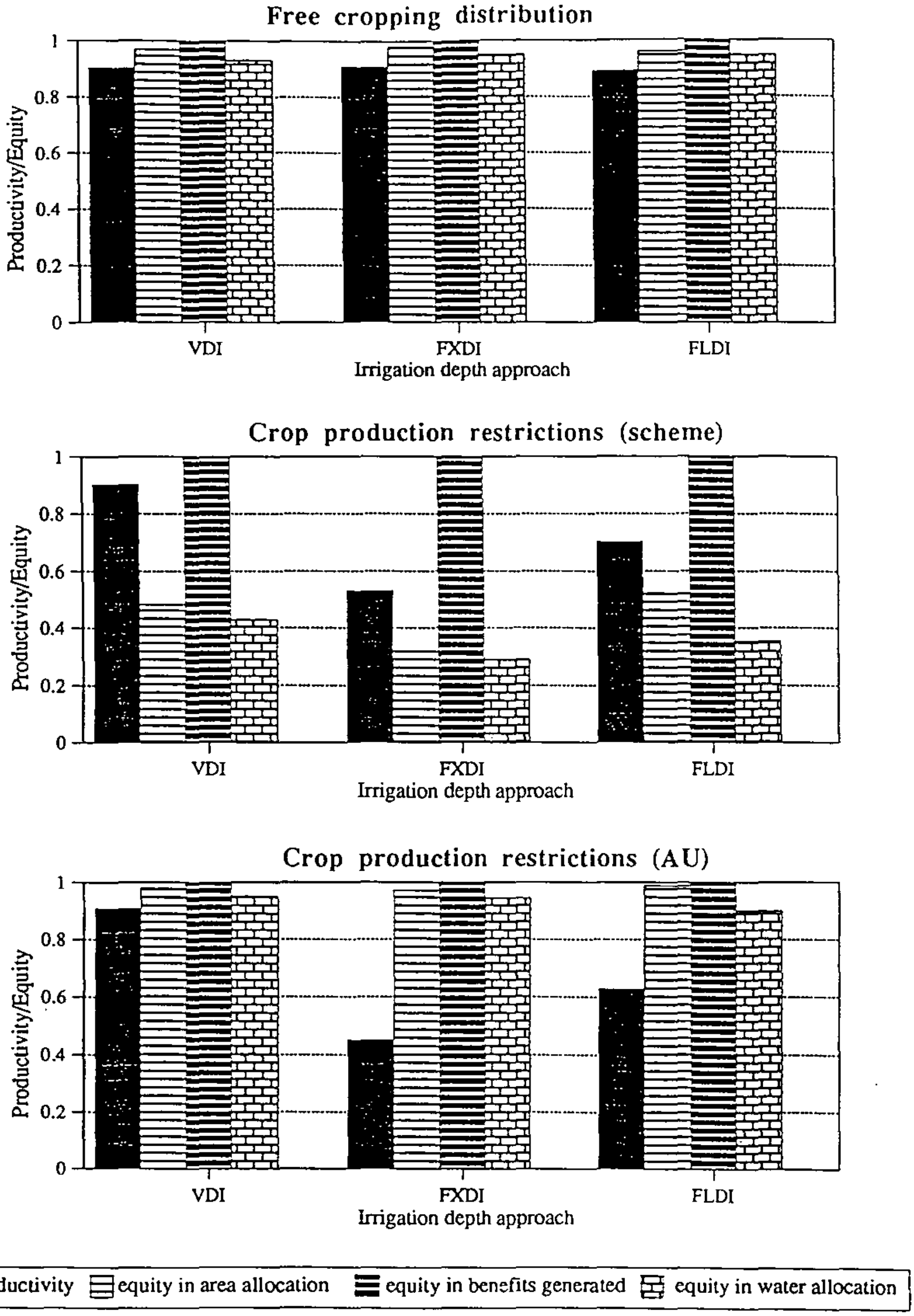


Figure 10.30 The measures of productivities and equities in allocation for the best set of irrigation intervals of each irrigation depth approach when allocation plans are obtained with equity in benefits generation

reduced for those parameters for which equity in allocation is not achieved. This is due to the cropping pattern being adjusted among different AUs to achieve equity in the prescribed parameter while maximising productivity. This lowers equity in other parameters.

Nearly the same productivity was obtained for all irrigation depth approaches in all equity cases with free cropping distribution. This was due to the single most profitable crop appearing in the allocation plan. However with prescribed cropping distribution at scheme level or AU level involving all crops, variable depth irrigation approach proves to be more beneficial with all equity cases.

10.6.7 Comment on Hypothesis-4

In Sections 6.3 and 10.4, the formulation of the model to include productivity and equity while obtaining the allocation plans is explained. The different irrigation depth approaches including variable irrigation depth approach (deficit irrigation) can be incorporated in this process through corresponding irrigation strategies (See Section 5.2). It was emphasised that different goals of achieving productivity and equity exist in the irrigation scheme, and which to choose depends on various local situations. While formulating AWAM, different situations were studied and incorporated. In the preceding subsections, the AWAM was examined to obtain allocation plans with some productivity and equity goals for different irrigation depth approaches. The AWAM proved to be successful in achieving these goals, thus verifying the Hypothesis 4.

10.7 PRODUCTIVITY-EQUITY RELATIONSHIP

Productivity is the single most important performance goal in irrigation water management, followed by equity. However while obtaining allocation plans, these are not considered together, excepting in a few cases of evaluation models. As equity defines the distribution of output or the resources over which the generation of output depends, productivity and equity are inter-related (however it is pointed out that equity in relation to productivity has relevance only when water is scarce in the scheme). Therefore when the allocation plans are obtained for optimising the productivity and equity, the management strategies formulated to maximise one of these gaols may have an effect on another goal. No clear-cut nature of dependence between these two goals was found from the studies conducted in this direction. Two opposite types of relationships between productivity and equity were encountered. In one type productivity and equity are complimentary to each other (Abernethy, 1986 and Steiner,

1991) and in another type these are contrasting one another (Burton, 1992 and Hales, 1994)

Abernethy (1986:9) opined that equity has direct influence upon productivity. According to him

"inequity - regardless of its social undesirability, which may be a matter of political attitudes - is undesirable because it implies poor utilisation of some water, and therefore reduced productivity of the available water."

He analysed the situation by postulating that the parts of system that receive less water than their crop water requirement will produce less than potential and the areas which receive more water than they need do not show improvement in yield as excess water does not serve any productive purpose. Steiner (1991) compared three allocation rules for studying the dependence of productivity and equity on each other. In allocation rule-1, the shortage is equally shared among all fields while according to allocation rule-2, those who have settled first in the system have the full right to the water. Allocation rule-3 spreads the shortage over all the fields but not in equal manner. Those at the head end receive a greater proportion of their demand than those at the tail. He found the greatest overall production by allocation rule-1 where in shortages are spread equally and least overall production by allocation rule-2 where in the shortages are not shared equally. The reasons attributed were less percolation losses and more careful use of water as it becomes more scarce.

Burton (1992) analysed the several water allocation policies for Mogambo Irrigation Project, Somalia, two of which were equally dividing the water available based on the calculated crop water requirement and dividing the water available based on the gross area of each tertiary unit or land holding. He found maintaining equitable distribution of supplies to all localities costly. When these two policies were compared to the best performing policy (in respect of total production value), the losses in production value of 56 to 63 % were observed. The reasons ascribed were higher losses in conveyance for distributing water to the whole system. Likewise Hales (1994) compared eight water allocation policies for Rio Cobre Irrigation Scheme, Jamaica, three of which were related to equitable allocation of water (allocation proportional to gross area, allocation proportional to crop area and allocation proportional to water requirement). These policies ranked lower when compared for output from the scheme. The water allocation policy to allocate to optimise crop production ranked first.

In the first type (Abernethy, 1986 and Steiner, 1991), it appears that even though the water is scarce the deficit irrigation was not thought about while deciding the area to be irrigated and once the area to be irrigated is decided, it is not varied for the changed circumstances of water allocation. Thus when more water is allocated than the maximum crop water requirement towards the head of the scheme, it is "wasted" instead of spreading it over additional area. Similarly the areas to be irrigated are not reduced towards the tail of the scheme when the shortage of water (due to excess delivery at the head of the scheme) would damage the crop over the prescribed area. In such situation of keeping fixed crop area whatever the availability of water, the productivity will be reduced with unequal water allocation. These are the situations where optimisation of the resources are not sought by adjusting the area to be irrigated or the water to be delivered. In the second type (Burton, 1992 and Hales, 1994) the maximum performing water allocation policy is the one which produces maximum crop production value. In these cases also, the areas to be irrigated were fixed. In maximum performing water allocation policy the water deliveries to different areas were adjusted so as to cause minimum wastage of water so that maximum production is obtained. When equitable water supply is sought, the water was spread over the entire locations in the scheme according to proportionality causing more wastage of water and therefore less overall benefits are obtained, though equity is achieved.

When allocation plans are obtained it is always desired to make optimum use of all resources such that maximum outputs are obtained under the given restrictions. When water is scarce, it calls for the deficit irrigation. In this case land and water resources should be utilised and adjusted in such a way that maximum productivity is obtained under the given restrictions including the equity in allocation. In such cases when maximum productivity is obtained without looking for any kind of equity, the allocations will be done for most productive areas or AUs. The AUs with less suitable soil, more losses of water in conveyance and distribution will tend to get less allocation. This in turn will lessen the equities in allocation. However when some sort of equity is attempted, the allocations to less productive areas or AUs will be enforced in the allocation plan. Due to wasteful use of water in less productive areas or AUs, the overall productivity will tend to be reduced. Thus when optimised allocation plans are to be obtained productivity and equity are not complimentary to each other but retrograde to each other. This formed the basis for Hypothesis 5 which states that

> Productivity is inversely related to equity in the process of allocation of the resources.

This hypothesis is verified in this section with the help of AWAM which allocates the resources optimally, and the data generated in Section 10.6.

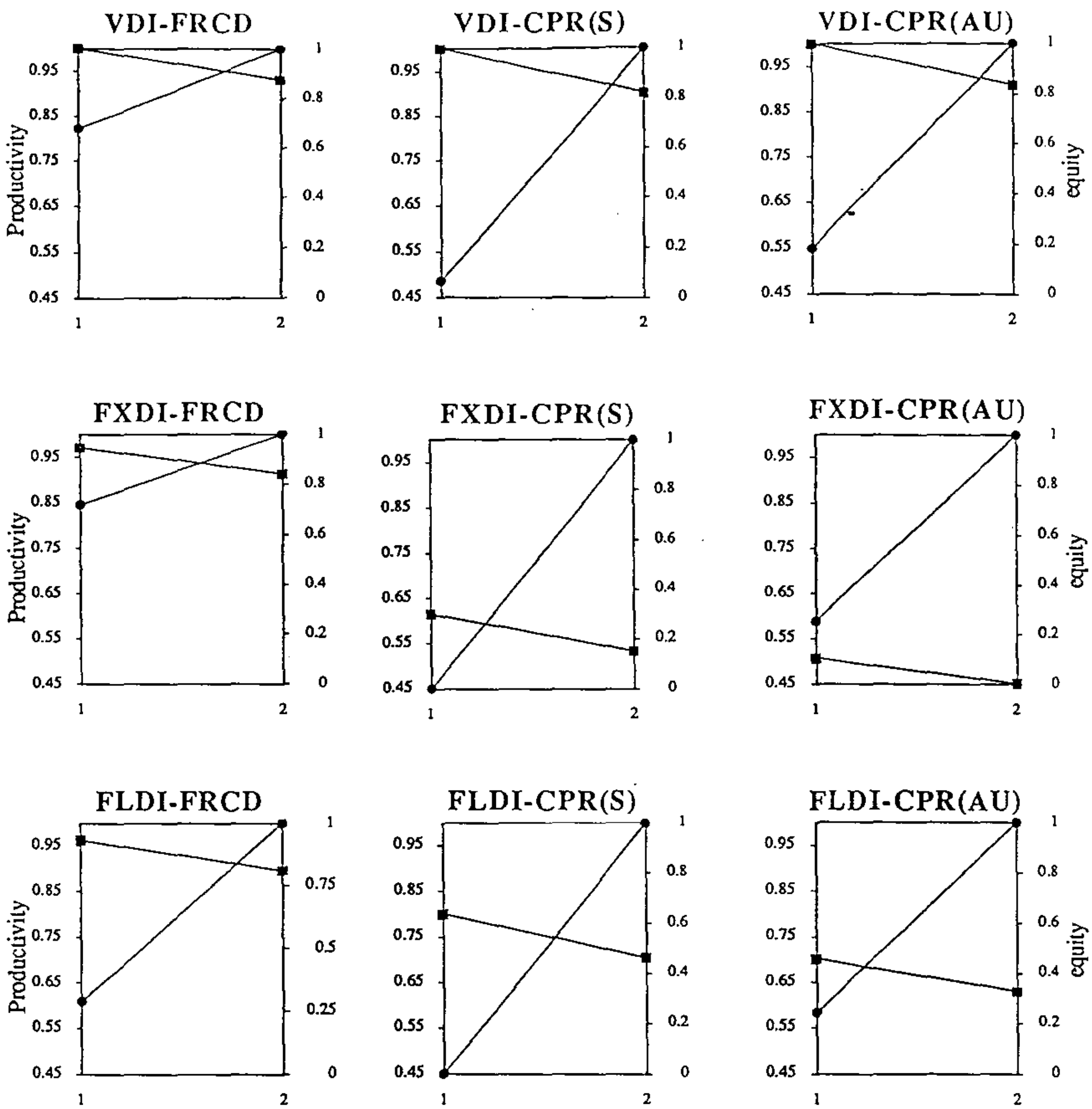
10.7.1 Productivity for Maximum Equity and Equity for Maximum Productivity

In Section 10.6, the allocation plans were obtained without consideration of equity and with equity in area allocation, water allocation and benefits generation. When equity in allocation is not considered, the allocation plan produced is for the maximum productivity under the given set of other restrictions. This is the case of maximum productivity for the set of given management options and restrictions. The equities in area allocation, water allocation (at AU) and benefits generation are computed for maximum productivity in Section 10.6.2. As explained above, three cases of equity in allocation were considered in Section 10.6. The productivity values for maximum equity (one) for each of these cases are computed in Section 10.6.3 (for equity in area allocation), 10.6.4 (for equity in water allocation) and 10.6.5 (for equity in benefits generation).

Productivity and equity values are computed for different management options (combination of irrigation depth approaches and irrigation interval) for different sets of restrictions (free cropping distribution and crop production restrictions at scheme and AU level). The productivity and equity values with no equity in consideration (the case of maximum productivity) shown in figures of Section 10.6.2 and with different equities in consideration (the case of maximum equity) shown in figures of Sections 10.6.3 to 10.6.5 indicate that for any given set of management options and other restrictions productivity decreased when maximum equity is obtained. Similarly equities decreased when maximum productivity is obtained.

The productivity and equity values with and without consideration of equity for the best set of irrigation intervals in each irrigation depth approach, for all the three cropping patterns, are shown separately in Figure 10.31 for equity in benefits generation, and in Figure 10.32 for equity in water allocation. These figures clearly indicate that when productivity increases, equity decreases and vice versa. This verifies the Hypothesis 5 that productivity is inversely related to equity in the process of allocation of the resources.

10.7.2 Productivity and Equity for their Intermediate Values



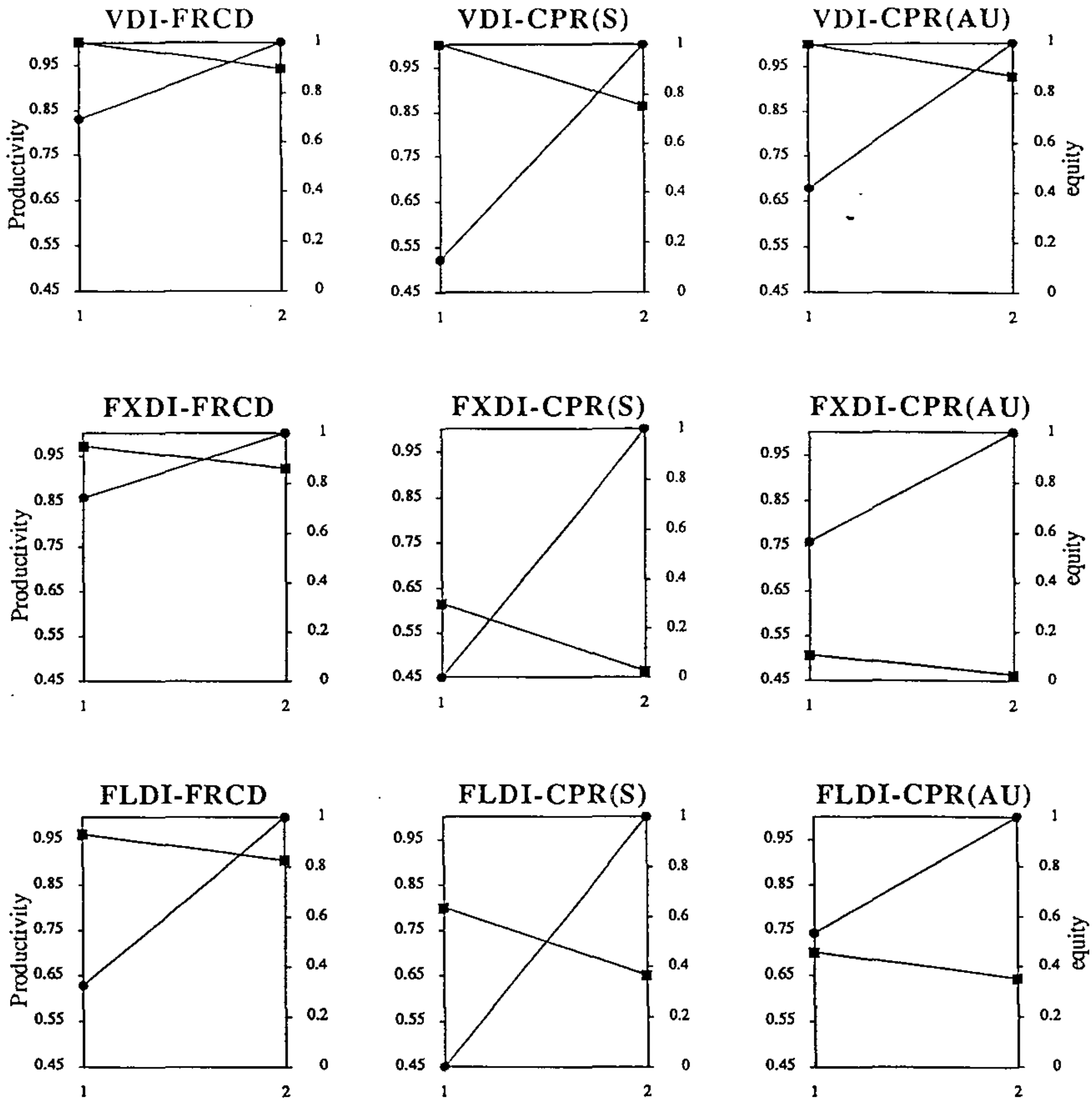
1-without equity in consideration
2-with equity in benefits generation

productivity

equity

VDI-variable depth irrigation approach
FXDI-fixed depth irrigation approach
FLDI-full depth irrigation approach
FRCD-free cropping distribution
CPR(S)-crop production restrictions at scheme level
CPR(AU)-crop production restrictions at allocation unit level

Figure 10.31 Productivity and equity when allocation plans are obtained without equity in consideration and with equity in benefits generation



1-without equity in consideration —■— productivity —●— equity
2-with equity in water allocation

VDI-variable depth irrigation approach
FXDI-fixed depth irrigation approach
FLDI-full depth irrigation approach
FRCD-free cropping distribution
CPR(S)-crop production restrictions at scheme level
CPR(AU)-crop production restrictions at allocation unit level

Figure 10.32 Productivity and equity when allocation plans are obtained without equity in consideration and with equity in water allocation

In Section 10.7.1, the productivity and equity values for maximum productivity and maximum equity were shown. In this section, these parameters for their intermediate values are found. Only one case of irrigation depth approach i.e. variable depth irrigation is chosen for this analysis. All the sets of irrigation interval and cropping pattern are considered for this irrigation depth approach. However only equity in benefit generation is considered to show the productivity and equity relations.

First the allocation plans for maximum equity and maximum productivity are obtained. The allocation plans are obtained by gradually decreasing the minimum limit on the benefits to be obtained from each allocation unit to zero, starting with the benefits obtained for each allocation unit with equity in benefits generation. When the minimum limit on benefits to be obtained from each AU is equivalent to the benefits obtained from each AU when equity in benefits generation is considered, the case of maximum equity and minimum productivity is obtained. When the minimum limit is decreased, the resources released on account of this decrease will be allocated to the most productive AUs. This results in increasing the total net benefits from the scheme and thus productivity. When the minimum limit is reduced to zero (or no limit), the resources are allocated to the most productive AUs to fulfil the objective function (in this case to attain maximum productivity in terms of total net benefits).

The productivity and corresponding values of equity in benefits generation are shown in Figure 10.33 for free cropping distribution, Figure 10.34 for crop production restrictions at scheme level, and Figure 10.35 for crop production restrictions at AU level. In free cropping distribution not many points could be found because there was little difference between equities for maximum and minimum productivity values. It is seen from these figures that as the equity increases, the productivity decreases and vice versa for all the sets of irrigation interval and cropping patterns. These figures again confirm the Hypothesis 5.

The reasons ascribed to the inverse relationship between productivity and equity are discussed in the beginning of this section. Here it should be pointed out that the Hypothesis 5 holds good when the resources are allocated optimally and equities are achieved for maximum productivity. It is possible that for non-optimal condition, the equity increases with productivity.

10.8 OTHER PERFORMANCE PARAMETERS (STABILITY AND SUSTAINABILITY)

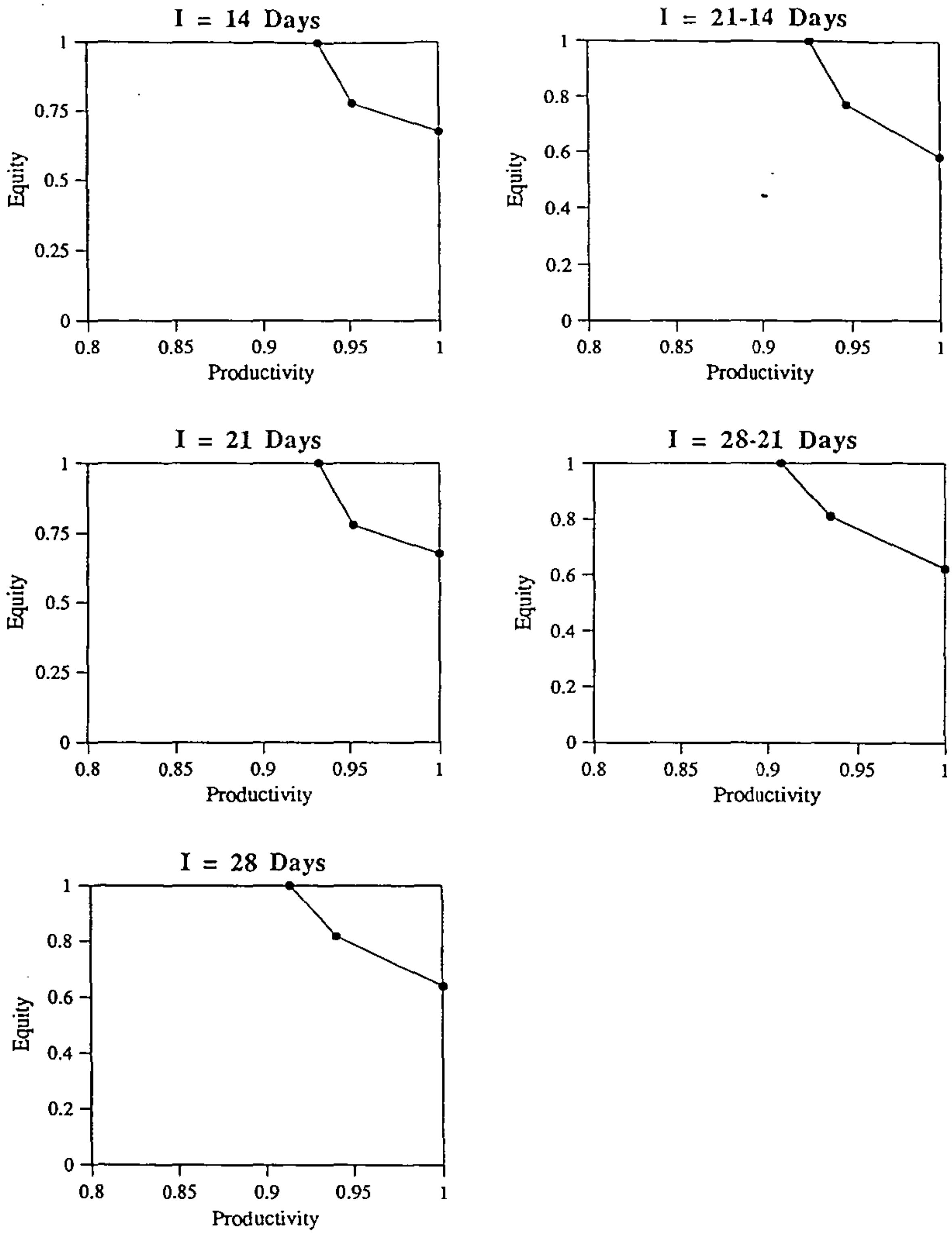


Figure 10.33 Productivity and equity relationships for free cropping distribution in variable depth irrigation approach

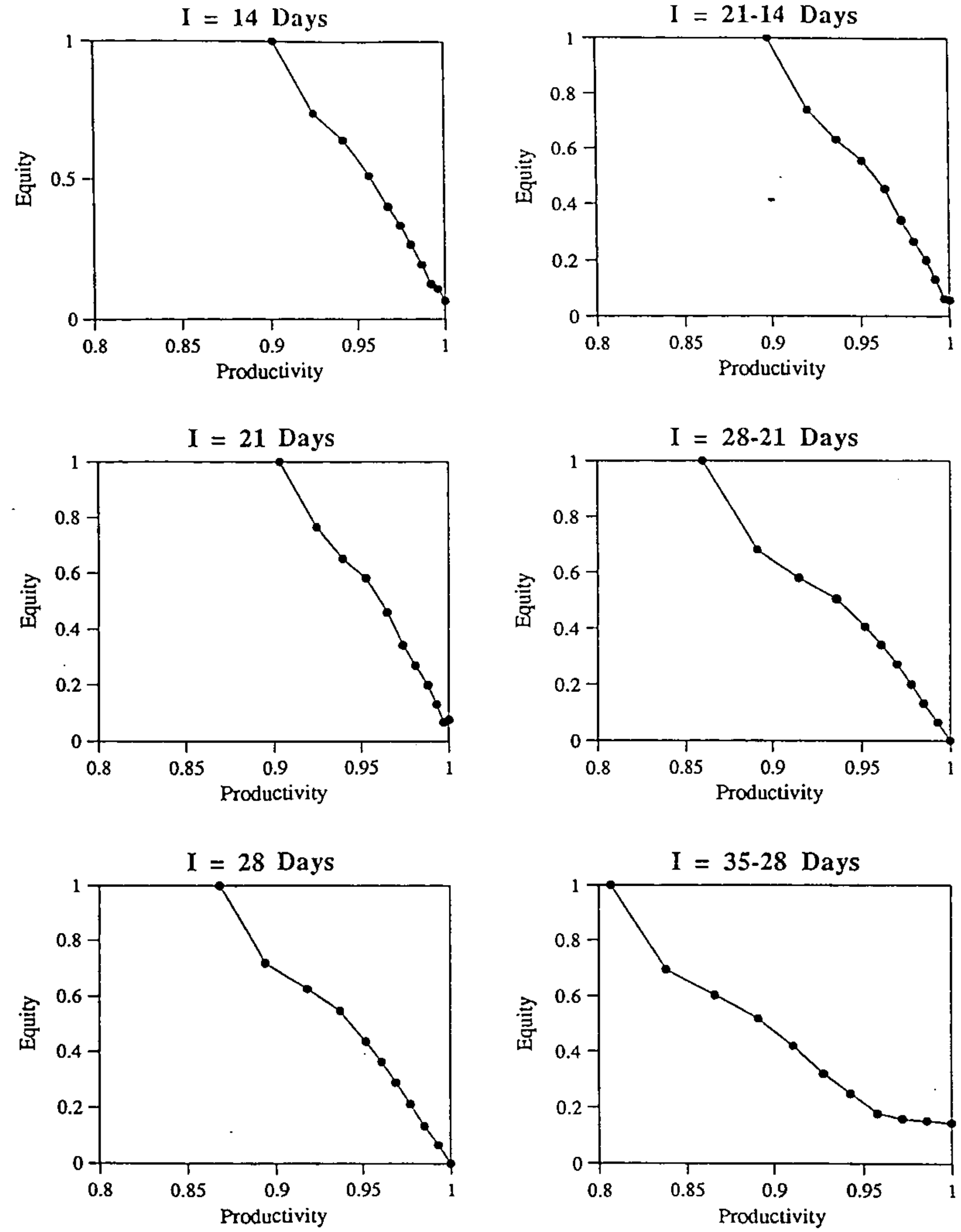


Figure 10.34 Productivity and equity relationships for crop production restrictions at scheme level in variable depth irrigation approach

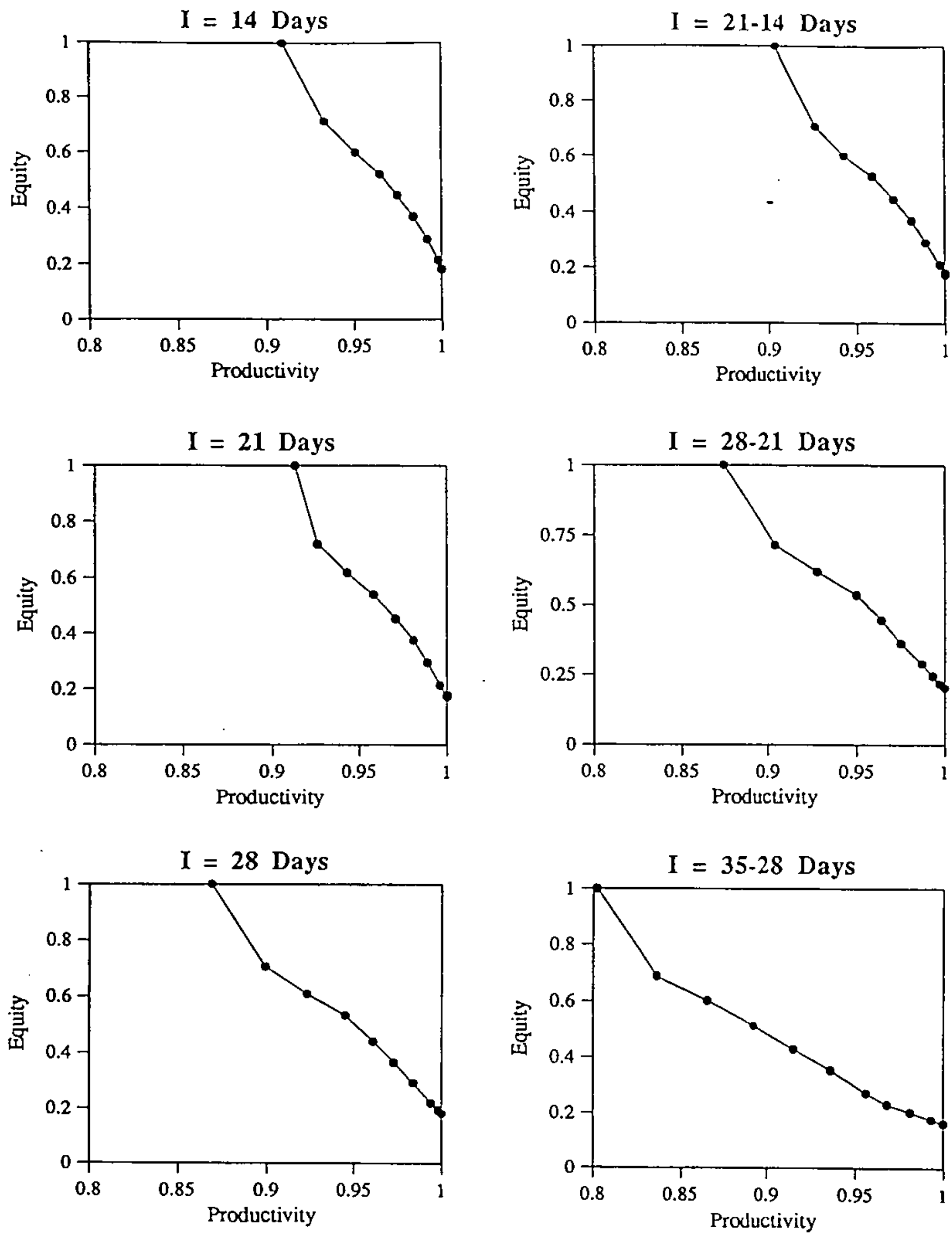


Figure 10.35 Productivity and equity relationships for crop production restrictions at AU level in variable depth irrigation approach

The other two performance parameters viz. stability and sustainability are considered for obtaining the allocation plans while developing AWAM. This section proposes the method for obtaining the stable allocation plan with AWAM and comments on sustainability in relation to AWAM.

10.8.1 Stability

The importance of stability and the considerations of stability in irrigation water management models described in Chapter II are discussed in Sections 10.2.3 and 10.3, respectively. The AWAM is also formulated to obtain steady allocation plans. The procedure similar to stochastic optimisation (Croley II, 1974) is developed to obtain steady allocation plan with AWAM. The AWAM in Evaluation Mode is used in this procedure. The procedure is described in Section 10.8.1.1 and is presented in Figure 10.36.

10.8.1.1 The procedure to obtain the steady allocation plan.

The procedure to obtain the steady allocation plan with AWAM is described below.

- 1. Setting the data: The following data are set
  crop, soil, region, irrigation scheme
  weather and streamflow data for maximum available years
  objective and constraints (this also includes cropping distribution)
  management option in terms of irrigation depth approach

- 2. Obtain the allocation plan for the weather and streamflow data starting with first year, with the AWAM in Planning Mode (Figure 4.8.5)

- 3. Obtain the modified allocation plan for the weather and stream flow data starting with first year with the AWAM in Evaluation Mode (Figure 4.10). Compute the performance parameters of interest such as productivity and/or equity in different forms (see Sections 10.4.1 and 10.4.2) for the modified allocation plan.

- 4. Repeat Step 3 for the weather and streamflow data of all the years.

- 5. Compute the statistical parameters such as mean, standard deviation, coefficient of variation, skewness coefficient etc. for the chosen performance parameters (performance parameters of interest)

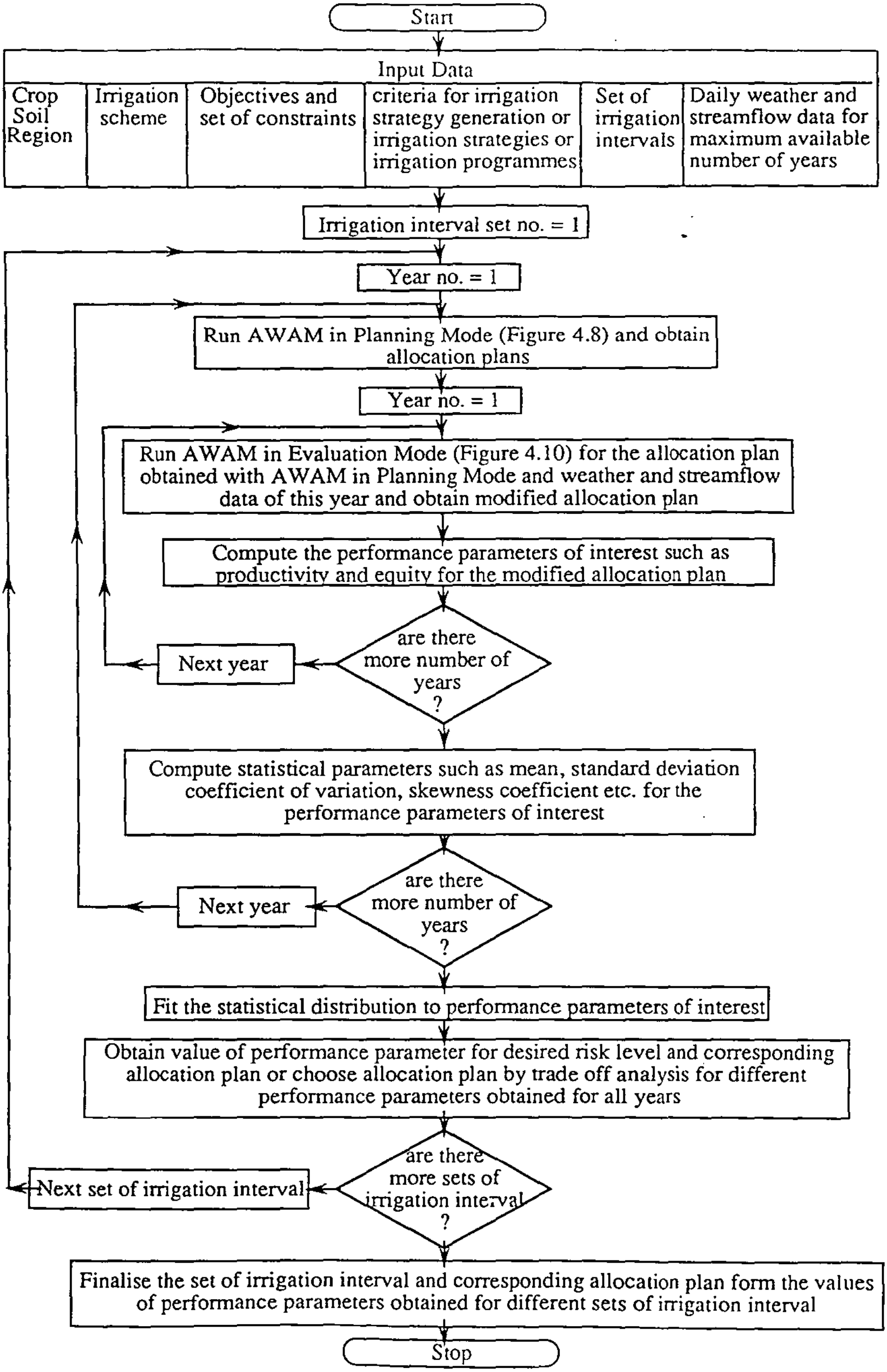


Figure 10.36 The flowchart for the procedure to obtain the steady allocation plan

- 6. Repeat Steps 2 to 5 for the weather and streamflow data of all the years.

- 7. Fit the statistical distribution to the chosen performance parameters with the help of values of statistical parameters computed in Step 5.

- 8. Obtain the value of chosen performance parameters for the desired risk level and the allocation plan corresponding to this value of performance parameter or select the allocation plan by performing the trade off analysis for the different performance parameters obtained for the weather and streamflow data of all the years and risk levels.

- 9. Repeat Steps 2 to 8 for all the selected sets of irrigation interval.

- 10. Finalise the set of irrigation interval and corresponding allocation plan from the values of performance parameters obtained in Step 8 for different sets of irrigation interval.

The procedure described in this section can be repeated for different management options and cropping distributions.

10.8.2 Sustainability

The sustainability is described in Section 10.2.4 and its role in irrigation water management models is discussed in Section 10.3. It is seen from Sections 10.2.4 and 10.3 that the sustainability parameters of interest are salinity and water logging. The irrigation programmes produced and used in the allocation process by AWAM does not schedule the irrigations which would cause overwatering. Therefore it is expected that the water deliveries scheduled according to the allocation plans obtained from AWAM will not be the cause for the salinity and waterlogging. However the salinity and water logging may be caused if other management policies are not followed properly for example, the excessive conveyance losses in the distribution network. Similarly the quality of the water used for the irrigation may be poor and soil may be already saline. AWAM does not produce the allocation plans which take care of salinity control. A possible extension to the model would be considered for the salinity control issues related to deficit irrigation with poor quality of water and saline soil. The SWAB and CRYB submodels used in the process of generation of irrigation programme in AWAM need to be suitably modified.

10.9 INTRASEASONAL OPERATION OF IRRIGATION SCHEME

Irrigation management models develop the allocation plans at the preseason planning for the particular weather and streamflow time series or steady allocation plans considering the weather variability over the number of years of data available. In real time operation, however, the time series is expected to deviate from those considered for developing the allocation plan. Therefore the water deliveries scheduled, according to the allocation plans developed at the preseason planning, may not produce the expected results during intraseason operation of irrigation scheme. If the year for which allocation plans are produced turns out to be a dry year, the production will be drastically reduced as the entire area planned for irrigation may not get water. Similarly if the year turns out to be a wet year, the expected output from the scheme will be obtained but some water may be wasted, which otherwise would have either irrigated more land or been used in increasing the output from the land already under irrigation. The use of a steady allocation plan reduces this effect caused due to deviation of time series in real time operation to a certain extent.

It is, therefore, necessary to have some method in the model developed for the allocation of the resources at the preseason planning which can modify the allocation plans during different irrigation periods in the intraseasonal operation of the irrigation scheme to optimise the use of water. The allocation models which are developed based on stochastic dynamic programming are able to give the plans for the varied time series through the transitional matrix of the weather parameters that are considered as random variable (Dudley et al., 1971[a]; Palmer-Jones, 1977; Bras and Cordova, 1981; Rhenals and Bras, 1981; Rees and Hamlin, 1983; Loftis and Houghtalen, 1987 and Vedula and Mujumdar, 1992). However in such models as the area under different crops is predecided, only the water deliveries are varied according to the changed conditions. The evaluation models (Burton, 1992 and Hales, 1994) are able to modify the allocation plan by operating the model at each irrigation period for the remaining season for the changed conditions. But these models do not consider the global optimisation while modifying the allocation plans in intraseasonal operation of the irrigation scheme. The land and allocation models developed previously have no such provision. Therefore there is a need to develop the procedure which can modify the allocation plan optimally while the irrigation scheme is in operation. This process can be referred to as "real time optimisation".

In the present study the AWAM in Operation Mode is formulated for the real time optimisation of the allocation plans. The AWAM in this mode is described in Chapter IV (Section 4.8.6). The procedure includes operating the AWAM in Planning Mode at the particular irrigation periods for modifying the allocation plans for the remaining irrigation season or the remaining part of the season (considering lag) with the changed conditions at the irrigation period and modifying some constraints. The constraints to be modified may include changing the range specified for the area to be irrigated under different crops (at scheme, allocation unit or soil group of allocation unit level) to the area under irrigation or to be irrigated for different crops in different soil groups of different allocation units. The changed conditions may include the moisture status in the soil root zone, crop conditions and the water availability in the reservoir. The changed conditions are obtained by running the AWAM from the beginning of the irrigation season to the irrigation period under consideration by running the AWAM in Evaluation Mode. Alternatively the actual changed conditions obtained from the field data can be used by modifying the input files of AWAM.

In this study only the procedure for real time optimisation is presented but not tested with the case study data. However it is expected that the model in AWAM in Operation Mode would be able to modify the allocation plans during the intraseasonal operation of an irrigation scheme, as it is essentially running the AWAM in planning mode with modified length of irrigation season, initial conditions and some set of constraints.

10.10 CONCLUSIONS

This chapter was assigned for the verification of part of Hypothesis 4 and Hypothesis 5. The following conclusions were drawn in this process.

1. The knowledge of performance of the various management options in obtaining the allocation plans is essential to know how the irrigation scheme responds to these options. In this study, however, it was emphasised that the development of allocation plans for the appropriate performance of the irrigation scheme i.e. including productivity and equity performance parameters is important to know performance oriented allocation plans and it is possible to include these aspects while producing allocation plans. The irrigation water management model (AWAM) is formulated in this study to perform this task. The allocation plans generated with the help of AWAM for different management options (which also include the variable depth approach suggested in this study) by including productivity and equity in allocation process

proves that the productivity and equity can be included while obtaining the allocation plans. This is the part of Hypothesis 4.

2. In previous chapters (Chapters VIII and IX), it was found that the variable depth irrigation approach based on deficit irrigation performs better over conventional fixed depth or full depth irrigation approaches in obtaining the maximum output from the irrigation scheme. The equity aspects were not considered in those chapters. In this chapter the allocation plans obtained with the inclusion of equity in area allocation, water allocation and benefits generation for all the three irrigation depth approaches indicate that the variable depth irrigation approach is superior to other irrigation depth approaches in achieving prescribed equity in allocation.

3. As the equity is a measure of either the distribution of output or the distribution of the resources over which output from the scheme depends, productivity and equity are related. The analysis of the productivity and equity for different equity scenarios, management options and different cropping patterns indicate that productivity reduces as equity increases. Thus productivity and equity are inversely related. This verifies the Hypothesis 5.

4. One of the objectives of the study was to propose the method to obtain the steady allocation plan. In this chapter the methodology to obtain the steady allocation plan with AWAM is described.

5. The Hypotheses 3 and 4 also state that the concept of deficit irrigation and productivity and equity aspects can be included during the intraseasonal operation of the irrigation scheme for allocating the resources. The AWAM in Operation Mode is formulated to perform this task. This was one of the objectives of the study. AWAM modifies the allocation plan during the intraseasonal operation of the irrigation scheme by considering the deficit irrigation and the productivity and equity aspects (real time optimisation). The real time optimisation with AWAM is not tested with the case study data in the present study but its utility in performing this task is explained in this chapter.

CHAPTER XI

CONCLUSIONS

Summary. This chapter describes the outcome of the research conducted in terms of formulated hypotheses and aimed objectives.

11.1 HYPOTHESES OF THE STUDY

This research is concerned with the planning and operation of those irrigation schemes which experience the water shortage for irrigating the crops with their maximum crop water requirements over their entire culturable command area. In such schemes the need exists to use available water efficiently. Several means are listed in Chapter I for efficient use of water in an irrigation scheme. These means are not alternatives but complementary to each other. The optimum allocation of land and water resources is one of those means and the present research specifically emphasises this issue.

In the last three decades several methods were devised through modelling studies (development of allocation models) to allocate land or water or land and water resources optimally in the water limiting condition. The Chapter II reviews various models or procedures developed previously by attempting to classify those according to the resources that were optimised. The review of these models indicated that the opportunities exist for utilising the resources efficiently in the allocation process. The system involved in the allocation procedure is quite complex (See Chapter V). The previous development of allocation models started with the representation of a simple system. It proceeded to modelling the system as closely as possible as the information on the various processes involved in the system was becoming available.

In this study efforts were made to build the model from the experiences gained from the earlier studies, for the efficient utilisation of water by allocating land and water resources optimally to different crops grown at different locations in the irrigation scheme. The approach involved is formulating the hypotheses, the inclusion of which in the model could lead towards addressing the issue of efficient use of water through optimum allocation of land and water resources more rationally, and verifying those hypotheses by constructing one case study. Chapter I describes the hypotheses. Chapters II and III provide the back ground to the selected hypotheses. Chapters IV through X attempt to verify those hypotheses and this chapter concludes the verification and the results obtained in the process of verification.

11.1.1 Hypothesis-1

The beneficial aspects of deficit irrigation in water limiting or plentiful situation are discussed in Chapter III. In the irrigation schemes considered in this study, the irrigation interval is uniform for all crops, soils and climatic conditions, though it can vary over the irrigation season, and it is predecided before the start of irrigation season. The irrigation water management models previously developed for efficient utilisation of water resources in such irrigation schemes were unable to contemplate the deficit irrigation suitably. To include the deficit irrigation option in the allocation process, it was thought necessary to find the means of causing deficit in such schemes.

It was hypothesised that prolonging the interval between two irrigations and/or applying water less than needed for full irrigation results in deficit irrigation. Three approaches were formed based on this. They represent the effect of varying irrigation interval only (Approach-1), the effect of varying irrigation depth only (Approach-2) and the effect of varying both irrigation interval and irrigation depth (Approach-3). The three approaches in conjunction with full depth irrigation, partial depth irrigation and fixed depth irrigation were used to verify the Hypothesis 1. The reduction in crop yield from maximum attainable crop yield was chosen as the indicator of deficit. The results from the case study data indicated that all the three approaches could lead to deficit irrigation for all crops and soils, except Approach-1 in some cases. This deficit occurred due to dropping the soil moisture in the root zone below the allowable depletion level, and occurrence of ET deficits. The results also indicated that deficit irrigation influenced crop yield and water consumption. Broadly it was found that deficit irrigation reduced both the water consumption and crop yield.

Partial depth irrigation and fixed depth irrigation varied the depth of irrigation at every irrigation, but the variation was effected uniformly over all the irrigations. The variation in irrigation interval could not be integrated with these variations in irrigation depths through partial or fixed depth irrigations. The optimum allocation of water is only possible if all the possibilities of distributing water are evaluated together, because of the different response of different crops with different amounts of water application in different periods of growth. This led to the introduction of "variable depth irrigation" in this study. In variable depth irrigation (VDI), the depth of irrigation or level of irrigation may be the same or different and the possibility of varying irrigation intervals is induced with zero irrigation depth at a particular irrigation. The variable depth irrigation, thus, considers the deficit brought about by all the three approaches. Therefore the VDI was incorporated in the present allocation model to make it possible to evaluate all the possibilities of distributing water and thus to contemplate deficit irrigation suitably.

The inclusion of deficit irrigation in the allocation process needs the examination of several alternatives as seen from the irrigation strategy generator (Section 5.2.3) and VDI (combination of different amounts of irrigation depth and zero irrigation) discussed in Chapter VIII. At field level it is impossible to generate the information on crop yield to these alternatives by conducting the experiments. In the past, several models have been formulated to simulate the response of the soil-plant-atmospheric subsystems to the input of water (See Chapter V). The simulation models developed for this purpose varied greatly from simple approximation to the close representation of the system. However all these models were designed to fulfil the specific purposes, and for this study it was necessary to develop a model which could take on several alternatives of deficit irrigation. As several alternatives are involved, it is evident that the system should be represented accurately to obtain the distinctive response of several alternatives. The development of the model in past studies revealed the possibility of representing the system closely, but with a huge amount of data and computer time. But in applying this to an irrigation scheme, it is expected to test the deficit irrigation for many crop-soil-climate combinations, and therefore proper consideration of the availability of data was important. At the same time, as the alternatives of deficit irrigation could run into thousands and with many crop-soil-climate combinations to be tested, the computer time was also a factor. Therefore it was necessary to formulate the model with these considerations. From the reviews of several such studies conducted in the past, it was hypothesised that the detailed process in the soil-plant-atmospheric subsystem can be modelled accurately to include the deficit irrigation in the computer program.

The submodels SWAB and CRYB were constructed considering all the associated factors described in the above paragraph. The model was designed for requiring a limited amount of data, representing the system appropriately and following the solution technique needing minimum computations. The feature of calibrating the model for those processes for which data might not be available was added in the submodels so thát the response of the system can be estimated as closely as possible. The submodels were tested for the field experimental data which incorporated the treatments of full irrigation and deficit irrigation. The model was able to represent the system to an acceptable level after calibration of certain processes. Later this submodel was incorporated in the allocation model and proved to be successful with the allocation model in obtaining the allocation plans for several situations.

Thus the study verified the Hypothesis 1 and in the process clarified the means of causing deficit for the type of irrigation schemes under study, investigating the approach which considers the deficit irrigation in such schemes rationally (variable depth irrigation), and developing the method and computer model which facilitates the incorporation of deficit irrigation in an allocation model.

11.1.2 Hypothesis-2

Hypothesis 1 established the means of causing deficit and its influence in reduction of crop yield and water consumption. However it needs to be evaluated whether deficit irrigation can be beneficial by spreading the water saved, due to reduction in water consumption, over an additional area and compensating for the reduction in crop yield by obtaining additional net benefits from the additional area. In a water limiting condition it was hypothesised that saved water could bring more incremental income and therefore Hypothesis 2 was formulated.

In Chapter IX, the variable depth with no stress (adequate irrigation) or minimum stress (when adequate irrigation is not possible for the given set of irrigation intervals), optimised variable depth irrigation (can be adequate or deficit irrigation), fixed depth irrigation and full depth irrigation (past studies generally used full depth for comparing with deficit irrigation) were compared for net benefits over the entire irrigation scheme with the help of case study data. The comparison revealed the interesting results. Overall the deficit irrigation proved to be beneficial over adequate irrigation obtained by variable depth irrigation. The results with full depth irrigation and fixed depth irrigation indicated that deficit caused due to prolonging the irrigation interval is not always beneficial. When the irrigation interval is increased beyond a certain limit, the net benefits drop. In a certain case the drop in net benefits was drastic. The drastic drop was observed only when the irrigation interval was increased to the extent which caused severe damage and resulted in enormous crop yield reduction. The comparison between deficit and adequate irrigation for different irrigation intervals indicated that deficit caused due to application of less irrigation depth is mostly beneficial. The results of variable depth irrigation with different sets of irrigation interval indicate that the net benefits are either not much influenced by irrigation interval or dropped drastically with increasing irrigation interval. The full irrigation was generally used to compare with deficit irrigation in past literature, and this research found that the deficit irrigation caused through VDI was always beneficial over the full irrigation for this case study.

As such the Hypothesis 2 is partly verified. This hypothesis states that "the reduction in water consumption by deficit irrigation brings additional area under irrigation, and the water saved through deficit irrigation, if applied to this additional area, gives higher incremental production or returns than by adopting adequate irrigation to satisfy maximum crop water requirements". However as indicated in the above paragraph the benefits produced from additional area do not always compensate for the reduction in crop yield caused by deficit irrigation. This depends on how the deficit is produced. These conclusions are from a particular case study but probably have wider applications.

The results obtained while attempting to verify this hypothesis indicated the possibility of efficient utilisation of water in the irrigation scheme by adopting the deficit irrigation in the process of allocation of land and water resources. It also indicated that there can be the cases where adequate irrigation is preferable. Therefore the allocation process should always consider both adequate and deficit irrigation. These outcomes while verifying Hypothesis 2 were also used in the development of the allocation model in the present study.

11.1.3 Hypothesis-3

The Hypotheses 1 and 2 resulted in investigating the means to produce deficit irrigation and the influence of deficit irrigation on the output obtained, when practised in the irrigation scheme with water limiting condition. The results obtained from Hypotheses 1 and 2 also indicated that both adequate and deficit irrigation should be considered while obtaining allocation plans.

The review of different irrigation management models (Chapter II) showed the need to allocate land and water resources in the irrigation scheme optimally to different crops at lower levels (AU or farm level) so that an allocation plan could be used in operation of the irrigation scheme. The deficit irrigation is useful for allocating the resources optimally. Therefore it was hypothesised in this study that the concept of deficit irrigation can be included in a computer model for the allocation of the resources at pre-season planning of an irrigation scheme. The variable depth irrigation approach suggested in this study integrates the adequate and deficit irrigation approaches and therefore was incorporated in the process of allocation.

The allocation process is not only limited by availability of resources but various other restrictions also act in the irrigation scheme. These are described in Chapter VI and include physical constraints, resource availability constraints and output requirement constraints. All these need to be considered while developing the model for allocation of the resources. The resources allocation (RA) submodel (Chapter VI) was formulated with the inclusion of VDI in the allocation process. The RA submodel allocates the land and water resources optimally to different crops grown at various levels (from scheme to farm level) by considering various constraints restricting the allocation.

The RA submodel was tested for the case study (Nazare Medium Irrigation Project, Maharashtra, India). The allocation plans were obtained for various alternatives related to irrigation interval, water available, cropping distribution, food requirement and efficiencies, to verify the applicability of the model in varying scenarios that could exist in such irrigation scheme (See Chapter IX). One detailed allocation plan is presented in Appendix C. The RA submodel formulated in Chapter VI and the applicability of this submodel in obtaining the allocation plans at preseason planning investigated in Chapter IX, indicate the verification of Hypothesis 3 for 'preseason planning' part. Hypothesis 3 also refers to intrseasonal operation of the irrigation scheme. This is discussed in Section 11.1.6.

The combination of SWAB, CRYB and RA submodels contributed the whole model that can be used as a tool in the allocation of the resources in a water limiting condition for the irrigation scheme where irrigation intervals are predicided. This model is the Area and Water Allocation Model (AWAM).

11.1.4 Hypothesis-4

Hypothesis 3 confirmed the allocation of the resources at the smaller unit level by incorporating the deficit irrigation in the allocation process. The model formulated for the said purpose maximises the productivity. However the productivity may not be the only goal or objective of the allocation of the resources in an irrigation scheme. When the allocation is sought at the smaller unit level, the distribution of the resources among these units (equity) becomes important and is often one of the important performance criteria of the irrigation scheme. Chapter X describes these aspects. This criterion was often neglected in the allocation process (See Chapter II) but, as described in Chapter X, it is important and has many facets.

Equity has been considered in previous evaluation models but these models do not optimise the allocation of the resources. The allocation plans obtained from the allocation model are meaningful if they consider the equity aspect in the required manner. In this study it was hypothesised that productivity and equity aspects can be included together in the allocation process. As deficit irrigation aids in enhancing the productivity of the irrigation scheme, the inclusion of deficit irrigation in combining productivity and equity is also important. This forms the extension of Hypothesis 4.

The different aspects of productivity were included in the allocation model (AWAM) through the objective function of RA submodel. Therefore it was thought appropriate to include the equity aspects in the form of constraints so that allocation can consider productivity and equity together. The different constraints are formed to include various aspects of equity and are included in AWAM under output requirement constraints (Chapter VI).

The formulation of AWAM for productivity and equity is tested for the case study in Chapter X. The allocation plans to include productivity and equity for some cases are obtained in Chapter X. The discussion presented in Chapter X indicates the applicability of AWAM in obtaining the allocation plan that includes the required equity criteria while maximising the productivity. Thus the formulation of the model in Chapter VI and the results presented in Chapter X confirm the Hypothesis 4. The important contribution of combining the productivity and equity for obtaining the optimum allocation plan for the irrigation scheme faced with water shortages is made while verifying the Hypothesis 4.

11.1.5 Hypothesis-5

Both way relationships between productivity and equity (that is productivity is directly related to equity and productivity is inversely related to equity) were noticed while reviewing the research works concerned with productivity and equity (Chapter X). However while allocating the resources for maximum productivity, the most productive allocation units tend to get allocation first and therefore equity decreases. Where the objective is to achieve equity, the less productive allocation units also get their quota, resulting in reducing overall productivity. This is discussed while presenting the results of equity in Chapter X. This may not be true when the resources are not allocated optimally (see Chapter X). Therefore it was hypothesised in this study that productivity is inversely related to equity in the process of allocation.

The productivity and equity measures have been obtained for different cropping distributions using VDI by AWAM for optimised productivity and equity for two different scenarios of equity consideration (equity in benefit generation and equity in water allocation). The productivity and equity measures were also found for their intermediate values. These results indicated that productivity is inversely related to equity. This confirmed the Hypothesis 5.

11.1.6 Comments on Verification of Hypotheses

Chapters I to III indicated the need for efficient utilisation of irrigation water in the heterogeneous irrigation schemes faced with water shortages through the improved development of the procedure for optimum allocation of resources. Sections 11.1.1 to 11.1.5 discussed about the verification of hypotheses formulated in Chapter I, which could lead towards the development of a procedure for the optimum allocation of the resources. The process of verification of hypotheses with the case study data produced the irrigation water management model of land and water allocation type, AWAM. The important feature of the AWAM is that it includes deficit irrigation and productivity and equity criteria in the allocation process in accordance with Hypotheses 3 and 4. The part of Hypotheses 3 and 4 states that the deficit irrigation and productivity and equity criteria can also be included in the process of intraseasonal operation of the irrigation scheme. The importance of intraseasonal operation of the scheme is outlined in Chapter II and X. The formulation of AWAM also includes these aspects (deficit irrigation and productivity and equity criteria) in intraseasonal operation of the irrigation scheme (See Section 4.8.6).

The AWAM is not tested for these aspects with case study data. But as indicated in Chapter X (Section 10.9), obtaining the allocation of the resources at pre-season planning and modifying those allocation plans during intraseasonal operation of the irrigation scheme differ mainly in changing the time span of irrigation (from the full irrigation season to remaining irrigation periods over which modified allocation plan is required), modifying the initial conditions (availability of soil moisture in the root zone, water availability in the reservoir etc.) and modifying some constraints (such as changing the constraints which specify the area to be irrigated under different crops in some prescribed range, to the constraints which specify the area to be irrigated under these crops equal to certain value which is obtained from the allocation of the resources at preseason planning). The utility of AWAM for obtaining the allocation plans with different initial conditions and constraints is already verified in Chapter IX and X for the irrigation season constituting two crops season. Therefore the AWAM should also be able to modify the allocation plans during the intraseasonal operation of the irrigation scheme, by running it in 'Operation Mode' (Figure 4.7), which is designed for intraseasonal operation of the irrigation scheme.

11.2 OBJECTIVES

Various irrigation water management models developed during the past three decades indicated the scope for improving the allocation process for the irrigation schemes faced with water shortages. Therefore the present study was aimed at developing the procedure for optimally allocating the land and water resources to different crops at allocation unit level in such schemes. The relevant hypotheses which could lead towards the optimum allocation of the resources and in term the allocation model were formulated. The specific objectives of the study behind the formulation and for the testing the outcome of the hypotheses are listed in Chapter I. This chapter describes the achievements while attaining the objectives.

11.2.1 Development of the Model

Objectives 1, 4 and 5 are concerned with the development of the model for efficient utilisation of water in the irrigation scheme. The irrigation schemes targeted in the present study are heterogeneous and with water delivery at predetermined irrigation intervals which are the same for all crop-soil-region units. The verification of the hypotheses formulated for the efficient use of limited water in the irrigation schemes with water shortages, and integrating productivity and equity, led to the development of a procedure for optimum allocation of land and water resources to different crops at the allocation unit level in such irrigation schemes. The computer model, Area and Water Allocation Model (AWAM), was constructed for the procedure developed. This is the important output of the present research. The procedures used in AWAM are described in Chapters IV, V and VI.

The study has succeeded in developing the model to produce the steady allocation plans and modify the allocation plans during the intraseasonal operation of the irrigation scheme due to variability of weather conditions over different years. The procedure to obtain the steady allocation plan with AWAM is developed and described in Chapter X (Section 10.8). The ability of AWAM in modifying the allocation plan during intraseasonal operation of the scheme is also discussed in Chapter X (Section 10.9).

11.2.2 Applicability of the Model

The suitability of the model was tested by developing the case study for Nazare Medium Irrigation Project, Maharashtra Sate, India. The scheme lies in the semi-arid region of India and faced with the water shortages. The scheme is of heterogeneous type. The allocation plans are obtained for this irrigation scheme for varying situations which may exist in such irrigation schemes. These allocation plans are described in Chapter IX and X. The utility of the AWAM in obtaining the allocation plans for this scheme in varying situations proved the applicability of AWAM for such irrigation schemes.

11.2.3 Comparing the Procedure in the Model with the Traditional Approach

The fixed depth irrigation (FXDI) approach is used in the irrigation scheme used for the case study and many other irrigation schemes in the region. This approach has the advantage of ease in management because of delivering uniform depth of water to different crops grown on different soils and in different allocation units. The full depth irrigation (FLDI) approach is used in the development of many irrigation management models, especially of models of land allocation type (see Section 2.4.1). This approach produces maximum possible crop yield per unit area of land irrigated for the chosen irrigation interval. In the present study the variable depth irrigation (VDI) approach based on deficit irrigation is developed. By this approach, water is delivered in the optimum combination of different amounts of water (including missing a schedule) to different crops grown on different soils and in different allocation units. These three approaches were compared in Chapters IX and X for different situations. It was found that VDI generates more income from the irrigation scheme than FXDI and FLDI. However VDI may be comparable with FXDI and FLDI for some specific situations (such as in this case study, free cropping distribution with onion as the predominant crop in the allocation plan). The VDI approach produced 22% and 28% more benefits from the irrigation scheme than the FLDI and FXDI approaches, respectively when compared for a fixed cropping distribution (wherein all crops were included in the allocation plan) with the objective of maximising the productivity.

11.3 ACHIEVEMENTS AND SUGGESTIONS FOR FURTHER IMPROVEMENTS

11.3.1 Achievements

The achievement of the present study from the verification of hypotheses and fulfilment of the objectives can be summarised as follows.

- The development of the model, which produces the allocation plan at preseason planning and modifies the allocation plan during intraseasonal operation of the irrigation scheme, for the allocation of the land and water resources optimally to different crops grown on different soils and in different allocation units in heterogeneous irrigation scheme under rotational water supply and faced with water shortages. The developed model is Area and Water Allocation Model (AWAM) and considers the details of soil, plant and atmospheric processes, irrigation scheme and different restrictions in the allocation process.

- The development of the approach called variable depth irrigation which can integrate the deficit irrigation and adequate irrigation for the allocation of resources.

- The incorporation of two important performance parameters i.e. productivity and equity with deficit irrigation (through VDI) while obtaining allocation plans at pre-season planning and during intraseasonal operation of the irrigation scheme in the allocation model (AWAM)

- The development of the procedure which produces the steady allocation plans with AWAM, when weather conditions vary over the years.

11.3.2 Suggestions for Further Improvement

The procedures and model developed in the present study is aimed at efficient utilisation of water resources in the heterogeneous irrigation scheme under rotational water supply and faced with water shortages. The important aspects in the irrigation water management were included while developing the procedures and model. However as the issues in irrigation water management are more site specific, all the aspects could not be incorporated in the present study. The important suggestions for the future development are listed below.

1. The AWAM is developed with the assumption that soil and water used for irrigation is not saline and therefore the irrigation programmes generated in the second phase of AWAM does not include salinity aspect. However this aspect is important as 20 to 30 million ha land in the world is already severely affected by salinity (Hennessy, 1993) and many more can be added to this figure if the water resources are not efficiently managed. Therefore this aspect needs to be included in AWAM. The irrigation strategy

generator and SWAB and CRYB submodels in AWAM have enough flexibility to include the salinity aspect in the formulation.

2. Though over irrigation is not advisable in efficient irrigation water management, some times it is necessary to evaluate the performance of the situations where over irrigation is practised. AWAM does not simulate the crop yield under over irrigation. The CRYB submodel needs to be modified suitably for this.

3. The requirement of the computer time for obtaining the selected irrigation programmes (SOIP) with VDI is high when the irrigation interval is low (14 days and below). This can be overcome by reducing the increment between deficit ratio. But it may loose some accuracy. Therefore AWAM is formulated to run in different modes (such as running AWAM in planning mode is similar to running AWAM in generation and optimisation mode separately) to make the problem of computer time less observable. However this is not considered as the constraint in using AWAM for the development of allocation plans for the irrigation scheme, as nowadays most irrigation schemes have the good computer facility. But the computer code developed for AWAM in this study needs to be suitably modified to reduce the computer time for making AWAM useful in testing the several alternatives quickly. Similarly the AWAM is not user friendly model and needs modifications if it has to be used as the training tool.

11.4 CONCLUDING REMARKS

This research specifically addressed the issue of efficiently using the water in an irrigation scheme for increasing the productivity and achieving the desired distribution of water among the different users. The conclusions derived from this research work and its achievements are definitely in the direction of goal set by John Hennessy (1993), President, ICID before the water management community, though they do not fully answer all the issues in irrigation water management. Andras Szollosi-Nagy (1995:9), Director Division of Water Sciences, UNESCO cited J. F. Kennedy, President of USA once saying

"Anybody who can solve the problems of water will be worthy of two Nobel Prizes, one for peace and one for science"

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APPENDIX A

This appendix presents the values of following simulated parameters for adequate irrigation (IS-A) in Tables A.1 (a) and A.1 (b) and for deficit irrigation in Tables A.2 (a) and A.2 (b).

(Daily)

- effective rainfall (Rfe) in mm
- reference crop ET (ETr) in mm
- crop factor (Kc)
- maximum crop ET (ETm) in mm
- soil water depletion factor (p)
- root zone depth (Z) in mm
- actual crop ET (ETa) in mm
- potential transpiration (TM) in mm
- actual transpiration (TR) in mm
- actual soil evaporation (ESa) in mm
- deep percolation (P_D) in mm
- soil moisture content in the root zone at field capacity (θf^R) in mm
- soil moisture content in the root zone at wilting point (θw^R) in mm
- soil moisture content in the root zone at allowable level ($\theta \omega^P$) in mm
- soil moisture content in the root zone at depletion level (θp^R) in mm
- actual soil moisture content in the root zone (θ^R) in mm
- actual soil moisture content in the entire soil root zone (θ) in mm

(Irrigationwise)

- application depth at the time of irrigation (Ad) in mm
- irrigation depth at the time of irrigation (Id) in mm
- deficit ratio for irrigation (β) and
- stress index for the irrigation period (ξ)

Table A.1(a) The values of simulated parameters for irrigation schedule representing adequate irrigation (IS-A) (See Section 7.3)

t	RFe	ETr	Kc	ETm	p	Z	ETa	TM	TR	ESa	P_D
1	.00	3.37	.309	1.04	.800	150.00	1.04	.77	.77	.27	.00
2	.00	3.41	.340	1.16	.800	165.00	1.16	.89	.89	.27	.00
3	.00	3.56	.371	1.32	.800	180.00	1.32	1.05	1.05	.28	.00
4	.00	3.24	.402	1.30	.800	195.00	1.30	1.06	1.06	.25	.00
5	.00	3.14	.433	1.36	.800	210.00	1.36	1.12	1.12	.23	.00
6	.00	3.04	.463	1.41	.800	225.00	1.41	1.18	1.18	.22	.00
7	.00	3.42	.492	1.68	.800	240.00	1.68	.54	.54	1.14	42.69
8	.00	3.15	.522	1.64	.800	255.00	1.64	.93	.93	.71	.00
9	.00	3.00	.551	1.65	.800	270.00	1.65	1.11	1.11	.54	.00
10	.00	3.16	.579	1.83	.800	285.00	1.83	1.35	1.35	.48	.00
11	.00	3.12	.607	1.89	.800	300.00	1.89	1.47	1.47	.42	.00
12	.00	3.14	.635	1.99	.800	315.00	1.99	1.61	1.61	.38	.00
13	.00	2.91	.662	1.93	.800	330.00	1.93	1.60	1.60	.32	.00
14	.00	2.92	.688	2.01	.799	345.00	2.01	1.71	1.71	.30	.00
15	.00	3.17	.714	2.26	.774	360.00	2.26	1.97	1.97	.30	.00
16	.00	3.08	.740	2.28	.772	375.00	2.28	2.01	2.01	.27	.00
17	.00	3.25	.765	2.48	.752	390.00	2.48	2.22	2.22	.27	.00
18	.00	3.07	.789	2.42	.758	405.00	2.42	2.19	2.19	.23	.00
19	.00	2.86	.813	2.32	.768	420.00	2.32	1.37	1.37	.96	35.92
20	.00	2.50	.836	2.09	.791	435.00	2.09	1.55	1.55	.54	.00
21	.00	2.71	.858	2.33	.767	450.00	2.33	1.88	1.88	.45	.00
22	.00	2.95	.880	2.60	.740	465.00	2.60	2.20	2.20	.40	.00
23	.00	2.50	.902	2.25	.775	480.00	2.25	1.96	1.96	.29	.00
24	.00	2.57	.922	2.37	.763	495.00	2.37	2.11	2.11	.26	.00
25	.00	2.36	.942	2.22	.778	510.00	2.22	2.01	2.01	.21	.00
26	.00	2.60	.961	2.50	.750	525.00	2.50	2.29	2.29	.21	.00
27	.00	2.32	.980	2.27	.773	540.00	2.27	2.11	2.11	.17	.00
28	.00	2.54	.998	2.53	.747	555.00	2.53	2.37	2.37	.16	.00
29	.00	2.76	1.015	2.80	.720	570.00	2.80	2.64	2.64	.16	.00
30	.00	2.80	1.032	2.89	.711	585.00	2.89	2.74	2.74	.15	.00
31	.00	2.66	1.047	2.79	.721	600.00	2.79	2.19	2.19	.60	30.82
32	.00	2.59	1.062	2.75	.725	615.00	2.75	2.38	2.38	.37	.00
33	.00	2.54	1.077	2.73	.727	630.00	2.73	2.46	2.46	.27	.00
34	.00	2.82	1.090	3.07	.693	645.00	3.07	2.83	2.83	.24	.00
35	.00	2.37	1.103	2.61	.739	660.00	2.61	2.45	2.45	.17	.00
36	.00	2.33	1.115	2.60	.740	675.00	2.60	2.46	2.46	.14	.00
37	.00	2.66	1.126	3.00	.700	690.00	3.00	2.86	2.86	.14	.00
38	.00	2.86	1.137	3.25	.675	705.00	3.25	3.12	3.12	.13	.00
39	.00	2.49	1.146	2.85	.715	720.00	2.85	2.75	2.75	.10	.00
40	.00	2.53	1.155	2.92	.708	735.00	2.92	2.83	2.83	.09	.00
41	.00	2.66	1.163	3.09	.691	750.00	3.09	3.01	3.01	.09	.00
42	.00	2.51	1.171	2.94	.706	765.00	2.94	2.86	2.86	.07	.00
43	.00	2.46	1.177	2.90	.710	780.00	2.90	2.59	2.59	.31	25.38
44	.00	2.28	1.183	2.70	.730	795.00	2.70	2.51	2.51	.18	.00
45	.00	2.73	1.188	3.24	.676	810.00	3.24	3.08	3.08	.17	.00
46	.00	2.31	1.192	2.75	.725	825.00	2.75	2.64	2.64	.11	.00
47	.00	2.85	1.195	3.41	.659	840.00	3.41	3.29	3.29	.12	.00
48	.00	2.94	1.198	3.52	.648	855.00	3.52	3.41	3.41	.11	.00
49	.00	2.78	1.199	3.33	.667	870.00	3.33	3.24	3.24	.09	.00
50	.00	3.14	1.200	3.77	.623	885.00	3.77	3.67	3.67	.10	.00
51	.00	2.88	1.200	3.46	.654	900.00	3.46	3.38	3.38	.08	.00
52	.00	2.94	1.200	3.53	.647	900.00	3.53	3.45	3.45	.08	.00
53	.00	2.91	1.198	3.49	.651	900.00	3.49	3.41	3.41	.07	.00
54	.00	2.73	1.196	3.26	.674	900.00	3.26	3.20	3.20	.07	.00
55	.00	3.09	1.192	3.68	.632	900.00	3.68	3.34	3.34	.35	20.65

56	.00	3.07	1.188	3.65	.635	900.00	3.65	3.41	3.41	.24	.00
57	.00	2.80	1.184	3.31	.669	900.00	3.31	3.14	3.14	.17	.00
58	.00	2.70	1.178	3.18	.682	900.00	3.18	3.03	3.03	.15	.00
59	.00	2.77	1.172	3.25	.675	900.00	3.25	3.11	3.11	.14	.00
60	.00	2.53	1.165	2.95	.705	900.00	2.95	2.83	2.83	.12	.00
61	.00	2.60	1.157	3.01	.699	900.00	3.01	2.89	2.89	.12	.00
62	.00	2.61	1.148	3.00	.700	900.00	3.00	2.88	2.88	.11	.00
63	.00	2.53	1.139	2.88	.712	900.00	2.88	2.77	2.77	.11	.00
64	.00	2.68	1.128	3.02	.698	900.00	3.02	2.91	2.91	.11	.00
65	.00	2.67	1.117	2.98	.702	900.00	2.98	2.87	2.87	.11	.00
66	.00	2.74	1.106	3.03	.697	900.00	3.03	2.92	2.92	.11	.00
67	.00	2.73	1.093	2.98	.702	900.00	2.98	2.45	2.45	.53	22.06
68	.00	2.71	1.080	2.93	.707	900.00	2.93	2.56	2.56	.36	.00
69	.00	2.84	1.066	3.03	.697	900.00	3.03	2.71	2.71	.31	.00
70	.00	2.84	1.051	2.99	.701	900.00	2.99	2.71	2.71	.28	.00
71	.00	2.70	1.036	2.80	.720	900.00	2.80	2.56	2.56	.24	.00
72	.00	2.81	1.020	2.87	.713	900.00	2.87	2.63	2.63	.23	.00
73	.00	2.75	1.003	2.76	.724	900.00	2.76	2.54	2.54	.22	.00
74	.00	2.63	.986	2.59	.741	900.00	2.59	2.39	2.39	.20	.00
75	.00	2.71	.968	2.62	.738	900.00	2.62	2.43	2.43	.20	.00
76	.00	2.93	.949	2.78	.722	900.00	2.78	2.57	2.57	.21	.00
77	.00	2.79	.930	2.59	.741	900.00	2.59	2.40	2.40	.19	.00
78	.00	3.42	.910	3.11	.689	900.00	3.11	2.88	2.88	.23	.00
79	.00	3.46	.889	3.08	.692	900.00	3.08	2.01	2.01	1.07	25.95
80	.00	3.40	.868	2.95	.705	900.00	2.95	2.24	2.24	.71	.00
81	.00	3.36	.846	2.84	.716	900.00	2.84	2.28	2.28	.56	.00
82	.00	3.48	.824	2.87	.713	900.00	2.87	2.37	2.37	.50	.00
83	.00	3.35	.801	2.68	.732	900.00	2.68	2.25	2.25	.43	.00
84	.00	3.73	.778	2.90	.710	900.00	2.90	2.47	2.47	.44	.00
85	.00	3.79	.754	2.86	.714	900.00	2.86	2.45	2.45	.41	.00
86	.00	3.50	.729	2.55	.745	900.00	2.55	2.20	2.20	.35	.00
87	.00	3.36	.705	2.37	.763	900.00	2.37	2.05	2.05	.32	.00
88	.00	3.73	.679	2.53	.747	900.00	2.53	2.20	2.20	.33	.00
89	.00	4.05	.653	2.65	.735	900.00	2.65	2.31	2.31	.34	.00
90	.00	3.58	.627	2.25	.775	900.00	2.25	1.96	1.96	.29	.00
91	.00	3.84	.601	2.31	.769	900.00	2.31	.95	.95	1.36	27.47
92	.00	4.03	.574	2.31	.769	900.00	2.31	1.38	1.38	.93	.00
93	.00	3.88	.546	2.12	.788	900.00	2.12	1.42	1.42	.69	.00
94	.00	3.48	.518	1.80	.800	900.00	1.80	1.29	1.29	.52	.00
95	.00	4.40	.490	2.16	.784	900.00	2.16	1.60	1.60	.56	.00
96	.00	3.64	.462	1.68	.800	900.00	1.68	1.28	1.28	.40	.00
97	.00	3.42	.433	1.48	.800	900.00	1.48	1.15	1.15	.34	.00
98	.00	3.52	.404	1.42	.800	900.00	1.42	1.12	1.12	.31	.00
99	.00	3.49	.375	1.31	.800	900.00	1.31	1.04	1.04	.27	.00
100	.00	3.49	.346	1.21	.800	900.00	1.21	.96	.96	.24	.00
101	.00	3.38	.316	1.07	.800	900.00	1.07	.86	.86	.21	.00
102	.00	3.60	.286	1.03	.800	900.00	1.03	.83	.83	.20	.00
103	.00	3.52	.256	.90	.800	900.00	.90	.11	.11	.79	40.10
104	.00	3.74	.226	.85	.800	900.00	.85	.34	.34	.50	.00
105	.00	4.74	.196	.93	.800	900.00	.93	.49	.49	.45	.00
106	.00	5.61	.166	.93	.800	900.00	.93	.55	.55	.39	.00
107	.00	4.63	.136	.63	.800	900.00	.63	.40	.40	.23	.00
108	.00	4.34	.106	.46	.800	900.00	.46	.30	.30	.16	.00

Table A.1(b) The values of simulated parameters for irrigation schedule representing adequate irrigation (IS-A) (See Section 7.3)

t	θf^R	θw^R	$\theta \omega^P$	θp^R	θ^R	θ	Ad	Id	β	ξ
1	59.96	37.68	37.68	42.14	50.23	380.97	60.00	80.00	1.000	.000
2	66.32	41.42	41.42	46.40	55.55	379.93				
3	72.68	45.17	45.17	50.67	60.76	378.77				
4	79.04	48.91	48.91	54.94	65.80	377.45				
5	85.40	52.66	52.66	59.21	70.85	376.14				
6	91.76	56.40	56.40	63.47	75.86	374.79				
7	98.12	60.14	60.14	67.74	98.12	390.69				
8	104.49	63.89	63.89	72.01	102.80	389.01				
9	110.85	67.63	67.63	76.28	107.52	387.36				
10	117.21	71.38	71.38	80.54	112.23	385.71				
11	123.57	75.12	75.12	84.81	116.76	383.88				
12	130.18	78.87	78.87	89.13	121.47	381.99				
13	136.78	82.61	82.61	93.45	126.09	380.00	60.00	80.00	1.000	.000
14	143.39	86.36	86.36	97.82	130.77	378.07				
15	149.99	90.10	90.10	103.66	135.37	376.06				
16	156.60	93.85	93.85	108.14	139.71	373.80				
17	163.21	97.59	97.59	113.90	144.04	371.52				
18	169.81	101.34	101.34	117.92	148.16	369.03				
19	176.42	105.08	105.08	121.66	176.42	390.69				
20	183.02	108.83	108.83	124.33	180.70	388.37				
21	189.63	112.58	112.58	130.50	185.22	386.28				
22	196.47	116.52	116.52	137.28	189.73	383.95				
23	203.30	120.47	120.47	139.14	193.96	381.35				
24	210.14	124.42	124.42	144.73	198.55	379.10				
25	216.97	128.37	128.37	148.07	203.01	376.73	60.00	80.00	1.000	.000
26	223.81	132.32	132.32	155.19	207.62	374.51				
27	230.64	136.26	136.26	157.72	211.96	372.01				
28	237.48	140.21	140.21	164.87	216.52	369.73				
29	244.31	144.16	144.16	172.22	220.82	367.20				
30	251.15	148.11	148.11	177.87	224.86	364.40				
31	257.99	152.06	152.06	181.57	257.99	390.69				
32	264.73	156.03	156.03	185.94	261.94	387.90				
33	271.47	160.01	160.01	190.50	265.93	385.15				
34	278.21	163.99	163.99	199.11	269.94	382.42				
35	284.96	167.97	167.97	198.55	273.61	379.34				
36	291.70	171.95	171.95	203.06	277.74	376.73				
37	298.44	175.93	175.93	212.63	281.88	374.13	60.00	80.00	1.000	.000
38	305.18	179.91	179.91	220.64	285.63	371.13				
39	311.93	183.89	183.89	220.44	289.12	367.88				
40	318.67	187.87	187.87	226.10	293.01	365.03				
41	325.41	191.85	191.85	233.18	296.83	362.11				
42	331.94	195.69	195.69	235.73	300.26	359.01				
43	338.47	199.54	199.54	239.77	338.47	390.69				
44	344.99	203.38	203.38	241.58	342.10	387.79				
45	351.52	207.23	207.23	254.02	345.93	385.10				
46	358.05	211.07	211.07	251.54	349.21	381.85				
47	364.58	214.92	214.92	265.90	352.99	379.10				
48	371.11	218.76	218.76	272.41	356.11	375.69				
49	377.63	222.61	222.61	274.30	359.12	372.17	60.00	80.00	1.000	.000
50	384.16	226.45	226.45	285.89	362.31	368.84				
51	390.69	230.30	230.30	285.74	365.07	365.07				
52	390.69	230.30	230.30	286.86	361.61	361.61				
53	390.69	230.30	230.30	286.21	358.09	358.09				
54	390.69	230.30	230.30	282.65	354.60	354.60				
55	390.69	230.30	230.30	289.39	390.69	390.69				

56	390.69	230.30	230.30	288.82	387.01	387.01				
57	390.69	230.30	230.30	283.45	383.36	383.36				
58	390.69	230.30	230.30	281.31	380.04	380.04				
59	390.69	230.30	230.30	282.35	376.86	376.86				
60	390.69	230.30	230.30	277.55	373.62	373.62				
61	390.69	230.30	230.30	278.53	370.67	370.67	60.00	80.00	1.000	.000
62	390.69	230.30	230.30	278.35	367.66	367.66				
63	390.69	230.30	230.30	276.50	364.67	364.67				
64	390.69	230.30	230.30	278.80	361.79	361.79				
65	390.69	230.30	230.30	278.14	358.76	358.76				
66	390.69	230.30	230.30	278.88	355.78	355.78				
67	390.69	230.30	230.30	278.16	390.69	390.69				
68	390.69	230.30	230.30	277.24	387.71	387.71				
69	390.69	230.30	230.30	278.85	384.78	384.78				
70	390.69	230.30	230.30	278.19	381.75	381.75				
71	390.69	230.30	230.30	275.16	378.77	378.77				
72	390.69	230.30	230.30	276.27	375.97	375.97				
73	390.69	230.30	230.30	274.55	373.10	373.10	60.00	80.00	1.000	.000
74	390.69	230.30	230.30	271.88	370.34	370.34				
75	390.69	230.30	230.30	272.36	367.75	367.75				
76	390.69	230.30	230.30	274.90	365.13	365.13				
77	390.69	230.30	230.30	271.90	362.35	362.35				
78	390.69	230.30	230.30	280.20	359.75	359.75				
79	390.69	230.30	230.30	279.65	390.69	390.69				
80	390.69	230.30	230.30	277.64	387.61	387.61				
81	390.69	230.30	230.30	275.91	384.66	384.66				
82	390.69	230.30	230.30	276.29	381.82	381.82				
83	390.69	230.30	230.30	273.35	378.95	378.95				
84	390.69	230.30	230.30	276.83	376.27	376.27				
85	390.69	230.30	230.30	276.12	373.36	373.36	60.00	80.00	1.000	.000
86	390.69	230.30	230.30	271.25	370.51	370.51				
87	390.69	230.30	230.30	268.27	367.95	367.95				
88	390.69	230.30	230.30	270.93	365.59	365.59				
89	390.69	230.30	230.30	272.74	363.05	363.05				
90	390.69	230.30	230.30	266.31	360.41	360.41				
91	390.69	230.30	230.30	267.28	390.69	390.69				
92	390.69	230.30	230.30	267.37	388.38	388.38				
93	390.69	230.30	230.30	264.28	386.07	386.07				
94	390.69	230.30	230.30	262.37	383.95	383.95				
95	390.69	230.30	230.30	264.90	382.15	382.15				
96	390.69	230.30	230.30	262.37	379.99	379.99				
97	390.69	230.30	230.30	262.37	378.31	378.31	60.00	80.00	1.000	.000
98	390.69	230.30	230.30	262.37	376.83	376.83				
99	390.69	230.30	230.30	262.37	375.41	375.41				
100	390.69	230.30	230.30	262.37	374.10	374.10				
101	390.69	230.30	230.30	262.37	372.89	372.89				
102	390.69	230.30	230.30	262.37	371.82	371.82				
103	390.69	230.30	230.30	262.37	390.69	390.69				
104	390.69	230.30	230.30	262.37	389.79	389.79				
105	390.69	230.30	230.30	262.37	388.94	388.94				
106	390.69	230.30	230.30	262.37	388.01	388.01				
107	390.69	230.30	230.30	262.37	387.08	387.08				
108	390.69	230.30	230.30	262.37	386.45	386.45				
Maximum crop yield = 3500 Kg/ha					Actual crop yield = 3500 kg/ha					

Table A.2(a) The values of simulated parameters for irrigation schedule representing deficit irrigation (IS-D) (See Section 7.3)

t	RFe	ETr	Kc	ETm	p	Z	ETa	TM	TR	ESa	P_D
1	.00	3.37	.309	1.04	.800	150.00	1.04	.77	.77	.27	.00
2	.00	3.41	.340	1.16	.800	165.00	1.16	.89	.89	.27	.00
3	.00	3.56	.371	1.32	.800	180.00	1.32	1.05	1.05	.28	.00
4	.00	3.24	.402	1.30	.800	195.00	1.30	1.06	1.06	.25	.00
5	.00	3.14	.433	1.36	.800	210.00	1.36	1.12	1.12	.23	.00
6	.00	3.04	.463	1.41	.800	225.00	1.41	1.18	1.18	.22	.00
7	.00	3.42	.492	1.68	.800	240.00	1.68	1.44	1.44	.24	.00
8	.00	3.15	.522	1.64	.800	255.00	1.64	1.42	1.42	.22	.00
9	.00	3.00	.551	1.65	.800	270.00	1.65	1.45	1.45	.20	.00
10	.00	3.16	.579	1.83	.800	285.00	.91	1.62	.70	.21	.00
11	.00	3.12	.607	1.89	.800	300.00	.48	1.69	.28	.20	.00
12	.00	3.14	.635	1.99	.800	315.00	.53	1.80	.33	.20	.00
13	.00	2.91	.662	1.93	.800	330.00	.53	1.75	.35	.18	.00
14	.00	2.92	.688	2.01	.799	345.00	.57	1.84	.40	.17	.00
15	.00	3.17	.714	2.26	.774	360.00	.66	2.08	.48	.18	.00
16	.00	3.08	.740	2.28	.772	375.00	.68	2.11	.52	.17	.00
17	.00	3.25	.765	2.48	.752	390.00	.76	2.31	.59	.17	.00
18	.00	3.07	.789	2.42	.758	405.00	.76	2.27	.61	.16	.00
19	.00	2.86	.813	2.32	.768	420.00	2.32	1.37	1.37	.96	31.81
20	.00	2.50	.836	2.09	.791	435.00	2.09	1.55	1.55	.54	.00
21	.00	2.71	.858	2.33	.767	450.00	2.33	1.88	1.88	.45	.00
22	.00	2.95	.880	2.60	.740	465.00	2.60	2.20	2.20	.40	.00
23	.00	2.50	.902	2.25	.775	480.00	2.25	1.96	1.96	.29	.00
24	.00	2.57	.922	2.37	.763	495.00	2.37	2.11	2.11	.26	.00
25	.00	2.36	.942	2.22	.778	510.00	2.22	2.01	2.01	.21	.00
26	.00	2.60	.961	2.50	.750	525.00	2.50	2.29	2.29	.21	.00
27	.00	2.32	.980	2.27	.773	540.00	2.27	2.11	2.11	.17	.00
28	.00	2.54	.998	2.53	.747	555.00	2.53	2.37	2.37	.16	.00
29	.00	2.76	1.015	2.80	.720	570.00	2.80	2.64	2.64	.16	.00
30	.00	2.80	1.032	2.89	.711	585.00	2.89	2.74	2.74	.15	.00
31	.00	2.66	1.047	2.79	.721	600.00	2.79	2.66	2.66	.13	.00
32	.00	2.59	1.062	2.75	.725	615.00	2.38	2.64	2.26	.11	.00
33	.00	2.54	1.077	2.73	.727	630.00	1.41	2.63	1.31	.10	.00
34	.00	2.82	1.090	3.07	.693	645.00	1.62	2.97	1.51	.10	.00
35	.00	2.37	1.103	2.61	.739	660.00	1.40	2.53	1.32	.08	.00
36	.00	2.33	1.115	2.60	.740	675.00	1.41	2.53	1.34	.07	.00
37	.00	2.66	1.126	3.00	.700	690.00	1.66	2.92	1.58	.08	.00
38	.00	2.86	1.137	3.25	.675	705.00	1.82	3.18	1.75	.08	.00
39	.00	2.49	1.146	2.85	.715	720.00	1.63	2.79	1.56	.06	.00
40	.00	2.53	1.155	2.92	.708	735.00	1.69	2.87	1.63	.06	.00
41	.00	2.66	1.163	3.09	.691	750.00	1.81	3.04	1.76	.06	.00
42	.00	2.51	1.171	2.94	.706	765.00	1.74	2.89	1.69	.05	.00
43	.00	2.46	1.177	2.90	.710	780.00	2.90	2.59	2.59	.31	9.46
44	.00	2.28	1.183	2.70	.730	795.00	2.70	2.51	2.51	.18	.00
45	.00	2.73	1.188	3.24	.676	810.00	3.24	3.08	3.08	.17	.00
46	.00	2.31	1.192	2.75	.725	825.00	2.75	2.64	2.64	.11	.00
47	.00	2.85	1.195	3.41	.659	840.00	3.41	3.29	3.29	.12	.00
48	.00	2.94	1.198	3.52	.648	855.00	3.52	3.41	3.41	.11	.00
49	.00	2.78	1.199	3.33	.667	870.00	3.33	3.24	3.24	.09	.00
50	.00	3.14	1.200	3.77	.623	885.00	3.77	3.67	3.67	.10	.00
51	.00	2.88	1.200	3.46	.654	900.00	3.46	3.38	3.38	.08	.00
52	.00	2.94	1.200	3.53	.647	900.00	3.53	3.45	3.45	.08	.00
53	.00	2.91	1.198	3.49	.651	900.00	3.49	3.41	3.41	.07	.00
54	.00	2.73	1.196	3.26	.674	900.00	3.26	3.20	3.20	.07	.00
55	.00	3.09	1.192	3.68	.632	900.00	3.68	3.61	3.61	.07	.00

56	.00	3.07	1.188	3.65	.635	900.00	3.65	3.58	3.58	.07	.00
57	.00	2.80	1.184	3.31	.669	900.00	3.31	3.25	3.25	.07	.00
58	.00	2.70	1.178	3.18	.682	900.00	3.18	3.12	3.12	.06	.00
59	.00	2.77	1.172	3.25	.675	900.00	3.25	3.18	3.18	.07	.00
60	.00	2.53	1.165	2.95	.705	900.00	2.46	2.89	2.40	.06	.00
61	.00	2.60	1.157	3.01	.699	900.00	1.97	2.94	1.91	.06	.00
62	.00	2.61	1.148	3.00	.700	900.00	1.97	2.93	1.90	.07	.00
63	.00	2.53	1.139	2.88	.712	900.00	1.89	2.82	1.83	.06	.00
64	.00	2.68	1.128	3.02	.698	900.00	1.98	2.95	1.91	.07	.00
65	.00	2.67	1.117	2.98	.702	900.00	1.96	2.91	1.89	.07	.00
66	.00	2.74	1.106	3.03	.697	900.00	1.55	2.95	1.47	.08	.00
67	.00	2.73	1.093	2.98	.702	900.00	2.98	2.45	2.45	.53	.00
68	.00	2.71	1.080	2.93	.707	900.00	2.93	2.56	2.56	.36	.00
69	.00	2.84	1.066	3.03	.697	900.00	3.03	2.71	2.71	.31	.00
70	.00	2.84	1.051	2.99	.701	900.00	2.99	2.71	2.71	.28	.00
71	.00	2.70	1.036	2.80	.720	900.00	2.80	2.56	2.56	.24	.00
72	.00	2.81	1.020	2.87	.713	900.00	2.87	2.63	2.63	.23	.00
73	.00	2.75	1.003	2.76	.724	900.00	2.76	2.54	2.54	.22	.00
74	.00	2.63	.986	2.59	.741	900.00	2.59	2.39	2.39	.20	.00
75	.00	2.71	.968	2.62	.738	900.00	2.62	2.43	2.43	.20	.00
76	.00	2.93	.949	2.78	.722	900.00	2.78	2.57	2.57	.21	.00
77	.00	2.79	.930	2.59	.741	900.00	2.59	2.40	2.40	.19	.00
78	.00	3.42	.910	3.11	.689	900.00	3.11	2.88	2.88	.23	.00
79	.00	3.46	.889	3.08	.692	900.00	3.08	2.85	2.85	.23	.00
80	.00	3.40	.868	2.95	.705	900.00	2.95	2.73	2.73	.22	.00
81	.00	3.36	.846	2.84	.716	900.00	2.84	2.63	2.63	.21	.00
82	.00	3.48	.824	2.87	.713	900.00	2.87	2.65	2.65	.22	.00
83	.00	3.35	.801	2.68	.732	900.00	2.68	2.48	2.48	.21	.00
84	.00	3.73	.778	2.90	.710	900.00	2.90	2.68	2.68	.23	.00
85	.00	3.79	.754	2.86	.714	900.00	2.86	2.63	2.63	.22	.00
86	.00	3.50	.729	2.55	.745	900.00	1.82	2.35	1.62	.20	.00
87	.00	3.36	.705	2.37	.763	900.00	1.60	2.18	1.41	.19	.00
88	.00	3.73	.679	2.53	.747	900.00	1.71	2.33	1.51	.21	.00
89	.00	4.05	.653	2.65	.735	900.00	1.79	2.43	1.57	.22	.00
90	.00	3.58	.627	2.25	.775	900.00	1.52	2.06	1.33	.19	.00
91	.00	3.84	.601	2.31	.769	900.00	2.31	.95	.95	1.36	.00
92	.00	4.03	.574	2.31	.769	900.00	2.31	1.38	1.38	.93	.00
93	.00	3.88	.546	2.12	.788	900.00	2.12	1.42	1.42	.69	.00
94	.00	3.48	.518	1.80	.800	900.00	1.80	1.29	1.29	.52	.00
95	.00	4.40	.490	2.16	.784	900.00	2.16	1.60	1.60	.56	.00
96	.00	3.64	.462	1.68	.800	900.00	1.68	1.28	1.28	.40	.00
97	.00	3.42	.433	1.48	.800	900.00	1.48	1.15	1.15	.34	.00
98	.00	3.52	.404	1.42	.800	900.00	1.42	1.12	1.12	.31	.00
99	.00	3.49	.375	1.31	.800	900.00	1.31	1.04	1.04	.27	.00
100	.00	3.49	.346	1.21	.800	900.00	1.21	.96	.96	.24	.00
101	.00	3.38	.316	1.07	.800	900.00	1.07	.86	.86	.21	.00
102	.00	3.60	.286	1.03	.800	900.00	1.03	.83	.83	.20	.00
103	.00	3.52	.256	.90	.800	900.00	.90	.73	.73	.17	.00
104	.00	3.74	.226	.85	.800	900.00	.85	.69	.69	.16	.00
105	.00	4.74	.196	.93	.800	900.00	.93	.76	.76	.17	.00
106	.00	5.61	.166	.93	.800	900.00	.93	.76	.76	.17	.00
107	.00	4.63	.136	.63	.800	900.00	.63	.52	.52	.11	.00
108	.00	4.34	.106	.46	.800	900.00	.46	.38	.38	.08	.00

Table A.2(b) The values of simulated parameters for irrigation schedule representing deficit irrigation (IS-D) (See Section 7.3)

t	θf^R	θw^R	$\theta \omega^P$	θp^R	θ^R	θ	Ad	Id	β	ξ
1	59.96	37.68	37.68	42.14	50.23	380.97	60.00	80.00	1.000	.000
2	66.32	41.42	41.42	46.40	55.55	379.93				
3	72.68	45.17	45.17	50.67	60.76	378.77				
4	79.04	48.91	48.91	54.94	65.80	377.45				
5	85.40	52.66	52.66	59.21	70.85	376.14				
6	91.76	56.40	56.40	63.47	75.86	374.79				
7	98.12	60.14	60.14	67.74	80.81	373.38				
8	104.49	63.89	63.89	72.01	85.49	371.69				
9	110.85	67.63	67.63	76.28	90.21	370.05				
10	117.21	71.38	71.38	80.54	94.92	368.40				
11	123.57	75.12	75.12	84.81	100.37	367.49				
12	130.18	78.87	78.87	89.13	106.49	367.00				
13	136.78	82.61	82.61	93.45	112.57	366.47				
14	143.39	86.36	86.36	97.82	118.64	365.94				
15	149.99	90.10	90.10	103.66	124.68	365.37				
16	156.60	93.85	93.85	108.14	130.62	364.71				
17	163.21	97.59	97.59	113.90	136.54	364.03				
18	169.81	101.34	101.34	117.92	142.38	363.26				
19	176.42	105.08	105.08	121.66	176.42	390.69				
20	183.02	108.83	108.83	124.33	180.70	388.37				
21	189.63	112.58	112.58	130.50	185.22	386.28				
22	196.47	116.52	116.52	137.28	189.73	383.95				
23	203.30	120.47	120.47	139.14	193.96	381.35				
24	210.14	124.42	124.42	144.73	198.55	379.10				
25	216.97	128.37	128.37	148.07	203.01	376.73	60.00	80.00	1.000	.000
26	223.81	132.32	132.32	155.19	207.62	374.51				
27	230.64	136.26	136.26	157.72	211.96	372.01				
28	237.48	140.21	140.21	164.87	216.52	369.73				
29	244.31	144.16	144.16	172.22	220.82	367.20				
30	251.15	148.11	148.11	177.87	224.86	364.40				
31	257.99	152.06	152.06	181.57	228.80	361.51				
32	264.73	156.03	156.03	185.94	232.76	358.72				
33	271.47	160.01	160.01	190.50	237.12	356.34				
34	278.21	163.99	163.99	199.11	242.45	354.93				
35	284.96	167.97	167.97	198.55	247.58	353.32				
36	291.70	171.95	171.95	203.06	252.92	351.92				
37	298.44	175.93	175.93	212.63	258.25	350.50				
38	305.18	179.91	179.91	220.64	263.34	348.85				
39	311.93	183.89	183.89	220.44	268.26	347.02				
40	318.67	187.87	187.87	226.10	273.37	345.40				
41	325.41	191.85	191.85	233.18	278.43	343.71				
42	331.94	195.69	195.69	235.73	283.14	341.90				
43	338.47	199.54	199.54	239.77	338.47	390.69				
44	344.99	203.38	203.38	241.58	342.10	387.79				
45	351.52	207.23	207.23	254.02	345.93	385.10				
46	358.05	211.07	211.07	251.54	349.21	381.85				
47	364.58	214.92	214.92	265.90	352.99	379.10				
48	371.11	218.76	218.76	272.41	356.11	375.69				
49	377.63	222.61	222.61	274.30	359.12	372.17	60.00	80.00	1.000	.000
50	384.16	226.45	226.45	285.89	362.31	368.84				
51	390.69	230.30	230.30	285.74	365.07	365.07				
52	390.69	230.30	230.30	286.86	361.61	361.61				
53	390.69	230.30	230.30	286.21	358.09	358.09				
54	390.69	230.30	230.30	282.65	354.60	354.60				
55	390.69	230.30	230.30	289.39	351.34	351.34				

56	390.69	230.30	230.30	288.82	347.65	347.65				
57	390.69	230.30	230.30	283.45	344.00	344.00				
58	390.69	230.30	230.30	281.31	340.69	340.69				
59	390.69	230.30	230.30	282.35	337.51	337.51				
60	390.69	230.30	230.30	277.55	334.26	334.26				
61	390.69	230.30	230.30	278.53	331.80	331.80				
62	390.69	230.30	230.30	278.35	329.83	329.83				
63	390.69	230.30	230.30	276.50	327.86	327.86				
64	390.69	230.30	230.30	278.80	325.97	325.97				
65	390.69	230.30	230.30	278.14	323.99	323.99				
66	390.69	230.30	230.30	278.88	322.03	322.03				
67	390.69	230.30	230.30	278.16	380.48	380.48				
68	390.69	230.30	230.30	277.24	377.50	377.50				
69	390.69	230.30	230.30	278.85	374.57	374.57				
70	390.69	230.30	230.30	278.19	371.54	371.54				
71	390.69	230.30	230.30	275.16	368.56	368.56				
72	390.69	230.30	230.30	276.27	365.76	365.76				
73	390.69	230.30	230.30	274.55	362.90	362.90	60.00	80.00	1.000	.145
74	390.69	230.30	230.30	271.88	360.14	360.14				
75	390.69	230.30	230.30	272.36	357.54	357.54				
76	390.69	230.30	230.30	274.90	354.92	354.92				
77	390.69	230.30	230.30	271.90	352.14	352.14				
78	390.69	230.30	230.30	280.20	349.55	349.55				
79	390.69	230.30	230.30	279.65	346.43	346.43				
80	390.69	230.30	230.30	277.64	343.36	343.36				
81	390.69	230.30	230.30	275.91	340.41	340.41				
82	390.69	230.30	230.30	276.29	337.56	337.56				
83	390.69	230.30	230.30	273.35	334.69	334.69				
84	390.69	230.30	230.30	276.83	332.01	332.01				
85	390.69	230.30	230.30	276.12	329.11	329.11				
86	390.69	230.30	230.30	271.25	326.25	326.25				
87	390.69	230.30	230.30	268.27	324.43	324.43				
88	390.69	230.30	230.30	270.93	322.83	322.83				
89	390.69	230.30	230.30	272.74	321.11	321.11				
90	390.69	230.30	230.30	266.31	319.32	319.32				
91	390.69	230.30	230.30	267.28	377.80	377.80				
92	390.69	230.30	230.30	267.37	375.49	375.49				
93	390.69	230.30	230.30	264.28	373.18	373.18				
94	390.69	230.30	230.30	262.37	371.06	371.06				
95	390.69	230.30	230.30	264.90	369.26	369.26				
96	390.69	230.30	230.30	262.37	367.10	367.10				
97	390.69	230.30	230.30	262.37	365.42	365.42	60.00	80.00	1.000	.177
98	390.69	230.30	230.30	262.37	363.94	363.94				
99	390.69	230.30	230.30	262.37	362.51	362.51				
100	390.69	230.30	230.30	262.37	361.20	361.20				
101	390.69	230.30	230.30	262.37	360.00	360.00				
102	390.69	230.30	230.30	262.37	358.93	358.93				
103	390.69	230.30	230.30	262.37	357.90	357.90				
104	390.69	230.30	230.30	262.37	357.00	357.00				
105	390.69	230.30	230.30	262.37	356.15	356.15				
106	390.69	230.30	230.30	262.37	355.22	355.22				
107	390.69	230.30	230.30	262.37	354.29	354.29				
108	390.69	230.30	230.30	262.37	353.66	353.66				
Maximum crop yield = 3500 Kg/ha					Actual crop yield = 2758 Kg/ha					

APPENDIX B

This appendix presents the daily values of the climatological parameters used for the present study. The values are for the year 1991-92 and the day-1 corresponds to 15th Oct. 1991.

Table B.1 Daily values of climatological parameters for the year 1991-92, used for the present study.

Day	temperature (^{o}C)		relative humidity (%)		wind velocity (Km/hr)	rainfall (mm)	sunshine hours	pan evapo. (mm)
	max	min	max	min				
1	33.10	16.90	73.00	30.00	2.10	.00	5.40	9.50
2	33.00	21.00	71.00	36.00	2.00	.00	6.00	5.60
3	32.80	18.00	73.00	39.00	1.90	.00	3.50	9.40
4	33.00	17.20	72.00	30.00	2.70	.00	4.70	9.60
5	33.10	18.20	64.00	27.00	2.90	.00	5.50	9.40
6	33.20	18.80	56.00	30.00	3.10	.00	2.20	9.50
7	33.20	17.60	66.00	32.00	2.10	.00	3.50	8.50
8	33.00	17.00	78.00	26.00	3.20	.00	6.00	6.90
9	32.50	15.70	74.00	26.00	1.90	.00	4.50	9.60
10	32.20	14.70	64.00	26.00	3.00	.00	5.40	9.30
11	31.60	18.70	66.00	22.00	2.50	.00	5.40	9.60
12	31.30	12.40	68.00	23.00	2.90	.00	4.60	9.50
13	31.40	18.00	69.00	25.00	2.20	.00	4.70	9.80
14	31.90	11.90	71.00	22.00	3.00	.00	5.00	9.80
15	31.50	10.20	58.00	18.00	4.50	.00	6.50	8.50
16	31.40	11.80	68.00	17.00	4.40	.00	6.80	9.10
17	31.90	10.00	74.00	14.00	4.00	.00	5.80	9.40
18	31.50	9.50	75.00	21.00	4.40	.00	9.30	5.60
19	30.40	12.10	65.00	29.00	3.20	.00	9.10	5.80
20	30.00	12.00	63.00	29.00	1.80	.00	9.20	4.60
21	30.50	13.10	69.00	29.00	2.10	.00	9.20	5.20
22	30.60	12.50	67.00	26.00	2.30	.00	9.30	5.50
23	31.20	12.50	68.00	24.00	2.00	.00	9.30	4.60
24	31.50	12.50	67.00	23.00	3.50	.00	9.40	4.60
25	31.60	12.60	71.00	26.00	2.50	.00	9.30	4.50
26	31.70	16.30	83.00	33.00	1.60	.00	6.00	4.30
27	31.30	15.40	80.00	31.00	1.40	.00	8.00	5.40
28	31.80	19.80	78.00	34.00	1.30	.00	9.20	3.00
29	30.50	14.90	80.00	41.00	1.90	.00	6.90	4.40
30	30.20	15.70	83.00	42.00	2.20	.00	8.20	4.00
31	31.00	16.00	74.00	33.00	2.50	.00	7.10	4.70
32	30.20	14.70	72.00	32.00	2.40	.00	8.70	4.20
33	29.00	14.00	72.00	48.00	5.70	.00	4.80	5.00
34	28.00	19.00	81.00	71.00	9.00	.00	.20	5.20
35	26.00	19.40	95.00	75.00	7.60	.20	.10	3.70
36	25.00	20.40	93.00	56.00	3.80	.00	3.90	2.40
37	28.70	18.00	84.00	50.00	1.80	.00	8.20	2.00
38	29.60	18.70	87.00	49.00	2.00	.00	7.30	3.50
39	29.60	17.10	82.00	45.00	2.30	.00	6.50	3.60
40	30.50	19.50	87.00	49.00	3.20	.00	7.00	4.10
41	29.60	12.70	91.00	51.00	3.70	.00	9.30	5.60
42	27.20	8.80	79.00	29.00	3.70	.00	9.50	5.40
43	28.60	12.00	73.00	40.00	3.10	.00	9.10	4.00
44	29.80	13.20	73.00	32.00	2.00	.00	8.00	4.40
45	30.90	13.20	78.00	31.00	2.20	.00	9.00	4.10
46	31.50	15.60	76.00	36.00	2.30	.00	9.00	3.90
47	30.50	13.30	69.00	26.00	1.60	.00	9.20	4.00
48	29.70	10.50	77.00	28.00	2.70	.00	9.00	4.70

49	29.00	11.00	80.00	35.00	1.80	.00	8.80	4.00
50	30.00	12.60	81.00	38.00	1.90	.00	7.90	4.40
51	30.00	14.50	80.00	38.00	2.00	.00	8.50	3.80
52	29.10	11.00	87.00	27.00	2.90	.00	9.20	3.40
53	29.00	8.00	57.00	26.00	2.70	.00	9.10	4.50
54	28.70	8.50	67.00	25.00	2.10	.00	9.10	4.00
55	29.50	9.50	74.00	23.00	1.80	.00	8.90	4.40
56	28.60	4.80	77.00	25.00	2.10	.00	9.20	4.00
57	28.20	9.20	79.00	30.00	1.60	.00	8.90	3.40
58	27.90	8.40	72.00	32.00	2.20	.00	8.90	2.80
59	26.40	9.20	70.00	33.00	3.10	.00	8.90	4.40
60	26.50	10.70	70.00	34.00	3.90	.00	9.20	3.90
61	26.30	8.70	76.00	34.00	3.50	.00	9.20	4.00
62	26.00	6.70	87.00	41.00	4.00	.00	5.60	4.00
63	25.40	8.20	83.00	41.00	2.90	.00	7.20	3.50
64	26.40	7.20	85.00	36.00	3.00	.00	8.90	3.70
65	27.20	8.20	81.00	39.00	2.30	.00	8.80	3.00
66	27.50	9.00	77.00	38.00	2.40	.00	8.70	3.70
67	29.20	11.50	70.00	39.00	2.10	.00	8.40	3.80
68	30.90	14.50	80.00	42.00	2.50	.00	8.90	4.10
69	30.80	11.00	79.00	33.00	2.60	.00	9.20	4.20
70	28.70	10.40	79.00	34.00	1.80	.00	9.10	4.40
71	29.20	8.90	70.00	41.00	1.60	.00	9.00	4.00
72	39.00	12.60	87.00	49.00	1.40	.00	5.50	3.50
73	25.70	7.00	89.00	43.00	4.10	.00	8.60	3.60
74	25.30	7.00	83.00	31.00	2.10	.00	9.00	3.00
75	25.50	5.00	76.00	39.00	1.90	.00	8.70	3.40
76	27.00	7.00	76.00	41.00	2.80	.00	8.70	3.60
77	25.50	8.70	77.00	36.00	3.00	.00	9.10	4.10
78	26.70	7.10	79.00	29.00	3.50	.00	9.20	4.00
79	23.50	4.40	86.00	30.00	2.40	.00	9.20	4.00
80	22.60	4.50	75.00	33.00	3.30	.00	9.00	3.90
81	25.00	5.50	74.00	26.00	2.00	.00	9.00	4.00
82	25.50	5.00	81.00	27.00	2.40	.00	9.10	3.50
83	25.80	5.30	71.00	20.00	2.50	.00	9.10	3.20
84	27.10	5.60	69.00	16.00	2.60	.00	9.40	3.00
85	27.80	3.80	65.00	18.00	2.00	.00	9.60	3.80
86	28.40	6.50	67.00	19.00	2.30	.00	9.40	4.70
87	29.50	7.40	76.00	16.00	1.80	.00	9.20	5.00
88	30.00	8.50	68.00	39.00	4.10	.00	9.30	4.40
89	30.20	9.70	79.00	30.00	4.60	.00	9.20	4.80
90	27.90	8.10	71.00	34.00	1.50	.00	9.30	4.50
91	27.60	9.40	75.00	31.00	2.40	.00	9.30	4.30
92	30.20	11.40	72.00	36.00	2.00	.00	9.20	4.50
93	30.20	11.20	81.00	34.00	3.10	.00	8.10	4.40
94	30.00	10.50	78.00	36.00	2.10	.00	8.20	4.00
95	29.50	9.20	83.00	28.00	1.80	.00	9.10	4.00
96	30.10	11.20	82.00	28.00	1.70	.00	9.10	5.00
97	31.10	11.30	80.00	29.00	3.30	.00	9.40	5.20
98	31.60	11.50	72.00	31.00	2.70	.00	9.40	5.50
99	30.50	10.00	79.00	35.00	1.60	.00	9.70	5.70
100	30.30	10.20	82.00	35.00	1.70	.00	9.30	5.20
101	29.70	9.90	75.00	33.00	2.00	.00	9.50	5.00
102	30.50	9.70	77.00	34.00	1.60	.00	9.30	4.80
103	30.50	10.90	78.00	39.00	1.90	.00	9.50	4.80
104	32.00	15.70	72.00	36.00	5.60	.00	9.20	6.50
105	31.90	12.50	70.00	31.00	2.80	.00	9.40	6.60
106	31.20	12.30	62.00	36.00	4.70	.00	9.40	6.30
107	30.50	11.70	56.00	38.00	5.00	.00	9.70	6.00
108	30.50	11.90	70.00	35.00	6.90	.00	9.60	7.70
109	30.00	10.40	85.00	29.00	5.50	.00	9.40	6.00
110	28.50	11.30	80.00	44.00	2.20	.00	9.60	3.80
111	30.50	9.50	68.00	34.00	3.40	.00	9.40	4.20
112	28.60	10.50	69.00	41.00	1.90	.00	9.30	5.40

113	29.60	12.20	80.00	43.00	2.90	.00	9.60	4.90
114	29.20	12.10	78.00	40.00	2.70	.00	9.60	4.90
115	29.90	11.50	77.00	33.00	2.20	.00	9.60	5.00
116	32.00	12.90	79.00	34.00	1.70	.00	9.70	4.80
117	32.10	10.60	72.00	26.00	3.70	.00	9.60	5.70
118	30.50	6.50	74.00	35.00	4.40	.00	9.80	4.60
119	28.10	7.60	76.00	35.00	2.50	.00	9.80	4.40
120	26.80	7.60	73.00	31.00	3.00	.00	9.90	6.00
121	27.00	9.10	77.00	15.00	2.50	.00	9.70	5.50
122	32.20	9.00	72.00	29.00	1.80	.00	9.60	5.00
123	32.00	7.00	85.00	28.00	1.60	.00	9.80	4.80
124	32.00	7.40	82.00	15.00	2.90	.00	9.80	5.00
125	30.00	5.00	68.00	12.00	2.40	.00	9.70	4.70
126	32.00	9.40	73.00	29.00	3.50	.00	9.60	5.60
127	28.00	7.80	80.00	26.00	3.60	.00	9.70	6.00
128	29.00	7.00	77.00	26.00	1.90	.00	9.40	4.60
129	30.00	9.00	72.00	35.00	3.10	.00	9.20	5.00
130	28.10	10.20	72.00	29.00	4.00	.00	8.40	5.20
131	27.80	10.20	69.00	30.00	2.70	.00	8.90	5.20
132	29.50	9.00	66.00	30.00	2.60	.00	9.20	4.70
133	28.90	8.50	83.00	18.00	3.10	.00	9.20	5.00
134	28.20	7.40	74.00	22.00	3.80	.00	9.30	4.00
135	30.00	7.50	69.00	21.00	2.90	.00	9.10	5.10
136	30.80	8.10	65.00	18.00	3.00	.00	9.50	4.80
137	30.50	9.10	70.00	19.00	2.50	.00	9.70	5.00
138	32.50	11.60	72.00	19.00	2.20	.00	9.90	6.50
139	33.80	7.50	79.00	18.00	2.10	.00	9.40	7.00
140	33.90	10.30	71.00	16.00	1.80	.00	9.40	6.00
141	34.00	11.60	69.00	18.00	2.40	.00	9.70	7.40
142	34.00	11.60	62.00	19.00	1.80	.00	9.80	6.80
143	35.40	12.00	64.00	21.00	2.10	.00	9.90	7.30
144	33.60	10.50	65.00	21.00	3.20	.00	8.80	7.40
145	33.00	11.50	64.00	17.00	2.60	.00	9.80	7.80
146	35.70	12.20	62.00	18.00	2.80	.00	9.60	7.90
147	34.60	12.50	58.00	20.00	2.40	.00	9.80	8.10
148	34.90	11.00	57.00	19.00	3.10	.00	9.80	7.10
149	33.50	11.80	60.00	23.00	3.10	.00	9.10	7.00
150	34.20	13.60	64.00	25.00	2.70	.00	9.80	7.20
151	34.60	14.00	62.00	21.00	2.70	.00	9.90	8.20
152	35.00	14.00	66.00	26.00	2.70	.00	9.40	7.50
153	36.00	15.10	65.00	19.00	2.90	.00	9.60	8.30
154	36.80	14.50	55.00	15.00	2.60	.00	9.10	8.50
155	35.80	11.70	56.00	16.00	2.80	.00	9.70	8.00
156	35.20	12.50	64.00	13.00	2.20	.00	9.70	7.60
157	36.80	12.00	52.00	14.00	2.60	.00	9.80	8.70
158	36.60	14.20	55.00	14.00	3.50	.00	10.10	9.00
159	38.10	14.00	56.00	15.00	2.80	.00	10.00	8.50
160	37.50	16.50	56.00	15.00	2.70	.00	9.50	8.90
161	37.80	17.20	59.00	21.00	2.60	.00	9.50	8.50
162	37.40	17.30	57.00	21.00	2.90	.00	9.80	8.10
163	38.00	16.60	55.00	19.00	2.00	.00	9.90	8.50
164	37.20	16.50	59.00	20.00	3.70	.00	9.80	9.50
165	37.60	17.20	46.00	21.00	3.20	.00	9.80	8.50
166	38.00	18.60	51.00	22.00	4.20	.00	8.30	9.00
167	37.70	18.00	52.00	25.00	3.90	.00	7.70	8.00
168	36.60	16.70	64.00	27.00	3.90	.00	9.40	8.00
169	34.50	15.30	67.00	25.00	3.00	.00	9.50	8.70
170	35.20	14.70	58.00	26.00	2.50	.00	9.60	8.50
171	35.80	15.00	54.00	24.00	2.90	.00	9.30	8.50
172	36.60	16.10	60.00	22.00	2.90	.00	10.10	8.40
173	37.20	15.30	55.00	23.00	4.20	.00	10.20	8.50
174	36.50	15.00	57.00	23.00	5.10	.00	10.00	7.90
175	36.00	14.50	60.00	20.00	4.90	.00	10.30	10.30
176	36.50	16.60	56.00	22.00	5.40	.00	10.20	10.10

177	37.00	17.60	54.00	21.00	5.10	.00	10.40	9.00
178	36.60	16.50	44.00	22.00	4.40	.00	10.60	9.50
179	37.80	19.40	66.00	25.00	4.00	.00	8.80	9.80
180	36.90	21.40	65.00	22.00	4.80	.00	8.60	8.50
181	37.00	17.40	73.00	22.00	4.20	.00	6.90	8.50
182	37.30	17.60	51.00	19.00	2.60	.00	10.00	9.60
183	38.60	20.00	39.00	19.00	3.80	.00	9.00	9.60
184	38.70	18.80	62.00	19.00	3.80	.00	8.90	11.00
185	39.00	18.10	43.00	21.00	3.70	.00	8.40	11.00
186	38.50	18.00	39.00	22.00	3.50	.00	9.80	10.30
187	38.80	19.00	45.00	20.00	4.10	.00	9.60	11.00
188	39.00	16.90	47.00	27.00	5.20	.00	9.90	11.40
189	37.90	17.80	51.00	17.00	3.60	.00	9.90	11.50
190	38.90	21.20	44.00	19.00	3.80	.00	10.00	10.30
191	38.00	22.00	40.00	19.00	4.60	.00	9.60	10.60
192	37.90	18.60	48.00	17.00	4.10	.00	9.60	10.70
193	39.90	18.00	41.00	17.00	2.90	.00	9.80	11.50
194	38.60	20.00	38.00	17.00	3.90	.00	10.00	10.00
195	38.90	22.00	38.00	20.00	4.70	.00	10.10	10.70
196	35.50	21.00	45.00	20.00	3.40	.00	10.40	12.70
197	38.80	23.80	46.00	20.00	4.20	.00	9.90	12.00
198	39.50	21.00	58.00	22.00	5.30	.00	9.20	11.50
199	40.00	23.20	51.00	18.00	3.80	.00	9.50	11.20
200	39.60	21.30	55.00	19.00	5.10	.00	8.60	11.80
201	39.00	22.50	49.00	18.00	4.00	.00	8.60	11.00
202	38.60	22.50	38.00	22.00	7.60	.00	9.80	10.60
203	37.60	18.00	41.00	19.00	9.30	.00	10.40	13.00
204	39.10	18.60	64.00	23.00	6.50	.00	10.90	12.00
205	38.20	22.20	47.00	31.00	3.90	.00	9.80	9.50
206	40.80	24.50	52.00	23.00	4.20	.00	9.30	12.00
207	41.10	20.40	38.00	21.00	3.80	.00	10.10	12.20
208	40.20	20.60	40.00	23.00	6.20	.00	9.70	12.40
209	39.50	19.20	50.00	23.00	5.20	.00	10.10	13.30
210	39.50	19.10	44.00	23.00	5.10	.00	9.50	13.00
211	40.00	24.70	50.00	26.00	6.70	.00	9.70	11.80
212	41.00	26.70	51.00	31.00	4.30	.00	9.20	12.40
213	40.40	27.50	51.00	30.00	5.40	.00	6.00	13.00
214	40.90	26.50	52.00	19.00	5.30	.00	9.30	13.20
215	41.00	26.30	92.00	26.00	8.80	.00	8.20	12.10
216	39.30	21.40	65.00	26.00	6.10	.00	7.10	12.00
217	39.40	18.70	60.00	20.00	7.00	.00	10.50	12.00
218	38.90	18.90	53.00	18.00	6.00	.00	11.00	11.50
219	39.80	18.20	62.00	23.00	6.90	.00	10.90	12.60
220	38.20	19.60	66.00	24.00	9.60	.00	10.60	12.00
221	38.90	20.40	68.00	23.00	5.80	.00	10.50	11.00
222	40.00	21.00	71.00	22.00	7.50	.00	10.20	12.00
223	41.50	22.60	73.00	25.00	7.70	.00	10.30	13.70
224	40.00	23.50	53.00	19.00	11.40	.00	9.90	15.00
225	41.20	23.50	74.00	21.00	10.40	.00	10.10	12.90
226	40.00	25.20	65.00	20.00	7.80	.00	10.40	13.10
227	40.00	23.50	68.00	24.00	7.20	.00	9.80	11.00
228	40.30	23.80	72.00	25.00	6.50	.00	9.20	10.10
229	39.40	24.30	57.00	29.00	7.30	.00	8.90	12.40
230	38.50	20.50	77.00	28.00	6.40	.50	7.40	10.30
231	39.00	19.70	64.00	27.00	4.60	.00	10.00	9.20
232	39.00	25.60	68.00	22.00	6.10	.00	8.50	9.20
233	39.50	26.70	74.00	27.00	7.40	.00	7.00	12.00
234	39.40	24.50	75.00	26.00	6.50	.00	8.20	11.80
235	40.50	23.00	71.00	32.00	5.00	.00	9.30	10.90
236	40.90	25.20	66.00	31.00	8.30	.00	8.50	11.70
237	40.80	24.50	82.00	34.00	7.00	11.80	8.80	9.90
238	38.00	22.00	76.00	34.00	6.70	.00	8.50	9.10
239	38.50	23.20	77.00	34.00	4.10	.00	10.30	9.60
240	39.80	26.50	76.00	36.00	7.50	.00	10.30	12.00

241	39.80	22.00	79.00	37.00	8.70	12.00	9.10	11.20
242	39.20	26.00	75.00	38.00	6.90	.00	9.90	10.00
243	38.80	25.50	76.00	43.00	6.70	.00	5.20	10.40
244	39.50	25.50	83.00	43.00	6.70	.00	6.70	9.80
245	38.20	21.00	83.00	51.00	11.00	34.80	5.90	12.00
246	36.40	24.60	90.00	55.00	8.50	.00	9.00	8.00
247	34.50	24.90	78.00	44.00	8.30	.00	1.30	7.40
248	34.10	26.50	74.00	49.00	11.50	.00	7.40	9.40
249	35.20	24.90	82.00	68.00	12.50	1.20	7.00	9.20
250	29.10	20.90	98.00	97.00	15.80	75.00	.00	.50
251	23.00	21.00	95.00	67.00	11.70	38.00	.00	5.00
252	28.20	22.00	84.00	60.00	9.80	2.50	.20	5.50
253	30.00	22.60	77.00	71.00	13.20	.00	1.80	4.80
254	27.40	21.60	82.00	54.00	9.00	1.80	.00	3.20
255	31.40	21.50	75.00	46.00	11.60	.00	3.60	4.00
256	32.20	23.10	74.00	46.00	12.90	.00	8.50	5.40
257	32.60	24.00	75.00	48.00	13.70	.00	8.50	7.80
258	33.10	22.50	80.00	50.00	12.70	.00	7.60	8.00
259	33.70	22.10	82.00	55.00	10.30	.00	8.70	9.90
260	32.50	22.00	88.00	45.00	6.90	.00	7.30	6.00
261	34.50	23.90	89.00	42.00	4.50	.00	6.30	6.90
262	34.60	22.50	78.00	40.00	7.70	.00	4.60	9.00
263	34.00	21.00	78.00	41.00	8.70	.00	10.00	10.00
264	34.50	22.00	73.00	40.00	4.50	.00	7.40	9.50
265	33.90	20.70	73.00	44.00	8.60	.00	9.70	9.00
266	34.20	20.60	71.00	38.00	6.70	.00	9.90	12.30
267	34.00	22.50	78.00	40.00	9.60	.00	10.00	10.00
268	33.80	21.40	78.00	43.00	10.60	.00	9.50	8.80
269	33.70	21.60	70.00	43.00	8.00	.00	9.60	9.00
270	33.50	21.70	78.00	41.00	3.20	.00	8.60	8.70
271	34.00	23.50	74.00	58.00	7.20	.00	9.90	8.00
272	32.20	23.00	87.00	55.00	4.60	4.20	5.10	4.40
273	33.20	23.20	98.00	88.00	5.00	2.00	9.40	8.00
274	31.00	22.00	88.00	61.00	2.30	7.00	2.90	4.00
275	32.20	22.50	90.00	62.00	6.20	17.00	5.40	7.90
276	31.60	22.60	88.00	61.00	8.70	.00	2.40	6.20
277	30.20	22.40	84.00	62.00	6.70	18.20	4.40	5.00
278	30.80	23.00	82.00	67.00	9.40	.00	4.30	4.90
279	29.90	23.40	87.00	64.00	14.00	.00	7.60	4.50
280	29.40	23.50	88.00	68.00	14.00	4.00	2.70	5.00
281	29.20	23.20	88.00	65.00	10.80	.00	3.60	3.60
282	29.80	23.20	84.00	63.00	11.90	.40	2.80	5.40
283	29.40	23.00	82.00	58.00	14.10	.20	4.30	5.50
284	30.60	23.00	81.00	58.00	13.90	.00	8.50	6.30
285	30.40	23.20	84.00	57.00	13.90	.00	7.30	7.20
286	30.50	24.00	81.00	72.00	12.50	.00	3.50	5.70
287	30.20	23.60	82.00	56.00	12.90	.00	3.10	6.00
288	30.20	23.20	79.00	77.00	16.00	.00	2.00	7.30
289	26.20	22.90	84.00	53.00	14.60	1.40	.00	6.80
290	30.80	21.90	73.00	64.00	16.20	.00	2.30	8.00
291	30.60	21.20	88.00	64.00	12.70	.00	6.80	6.60
292	31.00	22.00	82.00	60.00	11.00	.00	8.20	7.00
293	29.50	23.40	95.00	84.00	9.60	.00	1.70	5.80
294	27.60	22.30	90.00	72.00	5.00	11.70	.00	2.50
295	28.90	22.20	90.00	71.00	3.90	10.00	2.90	4.00
296	29.20	22.00	89.00	62.00	4.40	.00	3.80	4.00
297	30.60	22.50	87.00	55.00	4.70	.00	5.70	5.20
298	32.50	23.30	95.00	61.00	3.10	2.20	7.60	3.20
299	31.70	22.20	95.00	64.00	2.60	18.20	3.40	4.70
300	30.70	23.40	92.00	67.00	4.40	.00	5.20	4.70
301	30.40	22.40	87.00	61.00	4.50	13.80	1.10	4.50
302	29.70	23.00	93.00	87.00	9.50	.00	7.90	6.00
303	28.60	22.10	91.00	72.00	7.10	13.70	2.10	2.80
304	27.80	22.40	88.00	68.00	7.90	1.00	.70	3.50

305	28.40	22.50	91.00	67.00	7.40	.00	.20	5.00
306	29.00	22.40	88.00	78.00	8.70	1.20	1.20	4.20
307	26.40	22.40	84.00	71.00	7.00	.50	.00	2.80
308	27.40	22.50	85.00	74.00	8.50	.00	.00	3.30
309	28.40	22.50	85.00	60.00	10.20	.00	1.20	3.50
310	29.60	22.30	82.00	64.00	9.90	.00	5.50	5.50
311	30.40	22.50	85.00	84.00	10.60	.00	4.40	6.60
312	25.70	21.20	97.00	68.00	4.60	5.60	.00	1.40
313	27.00	20.50	90.00	68.00	5.70	1.00	.10	2.50
314	29.60	21.00	93.00	64.00	5.60	.00	2.20	3.90
315	29.40	21.00	82.00	56.00	4.00	.00	1.80	5.50
316	30.00	20.20	81.00	59.00	4.50	.00	5.80	5.60
317	29.50	21.00	84.00	65.00	7.00	.00	8.90	4.90
318	30.20	21.00	79.00	71.00	8.00	.00	4.90	4.00
319	28.40	22.40	88.00	63.00	8.60	.00	2.60	4.50
320	29.00	21.40	90.00	81.00	7.40	.00	3.10	5.00
321	29.20	21.50	91.00	66.00	3.90	14.00	2.00	3.60
322	29.00	22.10	83.00	82.00	4.50	.00	.30	3.40
323	28.50	22.50	92.00	81.00	3.90	.40	1.50	1.60
324	26.00	21.10	98.00	77.00	7.20	38.50	.00	2.80
325	26.30	22.50	90.00	87.00	5.30	13.30	.20	2.50
326	26.00	21.50	84.00	63.00	8.60	.50	.10	1.50
327	29.00	22.50	85.00	67.00	12.40	.00	7.30	4.00
328	29.50	21.80	84.00	63.00	11.20	.00	6.00	5.80
329	30.00	22.50	79.00	57.00	10.70	.00	8.60	7.60
330	28.00	21.50	85.00	57.00	10.40	.00	3.10	4.50
331	30.00	21.70	77.00	56.00	9.50	.00	6.60	5.80
332	29.80	18.40	82.00	53.00	4.60	.00	7.40	5.10
333	30.70	19.50	90.00	54.00	3.10	.00	8.00	4.20
334	30.00	17.90	87.00	55.00	3.60	.00	8.40	5.20
335	30.00	18.50	75.00	58.00	3.50	.00	6.80	5.70
336	30.30	19.90	83.00	47.00	4.90	.00	7.20	7.40
337	30.20	18.10	83.00	48.00	5.30	.00	7.10	5.60
338	31.10	16.60	89.00	40.00	3.30	.00	8.30	5.40
339	31.30	16.00	87.00	41.00	5.10	.00	8.60	5.40
340	31.90	18.60	82.00	44.00	4.10	.00	9.70	6.40
341	31.70	18.50	85.00	42.00	4.10	.00	8.20	7.00
342	32.50	20.40	84.00	42.00	3.00	.00	10.00	8.10
343	32.20	20.40	95.00	40.00	3.20	19.40	9.00	8.80
344	32.00	19.50	82.00	41.00	3.30	.00	9.70	7.00
345	32.60	20.50	84.00	34.00	2.90	.00	10.10	6.50
346	33.20	18.70	69.00	36.00	3.50	.00	10.10	6.40
347	33.10	17.50	70.00	30.00	2.80	.00	8.90	6.00
348	32.90	18.20	70.00	48.00	3.20	.00	10.00	6.20
349	32.00	18.80	69.00	45.00	3.20	.00	5.60	6.40
350	33.20	21.50	83.00	44.00	1.50	.00	8.80	6.00
351	33.00	22.40	84.00	49.00	4.30	.00	9.50	5.50
352	32.50	21.40	88.00	55.00	6.60	17.80	9.30	7.20
353	31.20	21.00	80.00	69.00	4.80	.00	8.10	5.20
354	31.30	21.20	85.00	58.00	4.10	.00	6.10	3.50
355	31.40	21.00	83.00	49.00	2.10	.00	8.20	3.50
356	32.50	19.80	82.00	31.00	2.40	.00	9.20	4.90
357	33.50	19.20	81.00	41.00	1.70	.00	10.40	4.30
358	33.80	19.20	73.00	40.00	2.30	.00	9.70	5.00
359	33.20	18.10	86.00	31.00	2.80	.00	7.90	5.10
360	34.00	17.50	74.00	37.00	3.30	.00	9.30	5.00
361	32.00	19.40	72.00	57.00	4.30	.00	5.90	5.30
362	30.00	22.00	97.00	95.00	8.10	4.20	.40	4.20
363	26.70	21.00	90.00	63.00	4.30	9.60	.60	1.60
364	29.60	19.60	89.00	42.00	7.40	1.00	6.60	4.80
365	31.00	17.00	81.00	24.00	3.20	.00	8.10	4.00
366	31.60	17.90	82.00	28.00	2.20	.00	9.60	4.80

APPENDIX C

This appendix presents the detail allocation plan at preseason planning for fixed cropping distribution with variable depth irrigation (see Section 9.3.4). The area to be irrigated, water to be delivered and expected net benefits are given for allocation unit, soil group in each allocation unit and crops in each soil group of allocation unit.

	Area to be irrigated (ha)	water to be delivered (ha-m)	expected net benefits (Rs.)

ALLOCATION UNIT NUMBER = 1

.780000E+02 .367326E+02 .473567E+06

Soil group number = 1 Soil Group = 001
.780000E+02 .367326E+02 .473567E+06

gram	.390000E+02	.140581E+02	.424093E+06

Irrigation programme no = 1 Area = .390000E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.249419E+01
3	.249419E+01
4	.226744E+01
5	.226744E+01
6	.226744E+01
7	.226744E+01
8	.000000E+00

sorghum	.000000E+00	.000000E+00	.000000E+00
onion	.000000E+00	.000000E+00	.000000E+00
wheat	.000000E+00	.000000E+00	.000000E+00
sunflower	.000000E+00	.000000E+00	.000000E+00
groundnut	.390000E+02	.226744E+02	.494748E+05

Irrigation programme no = 1 Area = .390000E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.408140E+01
2	.226744E+01
3	.226744E+01
4	.249419E+01
5	.340116E+01
6	.317442E+01
7	.272093E+01
8	.226744E+01

ALLOCATION UNIT NUMBER = 2
.720000E+02 .436624E+02 .436961E+06

Soil group number = 1 Soil Group = 002
.720000E+02 .436624E+02 .436961E+06

gram	.263552E+01	.904046E+00	.290273E+05

Irrigation programme no = 1 Area = .263552E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.275811E+00
3	.168551E+00
4	.153228E+00
5	.153228E+00
6	.153228E+00
7	.000000E+00
8	.000000E+00

sorghum	.000000E+00	.000000E+00	.000000E+00
onion	.000000E+00	.000000E+00	.000000E+00
wheat	.333645E+02	.143545E+02	.193728E+06

Irrigation programme no = 1 Area = .333645E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.484949E+01
2	.000000E+00
3	.252173E+01
4	.000000E+00
5	.310367E+01
6	.193980E+01
7	.193980E+01
8	.000000E+00
9	.000000E+00

sunflower	.263552E+01	.202261E+01	.159065E+05

Irrigation programme no = 1 Area = .263552E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.459684E+00
2	.000000E+00
3	.214519E+00
4	.245165E+00
5	.306456E+00
6	.306456E+00
7	.337102E+00
8	.153228E+00
9	.000000E+00

groundnut .333645E+02 .263812E+02 .198299E+06

Irrigation programme no = 1 Area = .333645E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.581939E+01

ALLOCATION UNIT NUMBER = 3
.160000E+02 .976744E+01 .939986E+05

Soil group number = 1 Soil Group = 002
.160000E+02 .976744E+01 .939986E+05

gram .000000E+00 .000000E+00 .000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .800000E+01 .344186E+01 .464512E+05

Irrigation programme no = 1 Area = .800000E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.116279E+01
2	.000000E+00
3	.604651E+00
4	.000000E+00
5	.744186E+00

ALLOCATION UNIT NUMBER = 4
.520234E+02 .311141E+02 .388763E+06

Soil group number = 1 Soil Group = 002
.520234E+02 .311141E+02 .388763E+06

gram .309047E+01 .106010E+01 .340381E+05

Irrigation programme no = 1 Area = .309047E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.323421E+00
3	.197646E+00
4	.179678E+00
5	.179678E+00
6	.179678E+00
7	.000000E+00
8	.000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

onion .525065E+01 .244216E+01 .970012E+05

Irrigation programme no = 1 Area = .525065E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.305270E+00
2	.305270E+00
3	.000000E+00
4	.305270E+00
5	.305270E+00
6	.305270E+00

2	.484949E+01
3	.368561E+01
4	.290969E+01
5	.387959E+01
6	.329765E+01
7	.193980E+01
8	.000000E+00

6	.465116E+00
7	.465116E+00
8	.000000E+00
9	.000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

groundnut .800000E+01 .632558E+01 .475474E+05

Irrigation programme no = 1 Area = .800000E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.139535E+01
2	.116279E+01
3	.883721E+00
4	.697674E+00
5	.930233E+00
6	.790698E+00
7	.465116E+00
8	.000000E+00

7	.305270E+00
8	.305270E+00
9	.305270E+00

wheat .186589E+02 .802766E+01 .108341E+06

Irrigation programme no = 1 Area = .186589E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.271205E+01
2	.000000E+00
3	.141026E+01
4	.000000E+00
5	.173571E+01
6	.108482E+01
7	.108482E+01
8	.000000E+00
9	.000000E+00

sunflower .834112E+01 .640132E+01 .503423E+05

Irrigation programme no = 1 Area = .834112E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.145485E+01
2	.000000E+00
3	.678928E+00
4	.775918E+00
5	.969898E+00
6	.969898E+00
7	.106689E+01
8	.484949E+00
9	.000000E+00

groundnut .166822E+02 .131828E+02 .990400E+05

Irrigation programme no = 1 Area = .133458E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.232775E+00
2	.000000E+00
3	.232775E+00
4	.217257E+00
5	.155184E+00
6	.131906E+00
7	.775918E-01
8	.000000E+00

ALLOCATION UNIT NUMBER = 5
.000000E+00 .000000E+00 .000000E+00

Soil group number = 1 Soil Group = 001
.000000E+00 .000000E+00 .000000E+00

gram .000000E+00 .000000E+00 .000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

ALLOCATION UNIT NUMBER = 6
.660000E+02 .387558E+02 .577463E+06

Soil group number = 1 Soil Group = 003
.660000E+02 .387558E+02 .577463E+06

gram .330000E+02 .111279E+02 .361381E+06

Irrigation programme no = 1 Area = .330000E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.326163E+01
3	.211047E+01
4	.191860E+01
5	.191860E+01
6	.191860E+01
7	.000000E+00
8	.000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

ALLOCATION UNIT NUMBER = 7
.109047E+03 .652093E+02 .882499E+06

Soil group number = 1 Soil Group = 002
.109047E+03 .652093E+02 .882499E+06

gram .000000E+00 .000000E+00 .000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

onion .189626E+02 .881983E+01 .350318E+06

Irrigation programme no = 1 Area = .189626E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.110248E+01

Irrigation programme no = 2 Area = .153477E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.267692E+01
2	.223076E+01
3	.169538E+01
4	.133846E+01
5	.178461E+01
6	.151692E+01
7	.892306E+00
8	.000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .000000E+00 .000000E+00 .000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

groundnut .000000E+00 .000000E+00 .000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .000000E+00 .000000E+00 .000000E+00

sunflower .330000E+02 .276279E+02 .216082E+06

Irrigation programme no = 1 Area = .330000E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.575581E+01
2	.191860E+01
3	.191860E+01
4	.326163E+01
5	.402907E+01
6	.422093E+01
7	.460465E+01
8	.191860E+01
9	.000000E+00

groundnut .000000E+00 .000000E+00 .000000E+00

2	.110248E+01
3	.000000E+00
4	.110248E+01
5	.110248E+01
6	.110248E+01
7	.110248E+01
8	.110248E+01
9	.110248E+01

wheat .400374E+02 .172254E+02 .232473E+06

Irrigation programme no = 1 Area = .400374E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.581939E+01
2	.000000E+00

3	.302608E+01
4	.000000E+00
5	.372441E+01
6	.232775E+01
7	.232775E+01
8	.000000E+00
9	.000000E+00

sunflower .189626E+02 .145925E+02 .115053E+06

Irrigation programme no = 1 Area = .121215E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.211421E+01
2	.000000E+00
3	.986631E+00
4	.112758E+01
5	.140947E+01
6	.140947E+01
7	.155042E+01
8	.704736E+00
9	.000000E+00

Irrigation programme no = 2 Area = .684117E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.119323E+01
2	.397742E+00
3	.477291E+00
4	.596613E+00
5	.596613E+00
6	.795484E+00

7	.835259E+00
8	.397742E+00
9	.000000E+00

groundnut .310841E+02 .245716E+02 .184654E+06

Irrigation programme no = 1 Area = .111849E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.195086E+00
2	.000000E+00
3	.195086E+00
4	.182080E+00
5	.130057E+00
6	.110549E+00
7	.650287E-01
8	.000000E+00

Irrigation programme no = 2 Area = .299656E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.522656E+01
2	.435546E+01
3	.331015E+01
4	.261328E+01
5	.348437E+01
6	.296172E+01
7	.174219E+01
8	.000000E+00

ALLOCATION UNIT NUMBER = 8

.440000E+02 .262421E+02 .286270E+06

Soil group number = 1 Soil Group = 002

.440000E+02 .262421E+02 .286270E+06

gram .531776E+01 .179320E+01 .581613E+05

Irrigation programme no = 1 Area = .531776E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.494675E+00
3	.463758E+00
4	.432841E+00
5	.000000E+00
6	.401924E+00
7	.000000E+00
8	.000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .166822E+02 .717724E+01 .968638E+05

Irrigation programme no = 1 Area = .166822E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.242474E+01
2	.000000E+00
3	.126087E+01
4	.000000E+00
5	.155184E+01
6	.969898E+00
7	.969898E+00
8	.000000E+00
9	.000000E+00

sunflower .531776E+01 .408107E+01 .320950E+05

Irrigation programme no = 1 Area = .531776E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.927517E+00
2	.000000E+00
3	.432841E+00
4	.494675E+00
5	.618344E+00
6	.618344E+00
7	.680179E+00
8	.309172E+00
9	.000000E+00

groundnut .166822E+02 .131906E+02 .991497E+05

Irrigation programme no = 1 Area = .166822E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.290969E+01
2	.242474E+01
3	.184281E+01

4	.145485E+01
5	.193980E+01
6	.164883E+01
7	.969898E+00

ALLOCATION UNIT NUMBER = 9
.000000E+00 .000000E+00 .000000E+00

Soil group number = 1 Soil Group = 002
.000000E+00 .000000E+00 .000000E+00

gram .000000E+00 .000000E+00 .000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

ALLOCATION UNIT NUMBER = 10
.118047E+03 .679291E+02 .102965E+07

Soil group number = 1 Soil Group = 002
.118047E+03 .679291E+02 .102965E+07

gram .000000E+00 .000000E+00 .000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

onion .279626E+02 .115427E+02 .496787E+06

Irrigation programme no = 1 Area = .279626E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.162573E+01
2	.162573E+01
3	.000000E+00
4	.162573E+01
5	.162573E+01
6	.162573E+01
7	.162573E+01
8	.178831E+01
9	.000000E+00

wheat .400374E+02 .172254E+02 .232473E+06

Irrigation programme no = 1 Area = .400374E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.581939E+01
2	.000000E+00
3	.302608E+01
4	.000000E+00
5	.372441E+01
6	.232775E+01
7	.232775E+01
8	.000000E+00
9	.000000E+00

sunflower .206075E+02 .158835E+02 .125418E+06

ALLOCATION UNIT NUMBER = 11
.112047E+03 .624152E+02 .864617E+06

Soil group number = 1 Soil Group = 002
.112047E+03 .624152E+02 .864617E+06

gram .392190E+02 .134530E+02 .431953E+06

8	.000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .000000E+00 .000000E+00 .000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

groundnut .000000E+00 .000000E+00 .000000E+00

Irrigation programme no = 1 Area = .883177E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.154043E+01
2	.000000E+00
3	.718865E+00
4	.821560E+00
5	.102695E+01
6	.102695E+01
7	.112965E+01
8	.513475E+00
9	.000000E+00

Irrigation programme no = 2 Area = .117757E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.205390E+01
2	.684634E+00
3	.821560E+00
4	.102695E+01
5	.102695E+01
6	.136927E+01
7	.143773E+01
8	.684634E+00
9	.000000E+00

groundnut .294392E+02 .232775E+02 .174970E+06

Irrigation programme no = 1 Area = .294392E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.513475E+01
2	.427896E+01
3	.325201E+01
4	.256738E+01
5	.342317E+01
6	.290969E+01
7	.171158E+01
8	.000000E+00

Irrigation programme no = 1 Area = .392190E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.410431E+01
3	.250819E+01

4	.228017E+01
5	.228017E+01
6	.228017E+01
7	.000000E+00
8	.000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .227810E+02 .980114E+01 .132276E+06

Irrigation programme no = 1 Area = .227810E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.331120E+01
2	.000000E+00
3	.172182E+01
4	.000000E+00
5	.211916E+01
6	.132448E+01
7	.132448E+01
8	.000000E+00
9	.000000E+00

sunflower .206075E+02 .158835E+02 .125418E+06

Irrigation programme no = 1 Area = .883177E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.154043E+01
2	.000000E+00
3	.718865E+00
4	.821560E+00
5	.102695E+01
6	.102695E+01
7	.112965E+01
8	.513475E+00
9	.000000E+00

Irrigation programme no = 2 Area = .117757E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.205390E+01
2	.684634E+00
3	.821560E+00
4	.102695E+01
5	.102695E+01
6	.136927E+01
7	.143773E+01
8	.684634E+00
9	.000000E+00

groundnut .294392E+02 .232775E+02 .174970E+06

Irrigation programme no = 1 Area = .294392E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.513475E+01
2	.427896E+01
3	.325201E+01
4	.256738E+01
5	.342317E+01
6	.290969E+01
7	.171158E+01
8	.000000E+00

ALLOCATION UNIT NUMBER = 12
.000000E+00 .000000E+00 .000000E+00

Soil group number = 1 Soil Group = 002
.000000E+00 .000000E+00 .000000E+00

gram .000000E+00 .000000E+00 .000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .000000E+00 .000000E+00 .000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

groundnut .000000E+00 .000000E+00 .000000E+00

ALLOCATION UNIT NUMBER = 13
.172915E+03 .867912E+02 .186692E+07

Soil group number = 1 Soil Group = 002
.172915E+03 .867912E+02 .186692E+07

gram .184960E+02 .612950E+01 .200517E+06

Irrigation programme no = 1 Area = .184960E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.193563E+01
3	.139796E+01
4	.139796E+01
5	.000000E+00
6	.139796E+01
7	.000000E+00
8	.000000E+00

sorghum .133582E+02 .361437E+01 .402571E+05

Irrigation programme no = 1 Area = .924802E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.129042E+01
2	.000000E+00
3	.591443E+00
4	.537675E+00
5	.000000E+00
6	.000000E+00
7	.000000E+00
8	.000000E+00

Irrigation programme no = 2 Area = .411023E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.645210E+00

2	.000000E+00
3	.310657E+00
4	.000000E+00
5	.000000E+00
6	.238967E+00
7	.000000E+00
8	.000000E+00

onion .668006E+02 .275747E+02 .118679E+07

Irrigation programme no = 1 Area = .668006E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.388375E+01
2	.388375E+01
3	.000000E+00
4	.388375E+01
5	.388375E+01
6	.388375E+01
7	.388375E+01
8	.427213E+01
9	.000000E+00

wheat .242130E+02 .103116E+02 .138976E+06

Irrigation programme no = 1 Area = .181597E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.263950E+01
2	.000000E+00
3	.147812E+01
4	.000000E+00
5	.137254E+01
6	.116138E+01
7	.105580E+01
8	.000000E+00
9	.000000E+00

Irrigation programme no = 2 Area = .605325E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.879832E+00
2	.000000E+00
3	.457513E+00
4	.000000E+00
5	.563093E+00
6	.351933E+00
7	.351933E+00

ALLOCATION UNIT NUMBER = 14
.131047E+03 .664720E+02 .101537E+07

Soil group number = 1 Soil Group = 002
.131047E+03 .664720E+02 .101537E+07

gram .556075E+02 .190747E+02 .612454E+06

Irrigation programme no = 1 Area = .556075E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.581939E+01
3	.355629E+01
4	.323299E+01

8	.000000E+00
9	.000000E+00

sunflower .206075E+02 .158835E+02 .125418E+06

Irrigation programme no = 1 Area = .883177E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.154043E+01
2	.000000E+00
3	.718865E+00
4	.821560E+00
5	.102695E+01
6	.102695E+01
7	.112965E+01
8	.513475E+00
9	.000000E+00

Irrigation programme no = 2 Area = .117757E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.205390E+01
2	.684634E+00
3	.821560E+00
4	.102695E+01
5	.102695E+01
6	.136927E+01
7	.143773E+01
8	.684634E+00
9	.000000E+00

groundnut .294392E+02 .232775E+02 .174970E+06

Irrigation programme no = 1 Area = .294392E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.513475E+01
2	.427896E+01
3	.325201E+01
4	.256738E+01
5	.342317E+01
6	.290969E+01
7	.171158E+01
8	.000000E+00

5	.323299E+01
6	.323299E+01
7	.000000E+00
8	.000000E+00

sorghum .163707E+02 .437822E+01 .487085E+05

Irrigation programme no = 1 Area = .163707E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.228429E+01
2	.000000E+00
3	.951788E+00
4	.000000E+00
5	.114215E+01

6	.000000E+00
7	.000000E+00
8	.000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .902179E+01 .388147E+01 .523841E+05

Irrigation programme no = 1 Area = .902179E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.131131E+01
2	.000000E+00
3	.681880E+00
4	.000000E+00
5	.839236E+00
6	.524523E+00
7	.524523E+00
8	.000000E+00
9	.000000E+00

sunflower .246214E+02 .190339E+02 .150709E+06

Irrigation programme no = 1 Area = .803987E+00 ha

Ir.no.	Irr. vol. (ha-m)
1	.140230E+00
2	.000000E+00
3	.654408E-01
4	.747895E-01
5	.934868E-01
6	.934868E-01
7	.102836E+00
8	.467434E-01
9	.000000E+00

Irrigation programme no = 2 Area = .238174E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.415419E+01
2	.138473E+01
3	.166168E+01
4	.207710E+01
5	.207710E+01
6	.276946E+01
7	.290794E+01
8	.138473E+01
9	.000000E+00

groundnut .254254E+02 .201038E+02 .151114E+06

Irrigation programme no = 1 Area = .254254E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.443465E+01
2	.369555E+01
3	.280861E+01
4	.221733E+01
5	.295644E+01
6	.251297E+01
7	.147822E+01
8	.000000E+00

ALLOCATION UNIT NUMBER = 15
.317182E+03 .159346E+03 .313086E+07

Soil group number = 1 Soil Group = 002
.317182E+03 .159346E+03 .313086E+07

gram .636380E+02 .214354E+02 .695047E+06

Irrigation programme no = 1 Area = .338816E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.354574E+01
3	.256082E+01
4	.256082E+01
5	.000000E+00
6	.256082E+01
7	.000000E+00
8	.000000E+00

Irrigation programme no = 2 Area = .297565E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.311405E+01
3	.190303E+01
4	.173003E+01
5	.173003E+01
6	.173003E+01
7	.000000E+00
8	.000000E+00

sorghum .301875E+02 .807340E+01 .898180E+05

Irrigation programme no = 1 Area = .301875E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.421221E+01
2	.000000E+00
3	.175509E+01
4	.000000E+00
5	.210610E+01
6	.000000E+00
7	.000000E+00
8	.000000E+00

onion .858153E+02 .354237E+02 .152460E+07

Irrigation programme no = 1 Area = .858153E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.498926E+01
2	.498926E+01
3	.000000E+00
4	.498926E+01
5	.498926E+01
6	.498926E+01
7	.498926E+01
8	.548819E+01
9	.000000E+00

wheat .373592E+02 .160732E+02 .216923E+06

Irrigation programme no = 1 Area = .373592E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.543012E+01
2	.000000E+00
3	.282366E+01
4	.000000E+00
5	.347528E+01
6	.217205E+01
7	.217205E+01
8	.000000E+00
9	.000000E+00

sunflower .500909E+02 .387331E+02 .306755E+06

Irrigation programme no = 1 Area = .500909E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.873679E+01
2	.291226E+01
3	.349472E+01
4	.436839E+01
5	.436839E+01
6	.582453E+01
7	.611575E+01
8	.291226E+01
9	.000000E+00

groundnut .500909E+02 .396068E+02 .297712E+06

Irrigation programme no = 1 Area = .500909E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.873679E+01
2	.728066E+01
3	.553330E+01
4	.436839E+01
5	.582453E+01
6	.495085E+01
7	.291226E+01
8	.000000E+00

ALLOCATION UNIT NUMBER = 16
.764938E+02 .345302E+02 .107574E+06

Soil group number = 1 Soil Group = 001
.764938E+02 .345302E+02 .107574E+06

gram .693537E+01 .217738E+01 .700588E+05

Irrigation programme no = 1 Area = .693537E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.000000E+00
3	.483863E+00
4	.483863E+00
5	.403219E+00
6	.403219E+00
7	.403219E+00
8	.000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .000000E+00 .000000E+00 .000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

groundnut .695585E+02 .323528E+02 .375152E+05

Irrigation programme no = 1 Area = .695585E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.727937E+01
2	.000000E+00
3	.404410E+01
4	.444851E+01
5	.647055E+01
6	.566173E+01
7	.444851E+01
8	.000000E+00

ALLOCATION UNIT NUMBER = 17
.145000E+03 .487707E+02 .964891E+06

Soil group number = 1 Soil Group = 004
.145000E+03 .487707E+02 .964891E+06

gram .525018E+02 .177041E+02 .574373E+06

Irrigation programme no = 1 Area = .525018E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.488389E+01
3	.305243E+01
4	.366292E+01
5	.305243E+01
6	.305243E+01
7	.000000E+00
8	.000000E+00

sorghum .500467E+02 .128026E+02 .144436E+06

Irrigation programme no = 1 Area = .500467E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.872908E+01
2	.000000E+00
3	.000000E+00
4	.407357E+01
5	.000000E+00
6	.000000E+00
7	.000000E+00
8	.000000E+00

onion .000000E+00 .000000E+00 .000000E+00 wheat .424514E+02 .182640E+02 .246081E+06

Irrigation programme no = 1 Area = .424514E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.567665E+01
2	.000000E+00
3	.345535E+01
4	.000000E+00

ALLOCATION UNIT NUMBER = 18
.147000E+03 .463052E+02 .103490E+07

Soil group number = 1 Soil Group = 004
.147000E+03 .463052E+02 .103490E+07

gram .695356E+02 .234480E+02 .760723E+06

Irrigation programme no = 1 Area = .695356E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.646842E+01
3	.404276E+01
4	.485132E+01
5	.404276E+01
6	.404276E+01
7	.000000E+00
8	.000000E+00

sorghum .628837E+02 .165841E+02 .189655E+06

Irrigation programme no = 1 Area = .200939E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.350474E+01
2	.000000E+00
3	.000000E+00
4	.163555E+01
5	.000000E+00
6	.000000E+00
7	.000000E+00
8	.000000E+00

ALLOCATION UNIT NUMBER = 19
.125593E+03 .541227E+02 .906632E+06

Soil group number = 1 Soil Group = 002
.125593E+03 .541227E+02 .906632E+06

gram .547568E+02 .187594E+02 .602737E+06

Irrigation programme no = 1 Area = .201332E+01 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.210696E+00
3	.152169E+00
4	.152169E+00
5	.000000E+00
6	.152169E+00
7	.000000E+00
8	.000000E+00

5	.394897E+01
6	.246811E+01
7	.271492E+01
8	.000000E+00
9	.000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

groundnut .000000E+00 .000000E+00 .000000E+00

Irrigation programme no = 2 Area = .427898E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.522434E+01
2	.000000E+00
3	.273656E+01
4	.000000E+00
5	.348289E+01
6	.000000E+00
7	.000000E+00
8	.000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .145808E+02 .627313E+01 .845214E+05

Irrigation programme no = 1 Area = .145808E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.194976E+01
2	.000000E+00
3	.118681E+01
4	.000000E+00
5	.135635E+01
6	.847720E+00
7	.932492E+00
8	.000000E+00
9	.000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

groundnut .000000E+00 .000000E+00 .000000E+00

Irrigation programme no = 2 Area = .527435E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.551967E+01
3	.337313E+01
4	.306648E+01
5	.306648E+01
6	.306648E+01
7	.000000E+00
8	.000000E+00

sorghum .394583E+02 .105528E+02 .117402E+06

Irrigation programme no = 1 Area = .394583E+02 ha

Ir.no.	Irr. vol. (ha-m)

1	.550581E+01
2	.000000E+00
3	.229409E+01
4	.000000E+00
5	.275290E+01
6	.000000E+00
7	.000000E+00
8	.000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .000000E+00 .000000E+00 .000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

ALLOCATION UNIT NUMBER = 20
.000000E+00 .000000E+00 .000000E+00

Soil group number = 1 Soil Group = 004
.000000E+00 .000000E+00 .000000E+00

gram .000000E+00 .000000E+00 .000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

ALLOCATION UNIT NUMBER = 21
.650000E+02 .166279E+02 .193317E+06

Soil group number = 1 Soil Group = 003
.650000E+02 .166279E+02 .193317E+06

gram .000000E+00 .000000E+00 .000000E+00

sorghum .650000E+02 .166279E+02 .193317E+06

Irrigation programme no = 1 Area = .650000E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.869186E+01
2	.377907E+01

ALLOCATION UNIT NUMBER = 22
.133524E+03 .369347E+02 .895685E+06

Soil group number = 1 Soil Group = 003
.133524E+03 .369347E+02 .895685E+06

gram .682455E+02 .202356E+02 .701540E+06

Irrigation programme no = 1 Area = .682455E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.000000E+00
2	.000000E+00
3	.872908E+01
4	.634842E+01
5	.000000E+00
6	.515809E+01
7	.000000E+00
8	.000000E+00

sorghum .652783E+02 .166991E+02 .194145E+06

groundnut .313780E+02 .248105E+02 .186493E+06

Irrigation programme no = 1 Area = .313780E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.547290E+01
2	.456075E+01
3	.346617E+01
4	.273645E+01
5	.364860E+01
6	.310131E+01
7	.182430E+01
8	.000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .000000E+00 .000000E+00 .000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

groundnut .000000E+00 .000000E+00 .000000E+00

3	.000000E+00
4	.000000E+00
5	.415698E+01
6	.000000E+00
7	.000000E+00
8	.000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .000000E+00 .000000E+00 .000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

groundnut .000000E+00 .000000E+00 .000000E+00

Irrigation programme no = 1 Area = .652783E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.872908E+01
2	.379525E+01
3	.000000E+00
4	.000000E+00
5	.417478E+01
6	.000000E+00
7	.000000E+00
8	.000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .000000E+00 .000000E+00 .000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

groundnut .000000E+00 .000000E+00 .000000E+00

ALLOCATION UNIT NUMBER = 23

.300000E+02 .802326E+01 .923094E+05

Soil group number = 1 Soil Group = 004

.300000E+02 .802326E+01 .923094E+05

gram	.000000E+00	.000000E+00	.000000E+00
sorghum	.300000E+02	.802326E+01	.923094E+05

Irrigation programme no = 1 Area = .300000E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.366279E+01
2	.000000E+00

ALLOCATION UNIT NUMBER = 24

.370000E+02 .989535E+01 .113848E+06

Soil group number = 1 Soil Group = 004

.370000E+02 .989535E+01 .113848E+06

gram	.000000E+00	.000000E+00	.000000E+00
sorghum	.370000E+02	.989535E+01	.113848E+06

Irrigation programme no = 1 Area = .370000E+02 ha

Ir.no.	Irr. vol. (ha-m)
1	.451744E+01
2	.000000E+00
3	.236628E+01

ALLOCATION UNIT NUMBER = 25

.000000E+00 .000000E+00 .000000E+00

Soil group number = 1 Soil Group = 004

.000000E+00 .000000E+00 .000000E+00

gram	.000000E+00	.000000E+00	.000000E+00
sorghum	.000000E+00	.000000E+00	.000000E+00

ALLOCATION UNIT NUMBER = 26

.000000E+00 .000000E+00 .000000E+00

Soil group number = 1 Soil Group = 004

.000000E+00 .000000E+00 .000000E+00

gram	.000000E+00	.000000E+00	.000000E+00
sorghum	.000000E+00	.000000E+00	.000000E+00

ALLOCATION UNIT NUMBER = 27

.000000E+00 .000000E+00 .000000E+00

Soil group number = 1 Soil Group = 004

.000000E+00 .000000E+00 .000000E+00

gram	.000000E+00	.000000E+00	.000000E+00
sorghum	.000000E+00	.000000E+00	.000000E+00

3	.191860E+01
4	.000000E+00
5	.244186E+01
6	.000000E+00
7	.000000E+00
8	.000000E+00

onion	.000000E+00	.000000E+00	.000000E+00
wheat	.000000E+00	.000000E+00	.000000E+00
sunflower	.000000E+00	.000000E+00	.000000E+00
groundnut	.000000E+00	.000000E+00	.000000E+00

4	.000000E+00
5	.301163E+01
6	.000000E+00
7	.000000E+00
8	.000000E+00

onion	.000000E+00	.000000E+00	.000000E+00
wheat	.000000E+00	.000000E+00	.000000E+00
sunflower	.000000E+00	.000000E+00	.000000E+00
groundnut	.000000E+00	.000000E+00	.000000E+00

onion	.000000E+00	.000000E+00	.000000E+00
wheat	.000000E+00	.000000E+00	.000000E+00
sunflower	.000000E+00	.000000E+00	.000000E+00
groundnut	.000000E+00	.000000E+00	.000000E+00

onion	.000000E+00	.000000E+00	.000000E+00
wheat	.000000E+00	.000000E+00	.000000E+00
sunflower	.000000E+00	.000000E+00	.000000E+00
groundnut	.000000E+00	.000000E+00	.000000E+00

onion	.000000E+00	.000000E+00	.000000E+00
wheat	.000000E+00	.000000E+00	.000000E+00
sunflower	.000000E+00	.000000E+00	.000000E+00
groundnut	.000000E+00	.000000E+00	.000000E+00

ALLOCATION UNIT NUMBER = 28
.000000E+00 .000000E+00 .000000E+00

Soil group number = 1 Soil Group = 004
.000000E+00 .000000E+00 .000000E+00

gram .000000E+00 .000000E+00 .000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .000000E+00 .000000E+00 .000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

groundnut .000000E+00 .000000E+00 .000000E+00

ALLOCATION UNIT NUMBER = 29
.000000E+00 .000000E+00 .000000E+00

Soil group number = 1 Soil Group = 004
.000000E+00 .000000E+00 .000000E+00

gram .000000E+00 .000000E+00 .000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .000000E+00 .000000E+00 .000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

groundnut .000000E+00 .000000E+00 .000000E+00

ALLOCATION UNIT NUMBER = 30
.000000E+00 .000000E+00 .000000E+00

Soil group number = 1 Soil Group = 004
.000000E+00 .000000E+00 .000000E+00

gram .000000E+00 .000000E+00 .000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .000000E+00 .000000E+00 .000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

groundnut .000000E+00 .000000E+00 .000000E+00

ALLOCATION UNIT NUMBER = 31
.000000E+00 .000000E+00 .000000E+00

Soil group number = 1 Soil Group = 004
.000000E+00 .000000E+00 .000000E+00

gram .000000E+00 .000000E+00 .000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .000000E+00 .000000E+00 .000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

groundnut .000000E+00 .000000E+00 .000000E+00

ALLOCATION UNIT NUMBER = 32
.000000E+00 .000000E+00 .000000E+00

Soil group number = 1 Soil Group = 004
.000000E+00 .000000E+00 .000000E+00

gram .000000E+00 .000000E+00 .000000E+00

sorghum .000000E+00 .000000E+00 .000000E+00

onion .000000E+00 .000000E+00 .000000E+00

wheat .000000E+00 .000000E+00 .000000E+00

sunflower .000000E+00 .000000E+00 .000000E+00

groundnut .000000E+00 .000000E+00 .000000E+00

SUMMARY OF RESULTS

Case No.	Total area irrigated (ha)	Total water required (ha-m)	Net benefits obtained (unit)
1	.204792E+04	.109282E+04	.153561E+08