Optimization of Tank Irrigation Systems in Watersheds of Semi Arid and Sub Humid Tropics

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Abstract

Watershed development and management has been adopted as a new approach for land and water resources management in India. Water resources are created (in the form of small tanks) in these watersheds along with other development activities. These tanks are primarily used for irrigation or groundwater recharge or for both purposes. Since gaps were found in the literature on the optimum design of watershed based tank irrigation systems this research was carried out with the aim to "Design an optimum tank irrigation system for the watershed".

The philosophy of watershed management and the nature of tank system in the watershed required a new approach for their optimum design. Therefore a comprehensive methodology has been developed in this research for design of optimum tank system in the watersheds of semi arid and sub humid tropics. A new classification of tank system is proposed. The concept of tank strategy is introduced and used in the methodology of optimum tank system design. The methodology takes into account the effect of *in situ* rainwater harvesting practices on the tank system, inflow coming to the watershed from upstream watersheds and downstream release from the candidate watershed. The methodology is based on the concept of Integrated Water Storage System (IWSS) in which three storage media in the watershed i.e. soil, tank and aquifer are integrated to derive the optimum tank system. Field, tank and aquifer water balances are simulated for deriving optimum tank system. The methodology has been converted into computer code which resulted into a computer model –SOFTANK (**S**imulation **O**ptimization **F**or **TANK**s).

The SOFTANK model was applied to two case study watersheds - Akola and Pimpalgaon Ujjaini. Both these watersheds come under semiarid region of Maharashtra state of India. When optimum tank strategies were derived for these watersheds, it was found that tank system was not economical for Akola watershed whereas it was economical for Pimpalgaon Ujjaini watershed. Accordingly the optimum tank system for the Pimpalgaon Ujjaini watershed was derived.

This research is expected to make an innovative and practical contribution to the literature on the design of optimum tank systems for watersheds in semiarid and sub humid tropics.

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List of Abbreviations

AMC	Antecedent moisture condition
BC	Benefit cost
CAPART	Council for Advancement of People's Action and Rural Technology
CCR	Catchment command ratio
CCT	Continuous contour trench(es)
CN	Curve number
CSC	Catchment-storage-command
CSR	Catchment storage ratio
CVB	Contour vegetative barrier(s)
DANWADEP	Danish Watershed Development Programme
DFID	Department for International Development
DP	Dynamic programming
DPAP	Drought Prone Area Programme
Dr. PDKV	Dr. Panjabrao Deshmukh Krishi Vidyapeeth
DRD	Design runoff depth
DSR	Downstream release
EAS	Employment Assurance Scheme
ENS	Environment News Service
ET	Evapotranspiration
GA	Genetic algorithm
GIS	Geographic Information System
GOM	Government of Maharashtra
GW	Groundwater
HP	Horsepower
ICRISAT	International Crop Research Institute for Semi Arid Tropics
IGWDP	Indo-German Watershed Development Programme
IRR	Internal rate of return
IWDP	Integrated Wasteland Development Programme
IWSS	Integrated Water Storage System
KAWAD	Karnataka Watershed Development Project
LP	Linear programming
MAD	Management allowed deficit
MOA	Ministry of Agriculture
MPKV	Mahatma Phule Krishi Vidyapeeth

NGO	Non governmental organisation
NLP	Nonlinear programming
NWDPRA	National Watershed Development Programme for Rainfed Areas
OFR	On farm reservoir
PBP	Pay back period
PU	Pimpalgaon Ujjaini
RBP	River Basin Projects
RL	Reduced level
RMSE	Root mean square error
RWH	Rainwater harvesting
SCS	Soil Conservation Service
S/E	Storage/Excavation
SI	Supplemental irrigation
SOFTANK	Simulation optimization for tanks
SSI	Small scale irrigation
SWC	Soil and water conservation
SWRRB	Simulator for Water Resources in Rural Basins
UNEP	United Nations Environment Programme
USDA	United States Department of Agriculture
USR	Upstream receipt
WGDP	Western Ghat Development Programme
WHI	Water harvesting irrigation
WHP	Water harvesting potential

List of Symbols

cm	Centimetre
cm/h	Centimetre per hour
gm	Gram
ha	Hectare
ha-m	Hectare-metre
km	Kilometre
L	Lagrange function
m	Metre
mm	Millimetre
mm/day	Millimetre per day
m^2	metre square
m^3	Metre cube
M	Million
Mha	Million hectare
q	Quintal
q/ha	Quintal per hectare
r^2	Regression coefficient
Rs	Indian National Rupees
t	Tonne

Chapter-1

INTRODUCTION

1.1 Summary

This chapter introduces the research thesis by discussing the background of the research; presenting research gaps and lack of knowledge in the area of research; and the need and main aim of the research; and finally defines the research problem with the proposed hypotheses and objectives.

1.2 Preamble

"*Water is fundamental for life and health. The human right to water is indispensable for leading a healthy life in human dignity. It is a pre-requisite to the realization of all other human rights*"- The United Nations Committee on the Economic, Cultural and Social Rights (ENS, 2002).

The above quote highlights the importance of water in human life. Recently the General Assembly of the United Nations proclaimed, in its resolution A/RES/58/217, the period from 2005 to 2015, the International Decade for Action, 'Water for Life', commencing on World Water Day, 22nd March 2005. The Decade will focus on water-related issues, at all levels and on the implementation of programmes and projects, and the furtherance of cooperation at all levels, in order to help to achieve the internationally agreed water-related goals contained in the United Nations Millennium Declaration, and in Agenda 21 and the Johannesburg Plan of Implementation (Water for life 2005). While launching the 'Water for Life' decade on 22nd March 2005, Kofi Annan, Secretary-General of the United Nations said

"*The world's water resources are our lifeline for survival, and for sustainable development in the 21st century. Together, we must manage them better*".

From the above quote and declaration it is clear that water has been given the top priority by the United Nations as many countries are facing acute water related problems. Almost all developing countries face increasing demands for water due to rapid population growth, urbanisation and industrial growth, as well as from increases in irrigation. Much of this demand comes from agriculture. One such country- India is no exception to this. The problems of land and water resources management in India in relation to agriculture are discussed below.

1.3 Problems of land and water resources management for agriculture in India

India is blessed with good water resources but its distribution is uneven in time and space resulting in floods and droughts at the same place at different times of the year or at different places at the same time. Though we cannot control mighty hydrological cycle but certainly we can regulate the hydrological cycle to some extent for our benefits.

India has a land area of 329 Mha. The all India average annual rainfall is 1170 mm, but it varies from 100 mm in western deserts to 11000 mm north-eastern regions, respectively. More than 50% of the rainfall takes place in about 15 days and less than 100 hours altogether in a year (Chaturvedi, 2001). Hence the problems of land and water resources management for agriculture in India arise mostly on account of high temporal and seasonal rainfall variability. Rainfall is highly erratic and often falls as convective storms, with high rainfall intensity and extreme spatial and temporal variability.

The poor distribution of rainfall over time therefore often constitutes a more common cause for crop failure than absolute water scarcity due to low cumulative annual rainfall. Occurrence of dry spells is a common feature of the monsoon rainfall in India. The frequency and length of dry spells may vary in different agro-climatic zones. At Solapur, in the semi-arid belt in Maharashtra state of India, these dry spells may extend from 2 to 13 weeks at a stretch (Patil *et al.*, 1981). The crop failure due to dry spells can be avoided if some form of supplementary irrigation is made available. Hence adapting to dry spells by creating storages is a key to improved water productivity in rainfed agriculture in semi-arid and dry sub-humid regions of the country.

Most of India falls in semi-arid tropics where rainfed areas cover 75% of the total cropped area and account for about 42% of food grain production (Gajri *et al.*, 1982). The semi-arid regions in India are the areas where annual rainfall is less than 1000 mm and are characterised by either tropical dry climate with 2-4.5 humid months or wet dry tropical climate with 4.5 -7 humid months. Water scarcity is therefore considered to be the primary factor limiting crop production in these areas. These regions cover an estimated area of 53% of the 329 Mha geographical area (Virmani *et al.*, 1978). Most of the rivers in this region are dry except during monsoon seasons and the landscape does not offer many sites for building large storage reservoirs. It is estimated that even after achieving the full irrigation potential, nearly 50% of the total cultivated area in India and 70% in Maharashtra state (a major semi-arid state in the country from which the case studies are drawn) will remain rain-dependent (Katyal and Venkateswarlu, 1993; Pathak *et al.*, 1999)

Due to high proportion of cultivated area in the country depending on the rain, rainwater harvesting plays a key role in boosting and sustaining crop production in this rainfed area.

1.4 Rainwater harvesting

As long as mankind has inhabited semi-arid areas and cultivated agricultural crops, it has practised some kind of rainwater harvesting (Evenari *et al.*, 1971). Rainwater harvesting can be practised as *in situ* or *ex situ*. *In situ* rainwater harvesting consists of practices such as ridges and furrows, mulching, contouring, deep ploughing, tied ridging and terracing. Whereas *ex situ* rainwater harvesting consists of collecting rain and runoff from a catchment, storing it in a pond or tank and using it for irrigation to the crops in the command area. The tank thus forms an important and integral component of this *ex situ* rainwater harvesting, the system often called 'tank irrigation' system.

Rainwater harvesting is not a new concept in India. On the contrary, the country has a long and ancient history of rainwater harvesting. Ancient rainwater harvesting systems (in the form of different tank systems) are found in almost all states ranging from Rajasthan in western India with a very low rainfall of 100 mm to the north eastern states with rainfall as high as 11000 mm. An excellent comprehensive review and discussion of rise and fall of ancient and contemporary rainwater harvesting systems in India has been given by Agarwal and Narain (1997).

1.6 Tank irrigation systems

Since tanks join two domains i.e. water harvesting domain and irrigation domain they are referred interchangeably as water harvesting systems or tank irrigation systems. India has a long history of tank irrigation. In the southern states in semiarid tropical India, small irrigation systems have existed since Vedic times. In India as a whole tanks account for over 20% of the total irrigated area (Li and Gowing 2005). These systems take different names from region to region like nadi, nalla bund, check dam etc. (They are described in detail in Chapter 4). But they are commonly called 'tanks' to differentiate them from big irrigation reservoirs. These tanks are created by construction of earthen dams across minor valleys. Although some tanks are new, most have existed for a long time and some for centuries. The tanks are primarily used for supplemental irrigation during the rainy season and full irrigation in the dry season and runoff is the main source of water to these tanks.

1.7 Design of tank irrigation systems

Tank irrigation system must be designed scientifically to get optimum performance in terms of net benefits from the system. Design procedures for big reservoirs can not be used for tank system design due to entirely different set of characteristics of the latter. Some of these characteristics are listed below.

1. These tank systems are location specific catering to the needs of local people with the scale ranging from a single farmer to a group of farmers.
2. The source of water is the flash floods during the rainy season.
3. The water is stored during the wet spells and immediately used during the following dry spells. Hence annual volume of irrigation is more than its one time storage capacity.
4. They are suitable for irrigating rainy season and post rainy season crops only.

Design of tank system involves determination of location, storage capacity and dimensions of the tank. In the stand alone systems, location is often decided with the knowledge of the site and convenience to the beneficiaries. Dimensions can be optimised once the storage capacity of tank is known with the help of site information. Hence storage capacity remains an important parameter in the design of a tank system. At present, they are determined based on local experience of the users. Analytically, Palmer *et al.* (1982 a) showed that tank capacity can be determined by matching the supply of and demand for water for a given crop situation. Tank capacity is increased or decreased till the supply and demand are met. This is done through a simulation modelling of the cropped area water balance and tank water balance. This approach for tank design was later followed by Panigrahi and Panda (2003) and Srivastava (1996 and 2001) for Indian conditions.

These tank systems were constructed as stand alone systems catering to the needs of local people. The issues of integration of different rainwater harvesting systems, resource conservation, upstream downstream conflicts etc. did not appear prominently in these systems. However later these issues became important. The solution to these issues was felt to be possible through the concept of watershed for the land and water resources management in the country.

1.5 Watershed development and management- a new approach for rainwater harvesting in India

A watershed is an area from which all water drains to a common point, making it an attractive unit for technical efforts to harness scarce water resources and conserve soil for agricultural production and natural resource conservation. Watershed management is seen as a way to raise rainfed agriculture production, conserve natural resources, and reduce poverty in the region. Watershed development and management implies an integration of technologies within the natural boundary of a drainage area for optimum development of land, water and plant resources, to meet people's basic needs in a sustained manner.

Indian watershed development programmes started from late 80s to develop semi-arid areas that the Green Revolution bypassed. By the late 90s watershed development became the focal point for rural development in the country, with an annual budget of over $450 million (Kerr, 2002). A wide variety of donors and development agencies have been promoting watershed development, including the central government, several state governments, the World Bank, bilateral assistance programmes with countries like UK, Germany, and Sweden. Government of India has set the guideline that the watershed is the most rational unit for planning and implementation of the programmes dealing with agricultural production. Subsequently, watershed management has become the cornerstone of planning and development of land and water resources in the country (Singh *et al.*, 1999).

The watershed development activity is a long term project and a typical watershed of say 1000 ha may take 3-5 years for development. Main development activities involve planning, designing and implementing different in-situ and ex-situ rainwater harvesting techniques in the watershed. However, according to Vaidyanathan (2001) a great deal of knowledge about the catchment hydrology is required for effective watershed development. Knowledge of contribution of *in situ* RWH systems as an individual practice and as a combination of practices is required. The mix of *in situ* and *ex situ* RWH systems for specific locations should be developed. He further stresses that knowledge on these aspects is far from adequate for a massive decentralised watershed programme adapted to varying local condition.

1.8 Watershed based tank irrigation systems

Due to the advent of watershed approach to the management of land and water resources, tanks are planned as an integral component of the watershed. Tanks are often constructed along with other *in situ* rainwater harvesting (RWH) practices like bunds, trenches, ridges to harvest maximum possible rainfall in the watershed. These *in situ* practices harvest considerable volumes of water, reducing the flow to the tanks; increasing soil water storage and groundwater recharge. Crops in the watershed are provided with irrigation from tank and/or groundwater. In this way the watershed approach of RWH attempts to make use of three water storage media in the watershed for productive water use i.e. soil, tank and aquifer. Due to the different nature of watershed based tank systems from stand-alone tank systems, the existing approaches of design of isolated tank systems (Palmer *et al* 1982, Panigrahi and Panda,2003, Srivastava, 1996)) can not be used and there is a need of new research approach to design such tank systems. Therefore a new research approach is proposed for the design of watershed based tank systems on the concept of "Integrated Water Storage System (IWSS)". Following sections describe the concept of IWSS and the research approach for design of tank systems in the watershed.

1.9 Integrated Water Storage System (IWSS)

The concept of Integrated Water Storage System (IWSS) is proposed in this research for the optimum design of tank system and is explained below.

Water can be stored in the watershed for crop production in three storage media- soil, surface tanks and aquifer. There are different techniques of rainwater harvesting which can be adopted to make use of these three storages. For example in-situ RWH techniques like tillage practices, trenches etc make use of the soil medium to store the harvested rainwater. Part of the rainfall which is in excess of the storage capacity of these practices flows downstream as surface runoff. This runoff is harvested by *ex situ* RWH techniques like irrigation tanks for irrigation to the crops in the watershed. Part of the water harvested by *in situ* RWH practices and *ex situ* RWH practices flows down the soil medium as deep percolation and joins the groundwater table. This groundwater is used for irrigating the crop in the watershed.

Thus three storage media are interlinked in the watershed and changes in one storage medium affects the storage in another medium. For example soils with *in situ* RWH practices harvest more rainwater than soils without such practices. This results in less runoff flowing downstream for tanks. (Chittaranjan *et al.*, 1997, MPKV, 2002). Irrigation requirements of crops (which may have met from the tank) cultivated on such soils are less, thus affecting both the supply and demand parameters of tank. This affects the tank design. Sandy soils allow more water to infiltrate down to the aquifers making less storage available in the soil and surface tanks and more storage available in the aquifers. In this case irrigation from groundwater is more important than tank irrigation. Hence integration of these storages is imperative and is referred to as IWSS in this study.

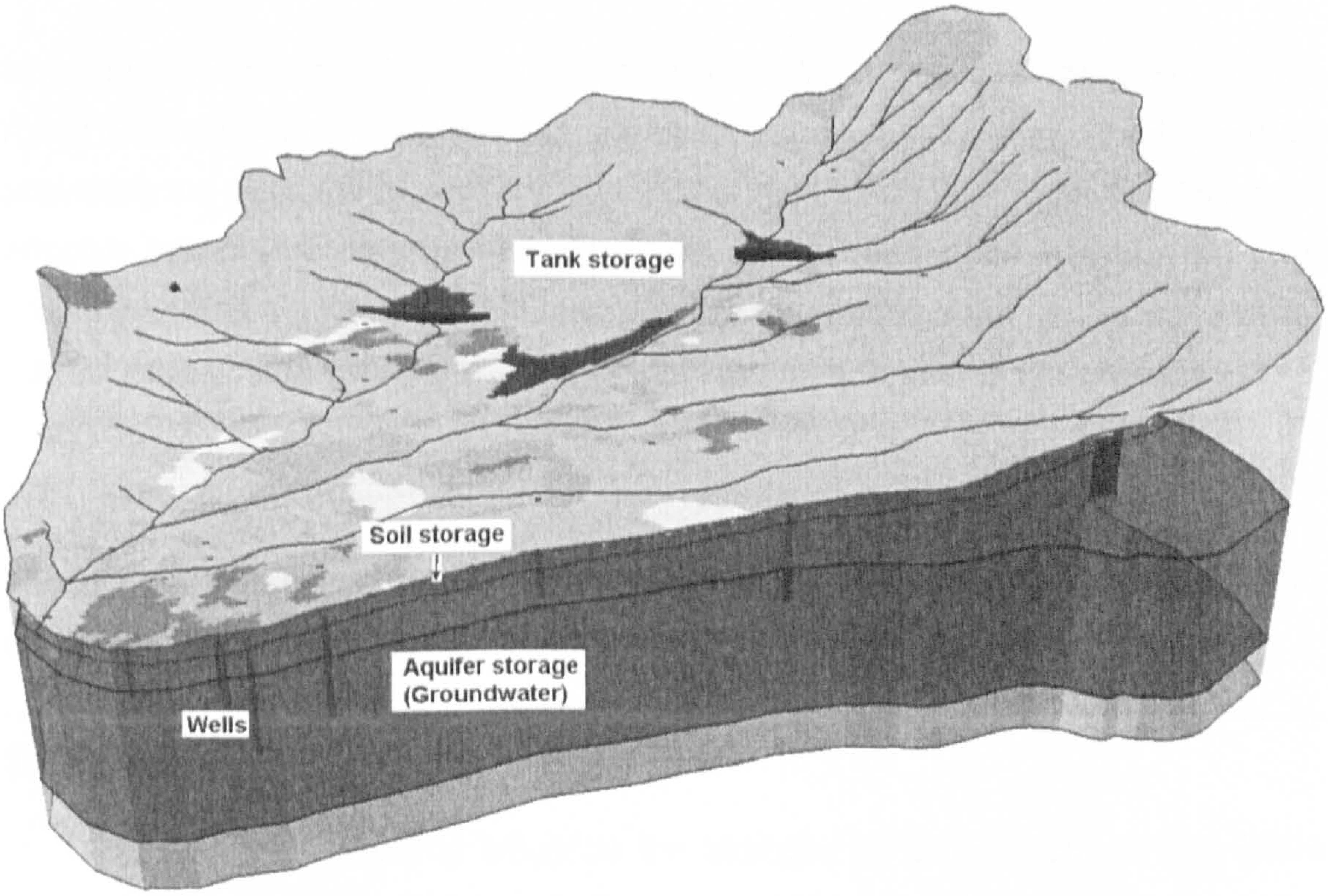


Figure 1.1 Illustration of the concept of IWSS

1.10 Research approach

Watershed based tank systems have some unique characteristics which are not found in the isolated tanks and need to be described. For example a typical watershed may have 1 to 5 numbers of tanks and their locations may vary on the main drainage line. The water from the tank can be used on downstream side or upstream side of the tank, changing the orientation and area of command of tank (This is discussed under 'tank type' in Chapter-4). In the proposed methodology these aspects have been integrated into a term 'tank strategy' (explained in Section

4.3.4). Moreover there is a need for downstream release of water for downstream users and ecological reasons (Sakthivadivel and Scott 2005, Sikka and Paul 2005). Hence the methodology should take into account all these factors when designing a tank system for the watershed.

Previous studies reviewed in Chapter 5 considered a 'tank' as an individual (or isolated) entity and did not consider the influence of different storages on each other while designing the tank system. Hence at present, gaps are found in the literature on the design aspect of tank system for rainwater harvesting and irrigation in watershed.

In a nutshell scientifically sound manipulation of the relationship between rainfall, runoff and recharge offers a vast opportunity for augmenting water availability and for alleviating the wide spatial and temporal vagaries of monsoon precipitation. The most effective option is to harvest rainwater *in situ* and *ex situ* in ponds, tanks etc. from properly developed micro-catchments, thereby conserving water in the soil profile, subsoil aquifers and small farm ponds. This research is based on this concept.

1.11 Aim

The aim of the research is to "Design an optimum tank irrigation system in the watershed for maximum net benefits".

1.12 Hypotheses

1. *In situ* RWH systems influence the storages of downstream *ex situ* RWH systems (tanks) and hence both *in situ* and *ex situ* RWH systems should be considered together in the methodology for optimum design of a tank system in the watershed.
2. Rational design of tank system for the watershed should be obtained by investigating different scenarios that result from the combination of number of tanks, their locations and types (hereinafter called 'tank strategy') as tank strategies affect greatly the outputs from the system (such as water available for consumptive use, crop production, benefits).
3. There is a need for integrating different storage systems (soil, tank and aquifer) while optimizing the use of available water for crop production and thus in turn for the optimum design of tank system.

4. It is possible to design the optimum tank system for the watershed for a desired downstream release of water (from the watershed).
5. The variability in supply and demand parameters influences the optimum design of tank system.

1.13 Objectives

Based on the above hypotheses the objectives of the study are

1. To study the effect of *in situ* RWH system i.e. continuous contour trenches on inflows to tanks and groundwater recharge (output of hypothesis 1)
2. To define tank strategies in terms of number of tanks, their types and locations and develop the methodology for generating these tank strategies (output of hypothesis 2).
3. To develop the methodology for optimally designing the tank system by integrating three storage media - soil, tank and aquifer and by simultaneously considering the downstream release of water (output of hypotheses 3 and 4).
4. To develop the methodology for obtaining a stable tank system for watersheds to account for stochastic nature of water supply and demand parameters (output of hypothesis 5)
5. To test the validity of the developed methodologies for design of tank system for watersheds in different agro-climatic zones of semi-arid tropics (output of hypothesis-3, 4 and 5).

1.14 Organisation of thesis

The thesis is organised in 11 chapters as discussed below.

1. Chapter 1: The chapter presents the background and need of research and introduces the problem of research in the form of hypotheses and objectives.

2. Chapter 2: This chapter reviews the role of *in situ* rainwater harvesting techniques in reducing runoff and presents case studies of adoption of integrated rainwater harvesting systems in watersheds in India.

3. Chapter 3: This chapter presents one *in situ* RWH practice i.e. continuous contour trenches (CCT) popular in India. The modelling approach for CCT is discussed.

4. Chapter 4: This chapter reviews the tank irrigation systems in India. A classification system for tanks is proposed and discussed. Data on some existing tank systems are analysed to study different aspects of tank systems.

5. Chapter 5: This chapter discusses the approaches used in the past for determining the storage capacity of tanks and ponds. It discusses the merits and limitations of these approaches in the context of the proposed methodology for IWSS for the watershed.

6. Chapter 6: The chapter presents the detailed methodology for deciding the optimum tank system for the watershed. It also describes the simulation optimization model - SOFTANK developed by converting the methodology into a computer code.

7. Chapter 7: This chapter discusses two case study watersheds in the semi-arid region of Maharashtra state in India and the results of the model calibration for these two case study watersheds.

8. Chapter 8: This chapter describes the results of evaluation of existing tank systems in the case study watersheds.

9. Chapter 9: This chapter presents the results of simulation of alternate tank strategies for the case study watersheds.

10. Chapter 10: This chapter discusses the results of optimization of tank systems for the case study watersheds.

11. Chapter 11: This chapter presents the conclusions and findings of the research work along with suggestions for future work.

12. Appendix: Appendices contain the case study data used in the analysis and some sample calculations.

Chapter-2

IN-SITU RAINWATER HARVESTING SYSTEMS IN INDIA

2.1 Summary

This chapter discusses different in-situ rainwater harvesting (RWH) systems, which make use of soil profile for storing harvested rainwater. The chapter also discusses the watershed approach for rainwater harvesting adopted in India since 80s, where different in-situ and ex-situ RWH systems are integrated to derive maximum RWH benefits. The popularity of the approach is shown with the help of some case studies on integrated RWH systems in the watershed.

2.2 Introduction

Rainwater harvesting has been an essential component of the agriculture in the arid and semiarid tropics of the world. A vast range of RWH systems can be found all over the world. Boers and Ben-Asher (1982) have given a review of such RWH systems. All these techniques involve collection of rainwater in some form and its application for successful crop production. The collected rainwater is stored for immediate or later use. The storage medium is soil, a surface structure or aquifer.

The concept of Integrated Water Storage System (IWSS) proposed in this study is explained in the first chapter. According to this concept, different storages (i.e. soil, surface and aquifer) should be integrated while adopting the rainwater harvesting (RWH) systems in the watershed. Different RWH systems are adopted to make use of these storage media. Therefore these systems are discussed under three storage media i.e. soil, surface structure (i.e. tanks in the present study) and aquifer

The first step in RWH is the adoption of *in-situ* RWH systems. Hence this chapter is devoted to review the different *in situ* RWH systems that are commonly adopted in the semiarid and subhumid tropics. The discussions are mainly drawn from reviews of *in situ* RWH practices from India, though some appropriate references from other countries of semiarid tropics are also included in the discussions. (The reference of the country is not given when the references are from India, where as it is mentioned for references from other countries). One special *in-situ* RWH practice i.e. continuous contour trenches which forms an important part of this study is discussed in detail in Chapter 3, whereas *ex-situ* RWH systems (referred to as tank irrigation systems) are discussed in detail in Chapter 4. This Chapter also discusses the watershed approach for rainwater harvesting adopted in India since 80s, where different *in-situ* and *ex-situ* RWH systems are adopted to derive maximum RWH benefits. Some case studies on integrated RWH systems in the watershed are also discussed to emphasize the popularity of these systems.

2.3 Why *In-situ* RWH systems need consideration?

The *in-situ* RWH systems increase the infiltration capacity of the soil, increase the opportunity time for water to infiltrate and reduce surface sealing. All these effects result in the reduction of runoff. This further reduces the runoff available for downstream *ex-situ* RWH (or tank irrigation systems) in the watershed. Following two examples are cited in support of this observation.

Chittaranjan *et al.* (1997) conducted an experiment at Bellary, Karnataka, with three ponds. The catchments of individual ponds were given single treatment of graded bunds, contour bunds or conservation ditches. During four years of study they found that it was possible to give supplementary irrigation to 30% of the catchment area in all the four years with the runoff stored in the pond with the catchment treated with graded bunds. But it was possible to do so in only one year in the case of ponds with the catchments treated with contour bunds and conservation ditches. In another study emphasizing the consideration of the *in-situ* RWH practice for design of *ex-situ* RWH system, Arnold and Stockle (1991) considered the effect of furrow diking in deciding the optimum farm pond size in USA. Furrow diking is a practice of building small temporary dikes across furrows to conserve water for crop production. In the model they considered specified amount of runoff (model input), the dikes are allowed to hold. If the estimated runoff from a storm is less than the furrow-dike storage, no runoff occurs and all precipitation is allowed to infiltrate. If estimated runoff exceeds the furrow-dike storage, the exceedence runs off while an amount equal to the furrow-dike storage is allowed to infiltrate.

The above two examples strengthened the hypothesis (hypothesis-1) that *in-situ* RWH practices store considerable volume of water resulting in less runoff available for downstream tanks/ponds. This assumes importance in the context of IWSS concept. It thus led to the motivation to review the effect of different *in-situ* RWH practices on runoff reduction.

2.4 Definitions

Some specific terms are used during the discussion of review, which need to be defined at the outset.

2.4.1 Drylands

Drylands are defined as terrestrial areas with a ratio of mean annual precipitation to mean annual potential evapotranspiration (aridity index) of less than 0.65 (excluding polar regions and some high mountain areas with a cold climate year-round that meet this criterion but have completely different ecological characteristics from other). Dry lands consist of hyper arid to dry sub-humid areas, the aridity criteria for which are given below (UNEP, 2005).

Climate type	Aridity Index
Hyper arid	less than 0.05
Arid	0.05 to 0.2
Semiarid	0.2 to 0.5
Dry sub-humid	0.5 to 0.65

(Source UNEP, 2005)

2.4.2 Rainfed agriculture

Rainfed agriculture here means the crop production is predominantly dependent on rain for its water needs. There is absence of any irrigation practice for meeting crop water requirements.

2.4.3 *In-situ* rainwater harvesting systems

In-situ RWH system comprises different techniques that harvest and conserve the rainwater where it falls or travels for a small distance. Normally these systems conserve rainfall and/or some form of sheet flow and make use of soil as storage medium. Examples of such systems are deep tillage, ridges and furrows, contour cultivation, bunds, terraces, trenches etc.

2.4.4 *Ex-situ* rainwater harvesting systems

Ex-situ RWH systems are the systems where water is collected from a catchment area, conveyed to a storage facility (usually a tank or pond) and then applied to the crop at a later period. These systems are discussed under the title of tank irrigations systems in Chapter-4.

2.4.5 Tank

This term is used for small reservoirs (to differentiate them from big irrigation reservoirs) that store the rain and runoff water from a catchment. The stored water is used for irrigating the crops in the command area and/or for groundwater recharge. They are characterised by their small scale in size, operation and management. In this study, this will be a broad umbrella term covering all small water harvesting reservoirs like farm ponds, check dams etc. used for irrigation and/or for groundwater recharge.

2.4.6 Watershed

This term needs to be elaborated as it is used in different contexts in different countries. Watershed is a concept for land and water resources development on sustainable basis. It is the geographical area draining to a common point. A watershed may be as small as a flowerbed or a parking lot or as large as a river basin covering hundreds of thousands of square kilometres (Singh, 2002). For planning, development and management purposes, it is often defined on the basis of its size and assumes the names as micro-watershed, mini-watershed, watershed, meso-watershed, river basin etc. The terms like watershed, catchment, and basin are conceptually the same. Watershed is a commonly used term in USA and India whereas catchment is a commonly used term in Europe. Though basin refers to big watershed of river, it is also often used for small plots on the field like 'check basin'. To avoid such confusion, in this study the term watershed (except where it is cited from the references of other scientists) is used to denote an area of around 500 to 2000 ha draining to a common point on the stream. This is the area, which is considered for watershed planning in India. Normally it encompasses a village and such area is found convenient for planning, development in a period of 3-5 years and later its management by the village community.

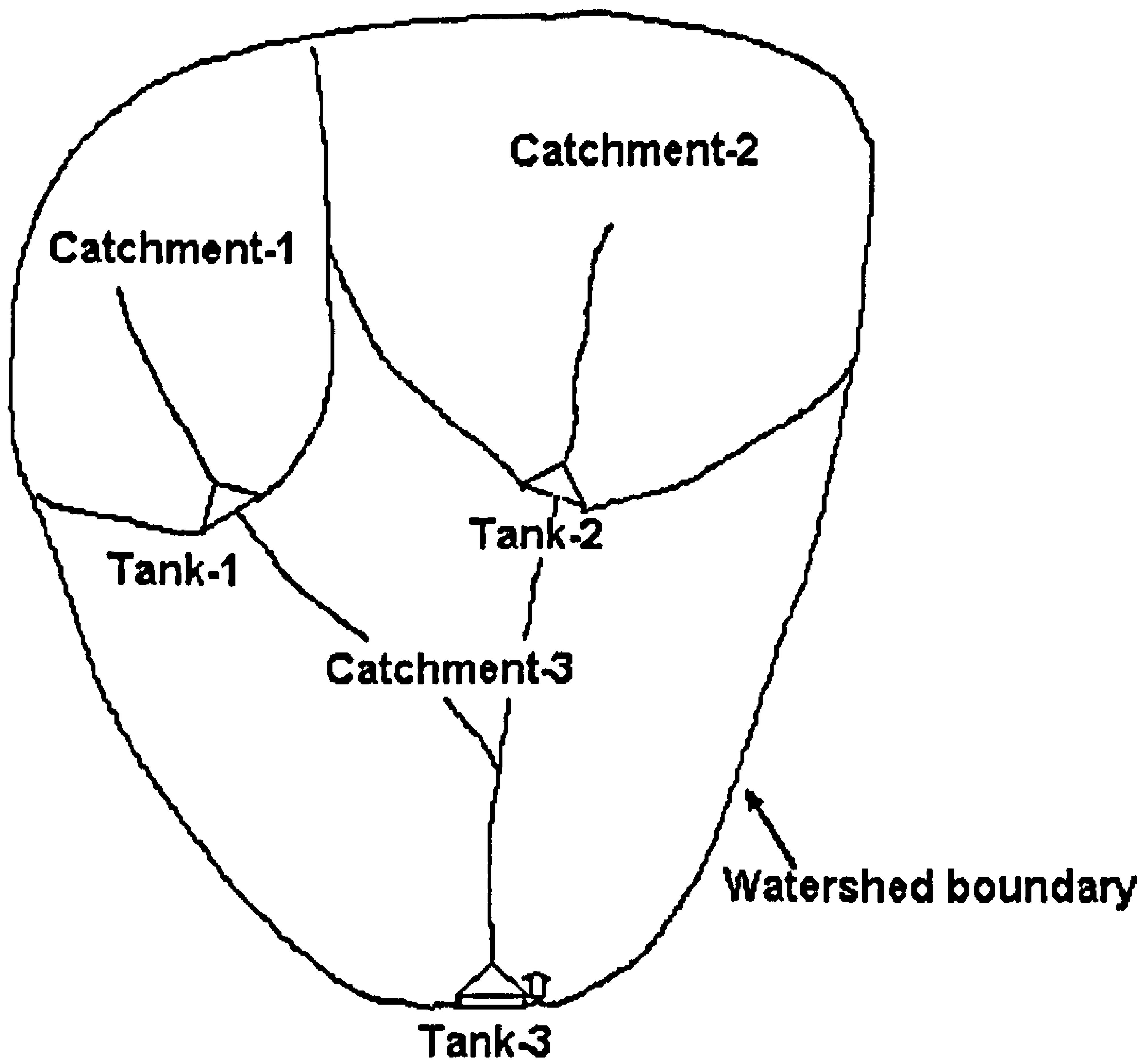


Figure 2.1 Illustration of watershed and catchment

2.4.7 Catchment

In the watershed development programme in India, tanks are constructed in the watershed. In this study the term catchment (again except where it is cited from the references of other scientists) is defined as that part of the watershed, which drains to the tank site in the watershed. Hence there can be number of catchments in a watershed depending on the number of tanks (Fig 2.1).

2.4.8 Command

This is the area in the watershed to which irrigation from tank can be applied for crop production. In addition to water stored in the tank, the source of water may also come from the water stored in groundwater storage, which may be recharged by the tank.

Other specific terms are explained in the thesis at appropriate places.

2.5 Soil storage for rainwater harvesting

When rainfall occurs some part of it is stored in the soil medium. This soil moisture is available in the unsaturated zone (i.e. the zone above the water table). This zone consists of root zone of crops and deeper layers, which support tree growth. The unsaturated zone can retain moisture up to its field capacity, where water is held under capillary tension. Any increase in water content, will gravitate further below and recharges the groundwater.

Different soils have different ability to supply moisture to crops. Some soils have large water holding capacity to supply water required for evapotranspiration of crops between two rainfall events. Whereas some soils have very low water holding capacity and plant stress occurs even during short rainless periods. Annual evapotranspiration will be more and annual runoff less from the soils with large water holding capacity than that from the soils with small water-holding capacity under the same climatic conditions.

There are different soil groups in India and the water holding capacity of these soils differ. For example in the lateritic soil areas of drought prone regions of India, it is estimated that about 60% of annual rainfall would be stored in the unsaturated zone. The 40% balance of rainfall would be in the shape of groundwater and surface water of almost equal proportion (Rao, 1996). About 15-18 Mha of vertisols are fallowed during the monsoon and only a post-monsoon season crop is grown on residual soil moisture in India. The residual soil moisture is determined by the amount of rain stored in the root zone. These soils often store less than 50% of the actual rainfall in the low rainfall areas and as low as 25% in high rainfall zones (Sharma and Helweg, 1982).

Apart from the above percentages, it has to be appreciated that a substantial quantity of rainfall is stored as soil moisture. This component is almost fully consumed during the cycle of a year through transpiration of crops (and trees) and evaporation. Storage in the soil profile is extremely important for crop production, but it is relatively short-term storage, often only sufficient for a period of days. The following sections describe different methods of rainwater harvesting that utilize soil medium to store rainwater.

2.5.1. *In-situ* rainwater harvesting systems

The first step in any rainwater harvesting (RWH) system involves methods to increase the amount of water stored in the soil profile by holding the rain where it falls. *In-situ* RWH is sometimes called 'water conservation' and is basically a prevention of net runoff from a given cropped area by holding rainwater and prolonging the time for infiltration. This system works better where the water holding capacity of soil is large enough and the rainfall is equal or more than the crop water requirements, but moisture amount in the soil is restricted by the amount of infiltration and or deep percolation.

Before discussing the *in-situ* RWH systems, it needs to be clarified here that conservation of soil and water goes hand in hand and many *in-situ* RWH practices discussed below have evolved as soil conservation techniques and hence are more popular as soil conservation techniques. The subtle differences start to begin when the runoff area and the collection area are different as in bunds, terraces and trenches. The concept of RWH involves inducement of runoff from larger area for use on a smaller area and hence treatments are often given to the catchment to increase runoff production. Whereas no such efforts are made in bunds, terraces and trenches since the objective is conservation and not harvesting. On the contrary efforts are made to decrease runoff in the inter-bund space by soil manipulation or land management. But these practices are discussed in literature as both i.e. soil conservation and water harvesting techniques. The reason must be lying in the fact that these practices slow down runoff, reduce soil erosion and store significant quantities of water, which recharges soil profile and groundwater, and hence meet twin objectives of soil conservation and water harvesting.

2.5.1.1 Deep tillage

Deep tillage normally assists in increasing the soil moisture holding capacity through increased porosity, increasing the infiltration rates and reducing the surface runoff by providing surface micro-relief or roughness which helps in temporary storage of rainwater, thus providing more time for infiltration. Dongale (1987) found that tillage enhanced cumulative infiltration and infiltration rate by 28.63 and 95.7 % respectively in medium black soil in Konkan region of Maharashtra. Rao *et al.* (1998) conducted experiments on the effect of tillage systems on infiltration and runoff, at ICRISAT, Hyderabad for six years consecutively. For a six-year period, they found that on a bare plot, cumulative runoff was 1168 mm for zero tillage, 1084 mm for shallow tillage and 929 mm for deep tillage.

2.5.1.2 Contour cultivation

Contour cultivation involves carrying out crop cultivation practices along the contours. The system is practically more feasible for less undulating lands. All farm husbandry practices are done along contours so as to form cross-slope barrier to the flow of water (Fig 2.2-a, b). Where this is not enough, it is complemented with ridges, which are sometimes tied (referred to as tied ridges as shown in Fig 2.2(c) to create a high degree of surface roughness to enhance the infiltration of water into the soil. At Rahuri, in the semiarid region of Maharashtra, Bangal *et al.* (1990) found that runoff (average of 2 years) was 13 mm from the plot with contour ridges and 21 mm from the control plot. Average soil moisture in the crop season was 32.6% in the plot with tied ridges and 23.7% in the control plot. In another experiment, Patil and Bangal (1991) reported that sowing crop across the slope (on a uniformly sloping research plot of 1.5% slope) reduced runoff by 18.7% as compared to sowing down the slope. Kale *et al.* (1994) found that runoff (average of 5 years) was 180 mm in the fallow plot and 112 mm in the strip-cropping plot of pearl millet, red gram and horse gram at Solapur in Maharashtra. Sahoo and Mohanty (1990) reported that at Hyderabad runoff from a ridged plot was 77 mm as against 141 mm in control plot. Singh *et al.* (1993) reviewed the research on different tillage systems and their role in soil and water conservation in south Asia. Tillage showed a marked influence on soil hydraulic characteristics. They emphasized the importance of conservation tillage in reducing runoff, soil loss and in ensuring sustainable agricultural production in the region. They also discussed the role of other tillage practices, like contour cultivation, contour bunding, terracing and tied ridging, in increasing the profile water storage.

2.5.1.3 Mulching

Mulch is a natural or artificial layer of plant residue or other materials on the surface of soil with an objective to reduce the loss of moisture, runoff and soil erosion, weed infestation and control the fluctuation of soil temperature and improve physical and chemical properties of soil. Common plant residues like wheat straw, sugarcane trash, paddy husk and dry leaves are often used as mulch in the dryland agriculture (Fig 2.2-d). As reported in Gupta and Sachan (1990), Rockwood and Lal (1974) observed runoff losses of 6.9, 4.9, 4.4 and 6 times higher in ploughed plots as compared to mulch plots of maize having slopes 1, 6, 10 and 15% respectively. Li (2003) studied the effect of gravel mulch on runoff and soil loss in China. There were 18 runoff producing storms from 91 rainfall events, producing total of 48.4 mm runoff from the bare plots while only 6 events produced 3.4 mm runoff from the gravel-sand mulched plots. Bhatt and Khera (2005) found that mean runoff was highest (50%) in no mulch plot while it was only 17% in the plot covered with rice straw mulch in Punjab.

2.5.1.4 Bunding

Bunding (or terracing) and trenching (discussed below) are the practices, which involve much earthwork. They are looked upon as second line of defence after the above-discussed *in-situ* RWH practices. They involve careful design, the parameters of design being mainly cross section and spacing between the two bunds or trenches. Two popular systems in India are contour and graded bunding. In these systems, a small earthen embankment is constructed along the contour lines for contour bunds (Fig 2.2-e) where as some grade is given for safe disposal of excess runoff in graded bunds. Embankments trap the water flow behind the bunds allowing deeper infiltration into the soil. The water is stored in the soil profile and above the ground to the elevation of the bund. Contour bunding in cultivated lands intercepts the runoff, reduces soil loss and provides increased opportunity time for water intake.

In the high rainfall outer Himalyan region of Palampur, terracing and bunding reduced runoff in an agricultural watershed of 26 ha from 65 to about 30-35% (Kumar, 1992 as reported in Sharda and Shrimali, 1994). On average, contour bunds had 27% higher soil moisture and 14 to 181 % higher fodder yield than flat surfaces on grasslands of western Rajasthan (Wasi-Ullah *et al.*, 1972). Graded bunding is recommended for areas having higher rainfall (>700 mm) for safe runoff disposal (Singh 1990). Sahoo and Mohanty (1990) reported 40.3 mm runoff from a graded bunded plot compared to 51.8 mm in cultivated fallow plot at Dehradun. Chittaranjan *et al.*, (1997) studied different soil and water conservation measures in vertisols of semiarid region on a small research watershed of 10 ha at Bellary in Karnataka. For seasonal rainfall of 497 mm they found 39 mm runoff in graded bunded plot, 10 mm in contour bunded plot, 34 mm in conservation ditch plot and 48 mm in control plot.

2.5.1.5 Trenches

These are excavations in the soils with typical cross section of 0.6 m width x 0.3 m depth and running across the full width of the field. These trenches are used both on hill slopes as well as on degraded and barren wastelands for soil and moisture conservation and afforestation purposes. The trenches break the slope and reduce the velocity of surface runoff. They are adopted on all slopes irrespective of rainfall conditions (i.e. in both high and low rainfall conditions), varying soil types and depths. Trenches can be continuous or interrupted. The interrupted trenches are in series or staggered (Fig 2.2-f). They are adopted in high rainfall areas. Continuous trenches are used for moisture conservation in low rainfall areas and require careful layout. (Fig 2.2-g). The trenches are to be constructed strictly on contours irrespective of the category. The size of the trench depends upon the soil depth. Studies have shown that it is possible to harvest 60-80 per cent rainfall with the continuous contour trenches (Deoulgaonkar 2004). Since continuous contour trenches (CCT) form an important part of the present study, they are discussed separately in Chapter-3.

2.5.1.6 Vegetative barriers

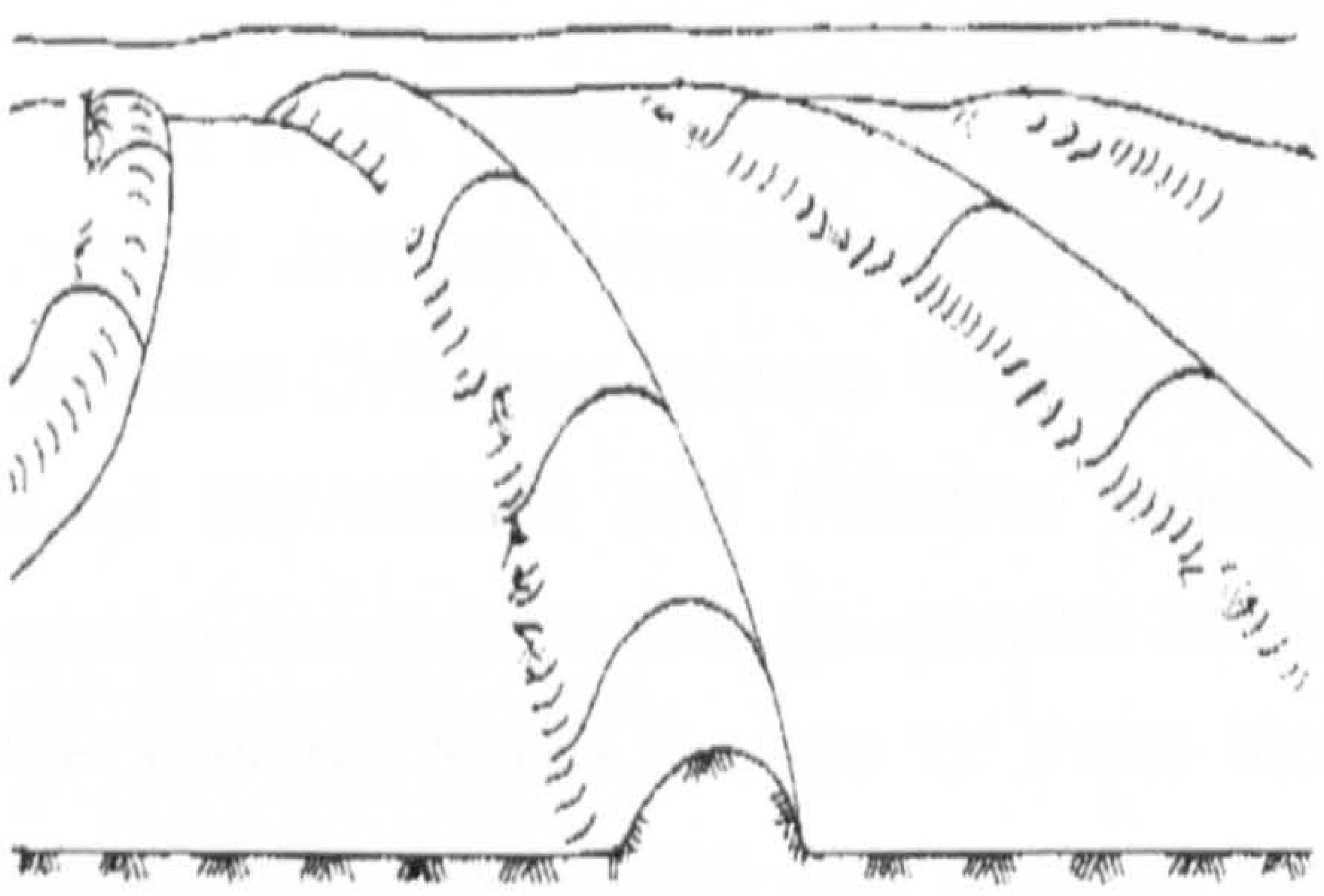
Vegetative barriers when taken on contour are called contour vegetative barriers (CVB). They are also called vegetative bunds since small soil bund is formed with the vegetative barrier due to erosion from the inter-barrier space. Perennial grasses or shrubs are planted at a regular interval on contours for conserving soil and water in sloping rainfed crop-fields (Fig 2.2-h). Generally, locally adopted, native, fast growing perennial grasses with extensive root system that form a dense hedge when planted in rows, are preferred. These vegetative barriers spread surface flow laterally, thus reducing the depth and velocity of flow. More water gets infiltrated into the soil and less runoff available past the vegetative barriers. Sharma *et al.* (1999) found that runoff volume and specific peak discharge were reduced by 28 to 97% and 22 to 96% respectively using CVB in Rajasthan, In an experiment with vegetative bunded fields at Kolhapur in sub humid region of Maharashtra, it was found that runoff was reduced by 65.60% (77.41 mm) in vegetative bunded field over the non bunded field (224.97 mm) (MPKV, 1999).

(a) Contour cultivation (*Maharashtra 2005*)

(b) Ridges and furrows (*Maharashtra 2005*)

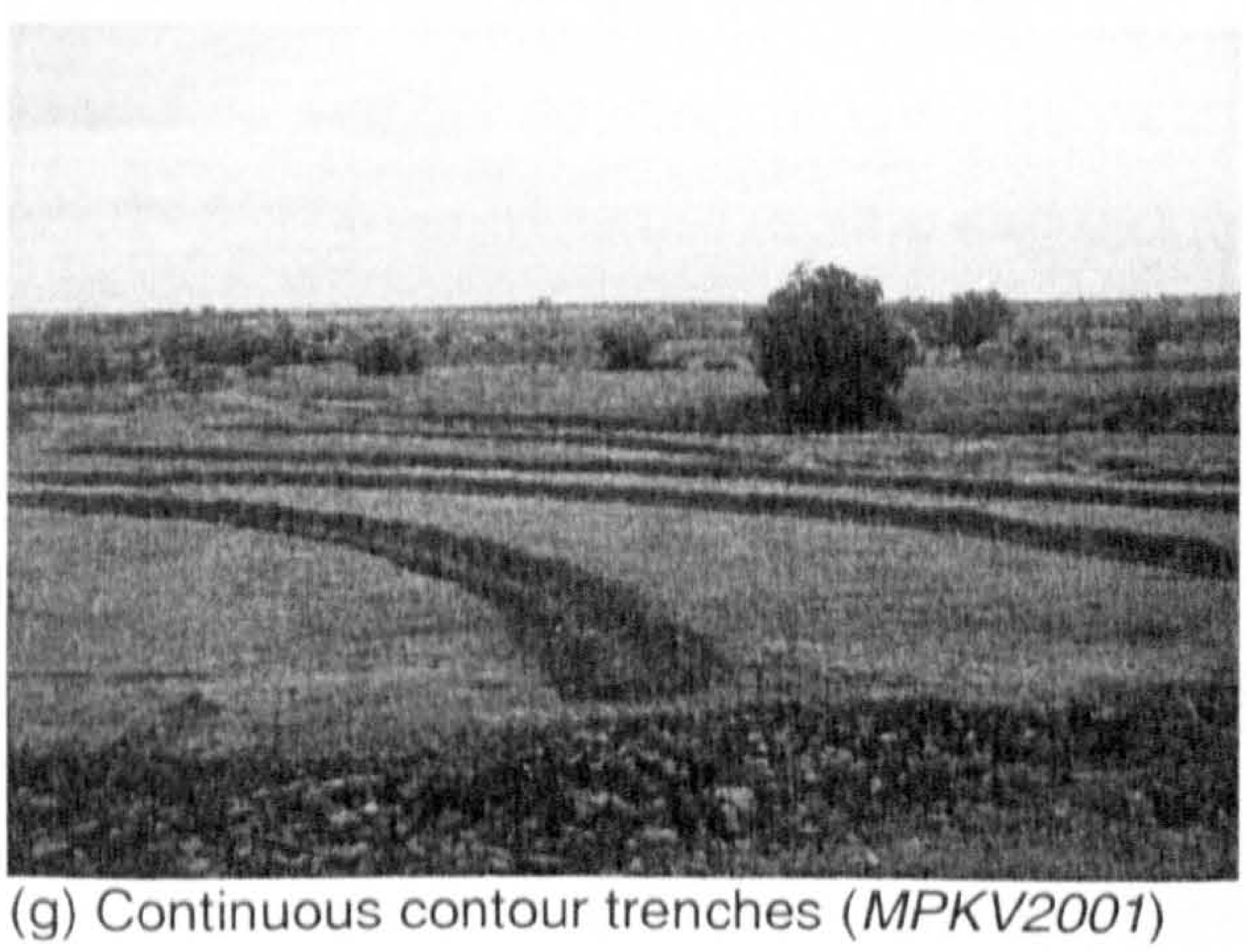
(c) Tied ridges (*FAO 2005*)

(d) Mulching (*WERU 2005*)

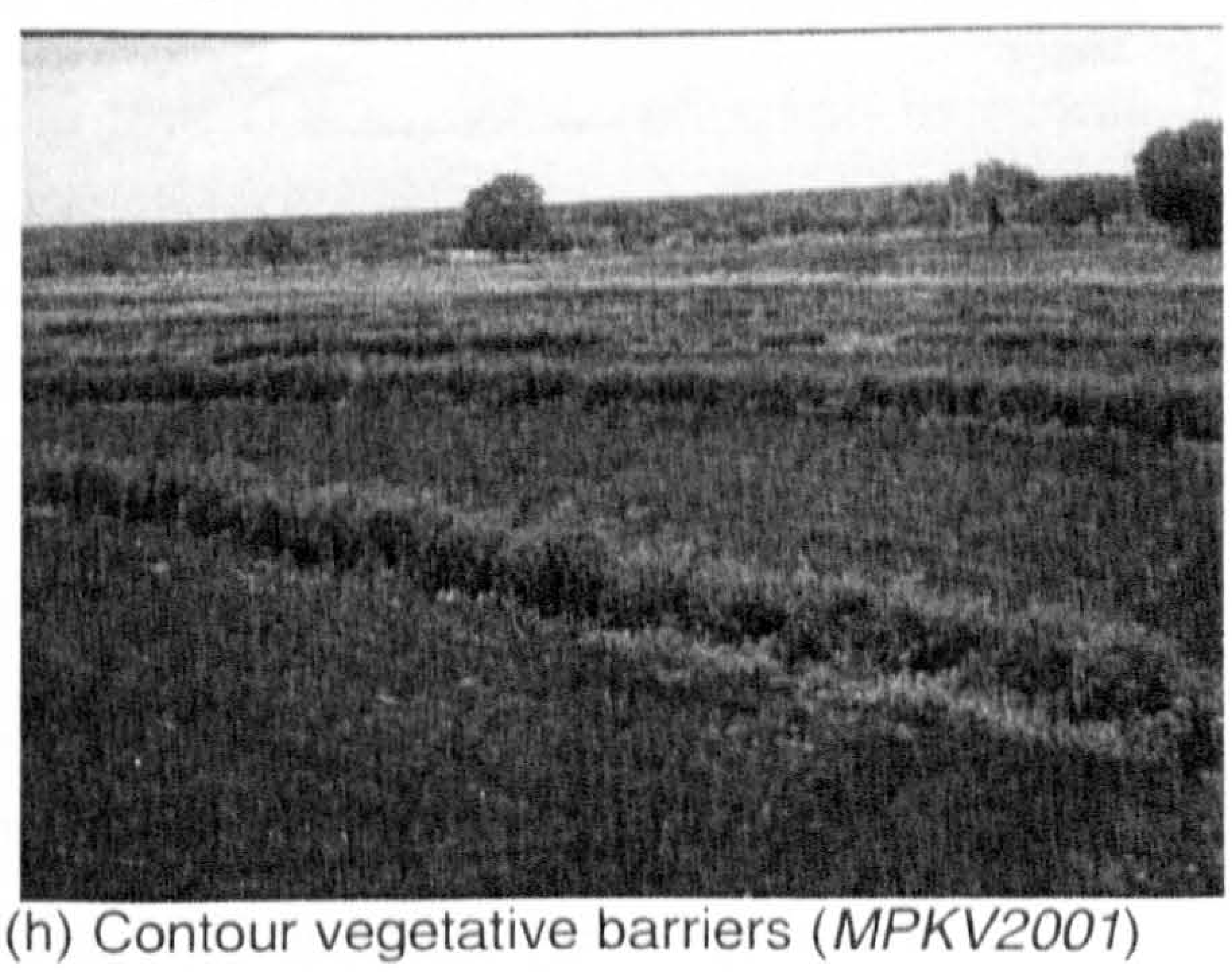


(e) Contour bunds (*Critchley and Siegert 1991*)

(f) Staggered trenches (*Maharashtra 2005*)



(g) Continuous contour trenches (*MPKV2001*)



(h) Contour vegetative barriers (*MPKV2001*)

Figure 2.2 *In-situ* rainwater harvesting systems

2.5.2 Modeling *in-situ* rainwater harvesting systems

Due to the motivation of including *in situ* RWH systems in my modelling approach of tank system design, literature was searched on the modelling aspects of these practices. But the literature obtained has been limited to that discussed in the preceding paragraphs. Most of the research results on *in-situ* RWH systems reported the effect of these systems in terms of some visible indicators like increase in soil moisture and crop yield; decrease in runoff and soil loss etc. Detail water balance of these systems is not reported. The research is highly location specific and results are assumed to be valid for the region. Though it is not possible to conduct field experiments for each location due to time and money constraints, modelling can be used for extrapolating the results spatially and temporarily. As stated in Chapter 1, Vaidyanathan (2001) also expressed concern about the lack of technical knowledge on the interrelationship among different techniques of conservation. Hence studies on the modelling of these RWH systems are important. One study on the design of vegetative barriers conducted in Rajasthan was found and is described below.

Sharma *et al.* (1999) derived the optimum spacing of contour vegetative barriers (CVB) at Jodhpur. Hydrologic processes with respect to crop response for digitally generated CVB layouts were simulated using the distributed numerical rainfall-runoff model SWAMREG and moisture storage- crop yield model SWACROP and a personal computer based geographic information system (GIS) for designing optimum CVB spacing. Inputs needed for these models were soil hydraulic parameters, daily meteorological data, and crop characteristics. Simulated outputs were validated with the observed runoff, soil moisture storage and pearl millet yield data. At an optimum simulated vertical spacing of CVB between 0.5 and 0.6 m, 24% reduction in runoff resulted in better moisture regime and crop yield improvement by 70% over control.

2.5.3 Conclusion

Different *in-situ* RWH systems discussed above harvest rainfall and runoff to varying degrees depending upon rainfall, soil, vegetation and topographic characteristics. The findings of different studies are summarised in Table 2.1 (at the end of the Chapter). The decrease in runoff (over control) ranged from 20 to 80% by adoption of *in situ* RWH practices. Normally these practices are more effective in normal to dry years and with low to average intensity storms. In wet years or heavy storms, these systems get saturated immediately and excess runoff flows downstream. However when integrated in the watershed, the knowledge of runoff harvested by these systems and their contribution to the groundwater table is necessary to design the storage capacities of downstream structures (irrigation tanks) with the concept of integrated water storage system. The methodology developed for the design of tanks in this study considers the influence of these systems on infiltration volume and runoff that eventually influences the amount of water stored in tanks.

The studies conducted in the past on *in-situ* RWH systems were mostly based on field experiments and hence are location specific. This was due to the fact that their focus was to investigate and demonstrate the soil and water conservation techniques to the policy makers and farmers. However it is necessary to mathematically model these systems to study their influence on the tank systems and make their findings transferable or applicable to other areas/regions. The literature indicates that the researchers have just begun to realise their importance in RWH. This study therefore attempts to model one popular *in-situ* RWH system i.e. CCT in the state of Maharashtra. The study further advances to analyse the influence of CCTs on design of tank systems. The detailed modelling procedure for CCT is explained in Chapter 3.

2.6 Integration of storages

Each of the three water storage systems i.e. soil, surface tanks and aquifers has comparative advantages and drawbacks under specific conditions. Storing water in the soil is the cheapest method but it is only available for few days or for duration of crop growth. Tanks can store substantial volume of water but they are faced with excess evaporation and seepage losses. Groundwater is not subjected to evaporation but aquifers should have sufficient capacity to store required water and at the same time there are cost implications associated with lifting of water. However, combining technologies of *in-situ* RWH, small tanks, and groundwater storage can achieve substantial gains in an integrated manner. A number of combinations already exist and work satisfactorily (Keller, 2000). Through integrated watershed development program carried out in India integration of these storages is considered. The results are very encouraging in terms of runoff reduction and groundwater recharge. Following paragraphs discuss the watershed approach for resource conservation adopted in India. This is followed by the description of case studies of integrated watershed development in India.

2.7 Watershed approach to rainwater harvesting

Water and watershed are difficult to separate for management purposes (Scott and Silva-Ochoa, 2001). Watershed development and management involves integration of technologies within the natural boundary of a drainage area for optimum development of land, water and plant resources to meet people's basic needs in a sustainable manner. Each watershed is an independent hydrological unit. It has become an acceptable unit of planning for optimum use and conservation of soil and water resources. The development efforts focus on conserving soil moisture for rainfed agriculture, recharging aquifers to augment groundwater irrigation, and capturing surface runoff water in small ponds. Water harvesting systems are combined with conservation systems for sustainable development since productivity and conservation objectives are highly complementary. The soil and water conservation management and water-harvesting programmes are implemented in an integrated manner on a watershed basis as shown in Fig 2.3.

2.7.1 Watershed development in India

A watershed development project in India is an ongoing process due to ever increasing demand for water in different sectors. Indian watershed projects spread widely in the late 80s and 90s in an effort to develop semi-arid areas that the Green Revolution had bypassed (Kerr, 2002). The country has made significant investments in watershed development projects during the decade from 1996-97 to 2006-07. The investment was. to the tune of US$ 2.9 billion in 1996-2001(9^{th} five year plan) and US$ 3.7 billion in 2002-07(10^{th} five year plan)periods (Sakthivadivel and Scott, 2005). Watershed development programmes range from state and centrally sponsored to internationally sponsored like the DFID funded Karnataka Watershed Development (KAWAD) project, Indo-German Watershed Development Programmes (IGWDP) and Danish watershed development programme (DANWADEP).

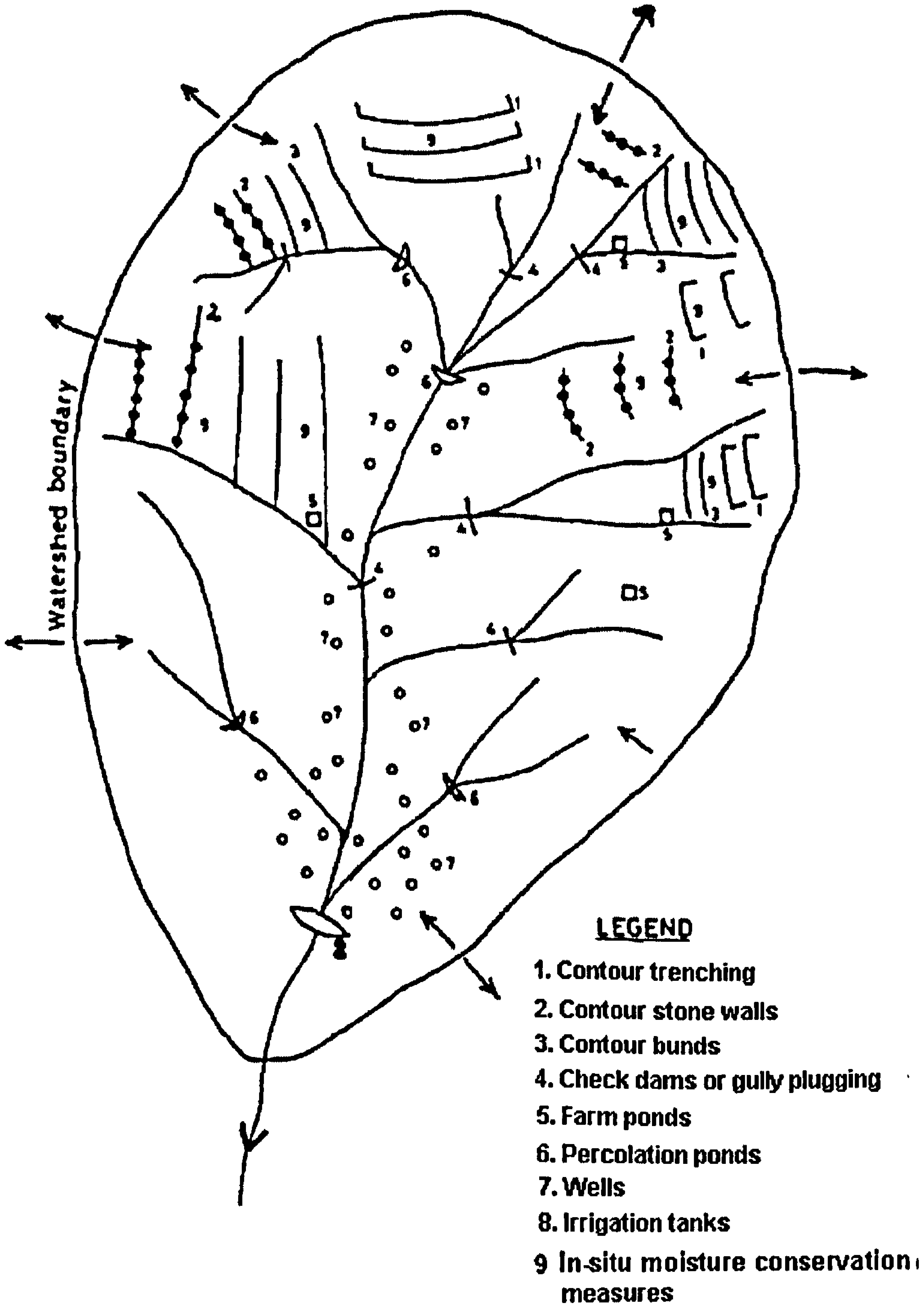


Figure 2.3 Soil and water conservation works in the watershed

(*Source: Sivanappan, 1995*)

2.7.2 Watershed development projects in Maharashtra

Maharashtra is the third largest state in the country with 30.8 Mha geographical area. The entire state broadly falls under tropical monsoon climate. Most of the area of the state comes under semiarid tropics. It is a pioneering state for watershed development in India. Many success stories like the watershed projects of Ralegan Siddhi and Hiware Bajar paved the way for watershed development programmes not only in the state but other parts of the country. The status of watershed development projects under different programmes in the state of Maharashtra as on 2002 is given in Table 2.2.

Table 2.2 Status of watersheds development projects under different programs in Maharashtra state *(Source: GOM, 2002)*

Schemes	No of watersheds	No of watersheds developed	No of watersheds to be developed
IWDP*	22302	7048	15254
NWDPRA	917	646	271
WGDP	97	43	54
RBP	114	59	55
DPAP	856	132	724
Adarsh Gaon	645	100	545
EAS 50%	1582	189	1393
CAPART	78	0	78
IGWDP	116	41	75
Total	26707	8258	18449

*(*IWDP= Integrated Wasteland Development Programme, NWDPRA= National Watershed Development Programme for Rainfed Areas, WGDP= Western Ghat Development Programme, RBP= River basin projects, DPAP= Drought Prone Area Programme, EAS= Employment Assurance Scheme, CAPART= Council for Advancement of People's Action and Rural Technology, IGWDP= Indo-German Watershed Development Programme)*

In western Maharashtra, the scarcity of water and favourable topography make water harvesting a high priority and focus of most projects. In these areas there are many opportunities to capture water behind small dams on the slopes for irrigation in the flat lands below. Soils in these areas are more porous and favour percolation of harvested water into groundwater aquifers. The structures include mainly check dams on drainage lines and continuous contour trenches in the uncultivated catchment areas. Since almost all the structures are built on non-arable lands with common access by all village inhabitants, the projects also promote collective action to protect vegetation in the catchment area. This reduces erosion and limits the silting that would reduce the storage capacity of water harvesting structures.

2.7.3 Effect of Integrated watershed development on water resources

Following paragraphs describe some important studies on integrated watershed development from different regions of India. Their detail description was found necessary to understand the range of practices adopted in these watersheds. In these studies the effect of watershed development was studied by observing the visual effect in terms of reduction in runoff, increase in groundwater recharge, number of wells in the watershed, and increase in cropped area over the predevelopment period. The studies were conducted over a period of 5 to 10 years. These studies are also summarised in a nutshell in Table 2.3 (at the end of the Chapter).

Maheshwari (1990) reported the study on watershed development at Tejpura watershed (Jhansi in Uttar Pradesh). This watershed was developed with integrated watershed development approach. Average annual rainfall at the watershed is 931 mm. Watershed development started in November 1983 and was completed in December 1985. Area of the watershed was 775.7 ha. The watershed was treated with contour bunding on 23.38 ha, field bunding on 558.94 ha. About 70 masonry drainage structures were constructed for field-to-field excess water disposal. A storm water diversion drain at the foothills measuring 1657 m in length was constructed. An area of 64.38 ha benefited with gully plugging and an area of 4.6 ha provided with land levelling. Four check dams were constructed across the seasonal nala of 6.5 km in length. The total water storage in the watershed was estimated to be 30 ha-m with 12 ha-m in 4 check dams, 4 ha-m in gully plugs and 14 ha-m in 2 water harvesting bundhis. This all helped in increasing the irrigated area from 20.2 ha to 510 ha during a period of six years. The underground water levels in wells increased by 3 to 7 meters, number of dug wells increased from 5 to 47 and average pumping of groundwater increased from 1-2 hour to 8-10 hours per day. Crop yields increased by 2.2 to 7.33 times. The crop productivity increased from 6 q/ha to 19.6 q/ha. The availability of water in check dams was found for 9 to 10 months. Cropping intensity increased from 83 to 185%

A case study of Gunj watershed in Akola district of Maharashtra was reported by Urade and Sagare (1993). Area of the watershed was 507.90 ha with an average slope of 1.58%. The watershed was treated with different soil and water conservation measures like graded bunding on 445.70 ha, stream bank training (1200 m), one farm pond with storage capacity of 960 m3, *vetivera* plantation on contours at vertical interval of 0.5 m on an area of 72.50 ha. Observations from 20 wells in the watershed revealed that the increase in the water table depth was 13.87% within the 5 years period from 1985-86 to 1989-90.

Gaur *et al.* (1995) reported the study of two watersheds with areas 1381 and 500 ha in Bundelkhand region. They found that integrated watershed management helps in the rejuvenation of degraded lands. Various soil and water conservation (SWC) measures like contour trenches, furrows, shallow pits and stone dykes, ponds, boulder check dams etc. were planned and executed on watershed concept. The specifications of different structures are given in Table 2.4. As a result an additional 2 ha-m *in situ* rainwater was harvested. Through trenching about 1.40 ha-m of runoff harvesting was accomplished during storms.

Table 2.4: Specifications of different *in-situ* RWH systems in a watershed in the Bundelkhand region

SWC* measure	Quantity	Spacing, m	Length, m	Width, m	Depth, m	Total Storage Volume, m^3
Staggered contour trenches	10,000 No.	3	3-4	0.6	0.4	9000
Continuous contour trenches	17 km	1.5-2.5	30-835	0.6	0.4	4080
Contour furrow	20 km	20 (VI)	68-355	0.4	0.3	1600
Shallow depth staggered pits	3.0 M	4-4.3	1.0-1.2	0.05-0.1	0.09-0.11	4500
Micro ponds	13 No		3.4-6.9	2.7-5.5	0.5-1.1	200

*(*SWC = Soil and Water Conservation)*

Singh (1995) reported the case study of integrated watershed development programme at Rendhar in Jalaun district of Uttar Pradesh, Bundelkhand region of India. The mean annual rainfall at the site is 880 mm. The area of watershed was 747.83 ha. The watershed was treated with contour bunding on 31.65 ha, field bunding on 577.95 ha, levelling on 26.89 ha, gully plugging and check dams on 197.58 ha, and water harvesting *bundhies* (a water impounding structure) on 47 ha were constructed. 25 check dams were constructed for water harvesting. Vegetative bunds were taken on 88.50 ha area. The watershed development started in 1983-84 and subsequently observations were taken each year till 1991-92. Results showed that water table rose by 3.7 m due to runoff control and its storage in water impounding structures over a period of 9 yeas as compared to the pre-project period. This increased recharge was used for irrigation and drinking purposes. The number of dug wells increased from 10 to 31 and shallow tube wells from nil to 51. The enhanced availability of water led to the increased cropping intensity from 100 to 185 per cent. The irrigated area went up from 56 to 690 ha. About 18 ha-m water was harvested every year in check dams, which was used for supplemental or protective irrigation on 180 ha land.

Rao *et al.* (1996) reported the results of hydrological analysis of a watershed of 143 ha at Bellary in Karnataka, before and after the treatment with different soil and water conservation measures. The measures included diversion drains and staggered contour trenches on non-arable land, graded bunds and stone checks on arable lands and rockfill dams, archweir and *nala* bund across the gully. These measures were implemented during 1984-86. Water levels were monitored at weekly interval in the 47 open wells in the watershed along with water levels in the wells located outside the watershed to assess the influence of conservation measures on groundwater recharge. Observations on well water levels and area cropped in the watershed were recorded consecutively for 8 years. Hydrological analysis revealed that integrated management of land and water resources consistently improved the groundwater regime. Surface runoff from the treated forest and agricultural catchment were only 27.4 and 57.4% of the untreated agricultural catchment at the end of eight years, reflecting in high infiltration of rainwater due to enhanced opportunity time. Consequently, water levels in the open wells rose by 0.5 to 1.0 m at the end of eight years, thereby increasing the area irrigated by wells by 172% when compared to the pre-project period, which in turn improved crop yields by 70%.

Goyal *et al.* (1997) reported the results of study of Jhanwar watershed in Rajasthan. It was a small 30 ha watershed. The watershed was treated with structures like stone check dams, brush wood dams, *anicuts* in 1987. Groundwater table in the area recorded average rise by 0.61 m/year during the period from 1987-94.

Mittal and Samra (2001) found that the integrated watershed development activities provided solution to the degraded fragile hill eco-systems in 3 Mha area in the Shiwalik hills regions of northern India. In the case study reported by them the watershed of 59 ha was treated with staggered contour trenches on slopes; stone check dams, gabions or crate wire check dams, grade stabilizers in channel. Vegetative measures included planting suitable grass and tree species to provide good ground cover to check soil erosion. A 13.5 m high dam with a designed storage capacity of 13.7 ha-m was constructed in 1992. The RWH from hilly catchments was done by constructing small earthen dams. Harvested rainwater was provided for supplemental irrigation to the farmers' field. This increased the yield of wheat from 0.8 to 4.35 t/ha, chickpea from 0.84 to 1.2 t/ha and mustard from 0.3 to 0.7 t/ha.

A small research watershed of 12 ha in the sub-humid region of Maharashtra was developed with different soil and water conservation treatments in 1990. The watershed has undulating topography with 5–10% land slope. Different conservation treatments comprised vegetative bunds with contour cultivation on 3.71 ha, CCTs with silvipasture system on 3.03 ha, contour cultivation on 2.06 ha, fallow land with native grasses 1.18 ha, low lying paddy fields 1.14 ha and one farm pond of 6400 m^3. Results of 10 years of research on the watershed indicated that annual runoff before the development of watershed was 21% of rainfall. The runoff decreased over time and at the end of 10^{th} year it was found to be 7% of the rainfall i.e. a reduction of 61% (MPKV, 2002).

All the case studies discussed above reported positive effects of watershed development with the help of visible indicators like reduction in runoff and rise in groundwater table, number of wells, irrigated area and crop yields. The strength of these studies lies in their length of records since most of the studies have data length from 5 to 10 years. However they do not address the detail water balance of the watershed. Watershed development changes the water flow paths in the watershed. After watershed development runoff decreases and evapotranspiration (due to increased irrigated area) increases. These patterns should be continuously monitored to have better control on the water resources. As reported by Sharma and Scott (2005), presently, the whole exercise of watershed development is being undertaken without really estimating how much water is received in, how much is stored where, and how much can be used under different availability scenarios (drought, normal, surplus years). Batchelor (2002) observed undesirable impacts of water harvesting in a case study watershed in Andhra Pradesh in the form of reduced tank water supplies for domestic purposes and uncontrolled groundwater extraction for irrigation.

Another most debatable issue facing the Indian watershed projects is the upstream downstream conflict. The land use and water related actions taken in one part of the catchment might have implications elsewhere in another part of the catchment to a varying degree. Sakthivadivel and Scott (2005) found that inflow to a reservoir in Gujarat was drastically reduced after large-scale development of small water harvesting structures took place in the catchment of the reservoir, whereas Sikka and Paul (2005) found that downstream reaches have benefited from the upstream watershed developments especially in hilly areas by reducing peak flows and flash floods, reducing soil erosion and sedimentation and maintaining dry season river flows. These differences might be attributable to the scale of watershed development activities in relation to the rainfall. Whatever may be the effect, it is necessary to know the upstream-downstream hydrology before and after watershed development to avoid future conflicts.

If the information about the impact of watershed development activities (taken in upstream reaches) on the downstream reaches is known beforehand, the upstream watershed development activities can be planned in harmony with the downstream water requirements. If it is required that certain amount of flow from upstream watershed should be allowed to go downstream for downstream users or ecological reasons, then the structures in the upstream watershed can be designed such that this predefined water goes to the downstream watershed as excess flow.

The above debate on the upstream-downstream water conflict led to the consideration of Downstream Release (DSR) criteria in the methodology of the tank design in this study (hypothesis-4). DSR gives the daily outflow from the watershed under consideration. If this criterion is specified before hand, tank system in the watershed will be optimised for the desired DSR criterion. This criterion also enables the planners to allocate water for environmental considerations. The details about the DSR criterion for tank system design are discussed in Chapter 6 (see Section 6.3.6).

2.7.4 Conclusion

The concept of watershed development for resources conservation has been discussed, followed by different case studies of integrated watershed development projects in India. All the studies reported positive effects of watershed development but lacked detail on the water balance of the watershed and upstream downstream water conflict. Discussion about the watershed development projects in India and scope of RWH in the state of Maharashtra highlights the scale of this research application.

2.8 Closure

Different *in-situ* rainwater harvesting systems and their integration in the watershed have been discussed in this chapter. Literature has strongly supported the fact that these RWH systems reduce runoff, increase infiltration and groundwater recharge. From the discussions on the case studies of integrated watershed development it has been shown that these *in situ* RWH practices are taken in the catchments of the tanks in the watershed. Hence the effect of *in situ* RWH systems in influencing the inflows to the tanks should be considered while designing the tank systems in the watershed. The literature review has thus supported the part of the first hypothesis of this research that *in situ* RWH systems influence the inflows to the tanks in the watershed.

When different *in situ* and *ex situ* RWH systems are integrated in the watershed (as shown by the case study examples in this Chapter), it has resulted into rise in available water resources through storage of water in the tanks and increase in groundwater levels through increased opportunity time for water to infiltrate as a result of these practices. Though it is not clear from the studies as how much water was stored in the three storage media i.e. soil profile, tanks and aquifer (groundwater) as a result of these practices, it has shown that this approach has been beneficial in terms of increases in water and crop resources in the watershed. Therefore literature on the case studies of integrated watershed development has supported the motivation of the concept of integrated water storage system (IWSS) for the watershed on which tank system for the watershed should be designed and thus supported the third hypothesis of this research.

It is indicated from the review of literature on *in situ* RWH practices in this Chapter that little work has been done on the modelling aspect of these practices. To contribute to the literature on the modelling of *in situ* RWH practices and to investigate the first hypothesis of this study, a modelling approach is proposed for continuous contour trenches. Next Chapter is devoted to the discussion of this modelling approach.

Table 2.1: Summary of different *in-situ* RWH systems discussed under literature review

RWH system	Place	Rainfall, mm	Slope, %	Soil	Crops	Runoff reduction as compared to control, %	Source
Contour cultivation	Rahuri (Maharashtra)	480	1.5	Black	Pearl millet	18.7	Patil and Bangal (1991)
Strip cropping	Solapur (Maharashtra)	623	1	Black	Pearl millet Redgram,	37.6	Kale *et al.* (1994)
Deep tillage	Hyderabad (Andhra Pradesh)	890	--	Alfisols	Sorghum, Maize	20.5	Rao *et al.* (1998)
Rice straw mulch	Punjab	1000	2	Sandy loam	--	66%	Bhatt and Khera (2005)
Gravel mulch	China	263	8	Sandy loam	Bare	93	Li (2003)
Contour ridges	Rahuri (Maharashtra)	480	3	Black	Pearl millet Sunflower	38	Bangal *et al.* (1990)
Ridging	Hyderabad (Andhra Pradesh)	750	--	Alfisols	Maize, chickpea	45	Sahoo and Mohanty (1990)
Vegetative barrier	Jodhpur (Rajasthan)	366	3	Sandy loam	Pearl millet	28 to 97	Sharma *et al.* (1999)
Vegetative bund	Kolhapur (Maharashtra)	1015	3-5	Silty loam	Pulses	66	MPKV (1999)
Graded bunding	Dehradun (Uttaranchal)	2073	4	alluvial	Maize, chickpea	22	Sahoo and Mohanty (1990)
Graded bunding	Bellary (Karnataka)	654	1-1.5	Deep black soils	Green gram, Sorghum	20	Chittaranjan *et al.* (1997)
Contour bunding	Bellary (Karnataka)	654	1-1.5	Deep black soils	Green gram, Sorghum	80	Chittaranjan *et al.* (1997)
Conservation ditch	Bellary (Karnataka)	654	1-1.5	Deep black soils	Green gram, Sorghum	29	Chittaranjan *et al.* (1997)

Table 2.3: Summary of different case studies of integrated watershed management

Watershed (State)	Area, ha	Rainfall mm	Topography	Major land use	Data length, years	Indicators and findings	Source
Bellary (Karnataka)	143	654	Low hills on the ridge draining to the centre drainage line	Agriculture and forest	8	No of wells increased from 47 to 120 Irrigated area increased by 172% (from 89 ha to 341 ha). Runoff decreased. Runoff as per cent of untreated agricultural catchment was 27.4% for forest land and 57.4% for agricultural land. Groundwater level increased by 0.5 to 1.0 m	Rao *et al.* (1996)
Tejpura (Madhya Pradesh)	775	931	Slopes 1-5 %	Agriculture	6	Irrigated area increased from 20.2 ha to 510 ha, Ground water levels increased by 3 to 7 meters, Number of dug wells increased from 5 to 47 and average pumping of groundwater increased from 1-2 hour to 8-10 hours per day, Crop yields increased by 2.2 to 7.3 times. crop productivity increased from 6 q/ha to 19.6 q/ha. Availability of water in check dams for 9 to 10 months.	Maheshwari, (1990)
Relmajra (Punjab)	59	1110	Steep slopes, high drainage density, low vegetation	Degraded land	20	Productivity of agricultural crops increased. Increased in yield of wheat from 0.8 to 4.35 t/ha, chickpea from 0.84 to 1.2 t/ha and mustard from 0.3 to 0.7 t/ha.	Mittal and Samra (2001)
Rendhar (Uttar Pradesh)	748	880	Ravine lands	Agriculture	9	Water table rose by 3.7 m. Dug wells increased from 10 to 31 and shallow tube wells from nil to 51. Cropping intensity increased from 100 to 185 %. Irrigated area increased from 56 to 690 ha., Crop productivity increase.	Singh (1995)
Jhansi (Madhya Pradesh)	500	920	Undulating, low drainage density	Degraded land	1	2 ha-m *in-situ* rainwater was harvested	Gaur *et al.* (1995)
Gunj (Maharashtra)	508	938	Average slope 1.6%	Agriculture	5	Water table increase by 13.87%	Urade and Sagare (1993)
Kolhapur (Maharashtra)	12	1015	undulating with 5–10% slope	Agriculture Silvipasture	10	61.41 % reduction in runoff during 10 years. Detail study on hydrology of the watershed	MPKV (2002)
Jodhpur (Rajasthan)	30	366	Hilly terrain with 5-20%	Degraded lands	8	Groundwater table in the area recorded average rise by 0.61 m/year	Goyal *et al.* (1997)

Chapter 3

CONTINUOUS CONTOUR TRENCHES

3.1 Summary

Different in-situ rainwater harvesting (RWH) systems were discussed in Chapter 2. This chapter discusses one in-situ RWH system i.e. continuous contour trenches (CCT). The concept, system details and design of CCT are discussed. A model to assist in the design and performance evaluation of CCTs is also discussed.

3.2 Introduction

Review and discussion on *in situ* RWH practices was presented in Chapter 2. The case studies of integrated watershed development presented the range of these practices adopted in the watershed. From the review it was concluded that these *in situ* RWH practices influence the inflows to the tank systems since these practices are adopted in the catchments of these tanks. It therefore becomes necessary to know how much water is intercepted by the *in situ* RWH practices, and how much water (of the intercepted volume) is infiltrated to recharge the groundwater. Though all the *in situ* RWH practices influence the runoff to varying degrees, one *in situ* RWH practice i.e. continuous contour trenches (CCT) has been selected in this study to test the first hypothesis of the research. The reason for selection of CCT for study is the popularity of this technique in the state of Maharashtra. A modelling approach based on the water balance across the trench system has been developed and discussed in this Chapter. It will be possible to assess the performance of the existing trench system for water harvesting and design a trench system to achieve the desired level of water harvesting with the help of the developed model.

3.3 What is continuous contour trench (CCT)?

Continuous contour trench is an *in situ* RWH system in which a small rectangular trench is excavated in the soil. The trench runs continuous along the contour covering the entire transect of the field, hence the name continuous. Two ends of the trench may join a field drain or a natural stream in the watershed. They are commonly referred to as CCT. Soil excavated is piled on the down-slope side of the trench forming a small bund. Trees are planted on these bunds for taking advantage of the moisture in the saturated soil surrounding the trench.

The primary objective of CCT is to harvest the runoff flowing down the slope and recharge the groundwater table. In addition, CCTs also serve the purpose of protecting the good arable lands down slope in the watershed from the high velocity erosive runoff and supplying moisture to the surrounding soil root zone for the growth of plantations. Soil lost due to erosion is trapped in the CCT thus reducing the silting problems of the downstream tanks. Soil deposited in the CCTs is removed after every 1 or 2 years by beneficiary farmers in the watershed. Fields, which are not suitable for common crops, are often treated with CCTs. Horticultural or silvipasture plantations are taken on these fields.

The CCT is very popular practice in the state of Maharashtra and CCT has become a buzzword in the water harvesting community. It is worth to quote Mr. Popat Pawar, village Sarpanch (constitutional head of the village) of Hiware Bazzar and crusader of watershed movement, that explains the wide acceptance of this technology by the rural people of the State (Deulgaonkar, 2004).

"We have been able to use every drop of rainwater because of CCT. It is a very low-cost and efficient method of rainwater harvesting and does not require any steel or cement, construction or structure. Studies have shown that with CCT 60-80 per cent of the total rainwater received will percolate. We decided that this rainwater is public property and that nobody should overuse it. You can dig wells but borewells are prohibited. That is why we were self-sufficient in water in 2002-03 when we received only a 200 mm rainfall. Any handpump here would give you water. We live a community life and that is the reason why we are all happy,"

Father Bachar, another champion of watershed development, with the help of the Indo-German Society has solved the water problem of many villages by the CCT method in the state of Maharashtra. In years with half the average rainfall, all the wells in these villages were filled with water. (Personal communication, 2003).

Techniques similar to CCT are also found in other countries. In the USA, they are called infiltration trenches to divert storm runoff into the soil and recharge groundwater. These trenches are bigger in size than CCT and filled with coarse aggregate material. Depending on the size, these trenches divert up to 90% of the annual runoff volume into the soil and are more effective in small to moderate storms

(Lowndes, 2000). In Jordan, the technique is called sand ditches since the excavations are filled with river sand having high infiltration rate. Abu-Zreig *et al.* (2000) reported a study on sand ditches to harvest rainfall and store it deeper in soil profile. For this they excavated trenches 80 cm deep, 5 m long and 1 m wide across the land slope between two rows of olive trees. The trenches were filled up to original ground level using local deposits of fractured rock and river sand. Results showed that sand ditches increased both the percentage of rainfall stored in the soil matrix and the infiltration depth of water during the two winter seasons from 1996 to 1998. At one particular instant, it was found that the infiltration depth and water content in the sand ditch area were 100 cm and 28% respectively compared to only 68 cm and 19% in the control area. Ratio of depth of water stored in sand ditch area to rainfall was 73% as compared to only 45% in the control area.

The people's acceptance of the CCT technology in Maharashtra state and studies carried out on the similar techniques in other countries (as shown by the above two examples) hold promise for the study of CCT as a sustainable RWH practice in the water scarce regions. Following sections describe the details of the trench system and the modelling approach.

3.4 A trench system

The trench system (here means CCT system) can be defined as the series of continuous contour trenches at some interval along the slope and running along the contour and covering the entire field or micro-catchment to achieve water harvesting and groundwater recharge. A trench means a single trench and the trench system constitutes collection of such trenches on a field within a specified boundary. It thus includes the trench and inter-trench area between two successive trenches. Definition sketch of the system is shown in Fig 3.1 and a trench system layout on the field is shown in Fig 3.2.

3.4.1 Design of trench system

The important design parameters of the trench system are spacing (or the horizontal interval) between the two consecutive trenches and the dimensions of the trench ditch (i.e. width and depth for rectangular cross section). The horizontal interval and dimensions of the trenches are designed to intercept and store the specified portion of runoff volume generated from the catchment between the two trenches. A typical trench system with trench size of 0.6 X 0.6 m spaced at 10 m horizontal interval will store about 360 m^3 of water on 1 ha area. This water is lost in a few days by the processes of infiltration and evaporation and trench becomes ready to store water from the next storm. These trench systems thus harvest and store a considerable volume of water in a rainy season and hence it becomes important to know the amount of runoff water harvested by these systems.

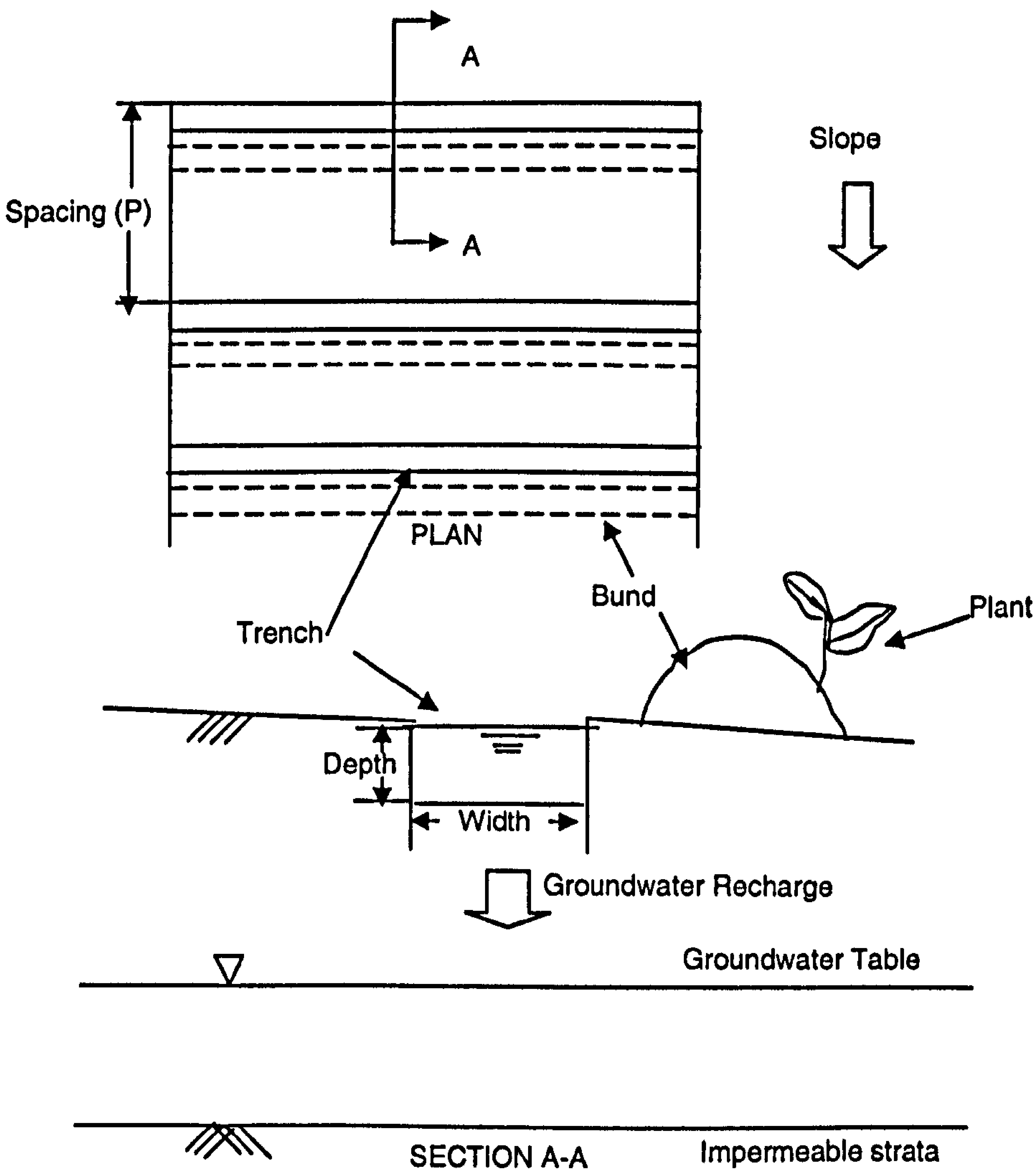


Figure 3.1: Sketch of continuous contour trenches

Figure 3:2 Layout of continuous contour trenches on the field
(Source: MPKV, 2001)

Presently the design specifications of these trenches have been standardised empirically; the size ranging from typically 0.3 x 0.3 m to 0.6 x 0.6 m in cross section and spacing between the trenches varying from 5 to 20 m depending on the slope. The formulae used for spacing the bunds and terraces are used for deciding the spacing of these trenches. Some empirical guidelines are available, which give the spacing and cross section of terraces as a function of land slope (Singh *et al.*, 1990). But specific design procedures are not available for deciding the spacing and cross section of these trenches.

According to a rule of thumb, commonly used in India, the volume of water intercepted by the trench system in a rainy season is approximately 7 to 8 times its capacity. This thumb rule assumes 7 to 8 runoff producing storms in a season. But the true capture volume depends on the temporal distribution of rainfall and runoff and trench system design. This indicates that there is a need to develop appropriate performance indicators to know the effectiveness of the trench system for water harvesting and methodology to estimate such indicators.

Previously Duchene *et al.* (1994), Guo (1998), and Akan (2002) developed performance indicators in different forms and proposed methodologies to estimate those indicators based on simulation model for infiltration trenches in the USA. Similar research needs to be done for CCTs in India.

3.5 Water harvesting potential

Since trench systems intercept considerable volume of runoff (that would have otherwise gone to tanks or rivers), it assumes importance to discuss their effectiveness in harvesting the rainfall and runoff. In this study the term "water harvesting potential" (WHP) is introduced as an indicator of the ability of the trench system to harvest the rainfall and runoff water and recharge the groundwater. Gross WHP is proposed to indicate the total water intercepted by the trenches and net WHP to indicate the total water infiltrated from the trenches. WHP would be useful indicator to know the performance of different trench systems in water harvesting.

The gross WHP and net WHP of the trench system are computed as given by equation (3.1) and (3.2)

$$GrossWHP = \frac{Qif - Qof}{Qif} x100 \quad (3.1)$$

$$NetWHP = \frac{Qif - (Qof + Qev)}{Qif} x100 \quad (3.2)$$

Where,

Qif = Inflow to the trench, m^3
Qof = Overflow from the trench, m^3
Qev = Evaporation from the trench, m^3

As explained later in Chapter 8, WHP is influenced by rainfall distribution and trench system design parameters, and estimation of WHP needs performing a water balance across the trench system. Hence a trench water balance model is developed to estimate the water harvesting potential of a trench system. This chapter describes the developed model. It is also possible with the help of the model, to decide the size and spacing of the trenches by conducting the water balance for different configurations of trench system. The model needs the input of daily climatic data, the specifications of the trench system and soil parameters. This model forms one component of the main

SOFTANK model discussed in Chapter 6. The utility of the model is explained for a case study in the state of Maharashtra and results are discussed in Chapter 8.

3.6 Simulation model

A Trench system is modelled with the simulation of field and trench water balance. Field water balance is simulated on daily basis and the trench water balance on sub-daily time steps. Infiltration from the field and trench saturates the soil profile, and excess from the soil profile recharges the groundwater. Inflows to the trench system are runoff and rain falling over the trench and outflows are infiltration, evaporation and overflow from the trench. The input parameters of the model are climatic data, trench size, trench spacing, soil and land use-land cover characteristics, and output parameters are different trench water balance components such as overflow, infiltration, and evaporation. For assessing the Gross and net WHP from a trench system, simulation needs to be carried out for number of years for which rainfall data are available.

The model is based on the following assumptions

1. Rainfall is uniform over the entire trenched field
2. Cross section and the water depth in the trench are uniform along the trench
3. Soil is uniform along the trench
4. The soil deposition is considered as minimum and hence it does not influence the infiltration in the trench. This assumption is particularly valid in non-arable lands with shallow soils, which is a case when trench systems are adopted. Trenches are also desilted after every 2-3 years.
5. Groundwater table does not interfere with the infiltration process
6. Inflows to and outflows from the trench are instantaneous

The flowchart of the model is presented in Fig 3.3. The computer programme was written in C language for the described model.

The different processes simulated in the water balance model of the trenches are runoff, infiltration and evaporation. These are discussed in the following sections.

3.6.1 Process representation in the model

Following processes are represented in the model

1. Runoff: Field runoff is estimated with the SCS CN method. This is described in detail in Chapter 6 (see Section 6.3.10.1).
2. Evaporation from the bare field is estimated on daily basis and from trench on sub-daily basis respectively by Penman (1948) method (Penman (1948) method for estimation of evaporation is given in Appendix A31)
3. Evapotranspiration from the cropped field is estimated with Penman-Monteith method
4. Infiltration from the trench is estimated with the Green Ampt method.
5. Field water balance
6. Trench water balance

3.6.1.1 Field water balance

Field water balance estimates the water balance parameters for the field between two successive trenches. Field water balance forms an important part of the methodology of tank system design and is described in detail in Chapter 6 (see Section 6.3.12). Here it only needs to mention that runoff from the inter-trench field water balance is the inflow to the trench system. The total volume of deep percolation from the field, total volume of water infiltrated from the trench (described below) and total volume of water infiltrated from tanks - termed as recharge volume, contributes to the groundwater storage. The rise in groundwater table is the function of recharge volume and drainable porosity.

3.6.1.2 Trench water balance

The components of the trench water balance are shown in Fig. 3.4. Trench water balance is carried out on sub-daily time step. Runoff from the inter-trench field and the rain falling over the trench are the inflow to the trench. This inflow instantaneously fills the trench. If the inflow volume is more than the available trench capacity, the excess water moves along the trench and joins the gully over the spillway of the trench as overflow (Qof). But for simplicity in the model, it is assumed that the overflow is also instantaneous. The volume of water in the trench is then subjected to infiltration and evaporation processes. New water level in the trench is updated at sub-daily time steps (minutes and hours). Two time parameters are important in the trench water balance estimation. Number of time steps and time increment for each time step. For example number of time steps may be two and time increments for the first time step

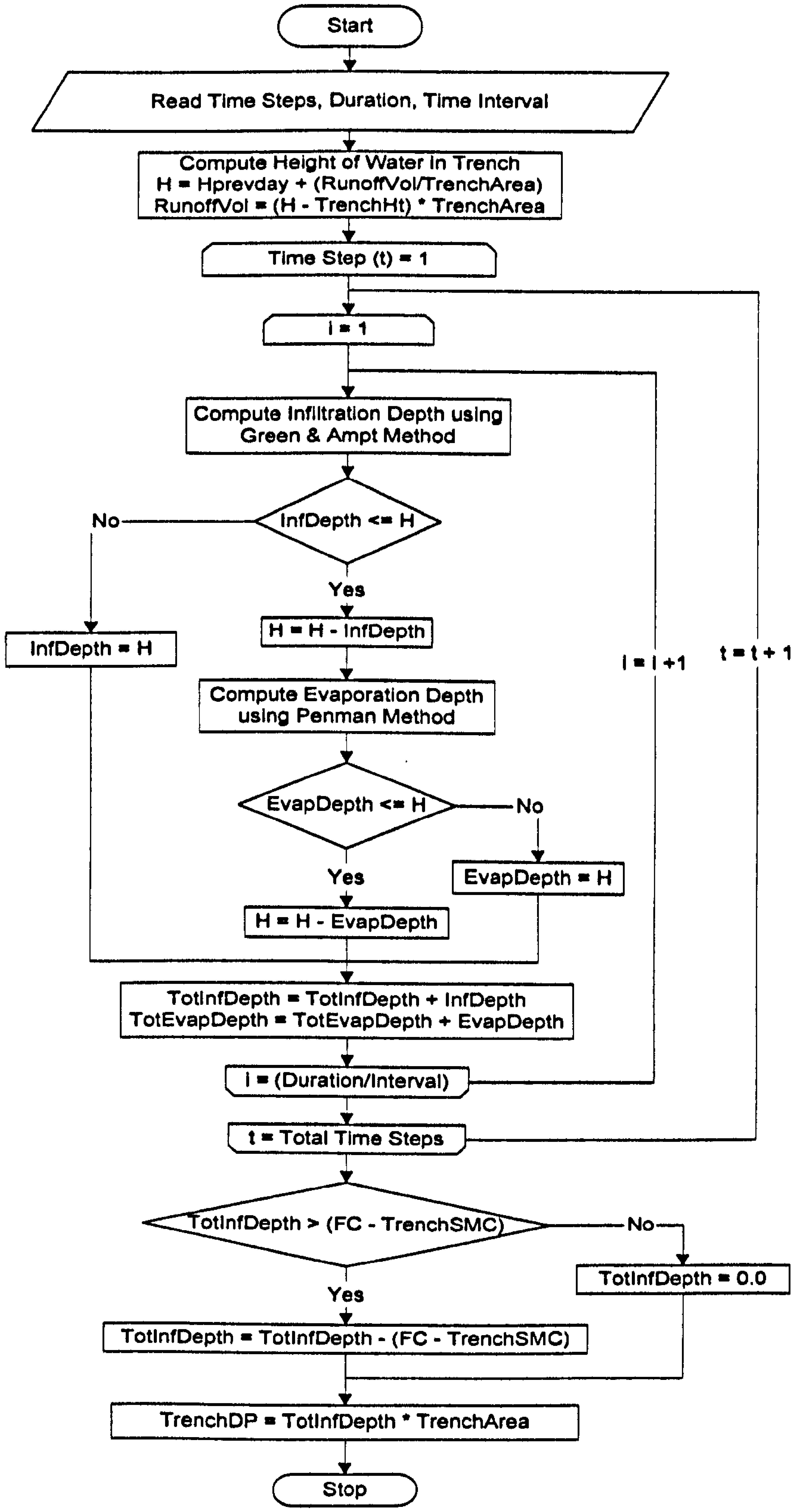


Figure 3:3: Flowchart of the trench system simulation model

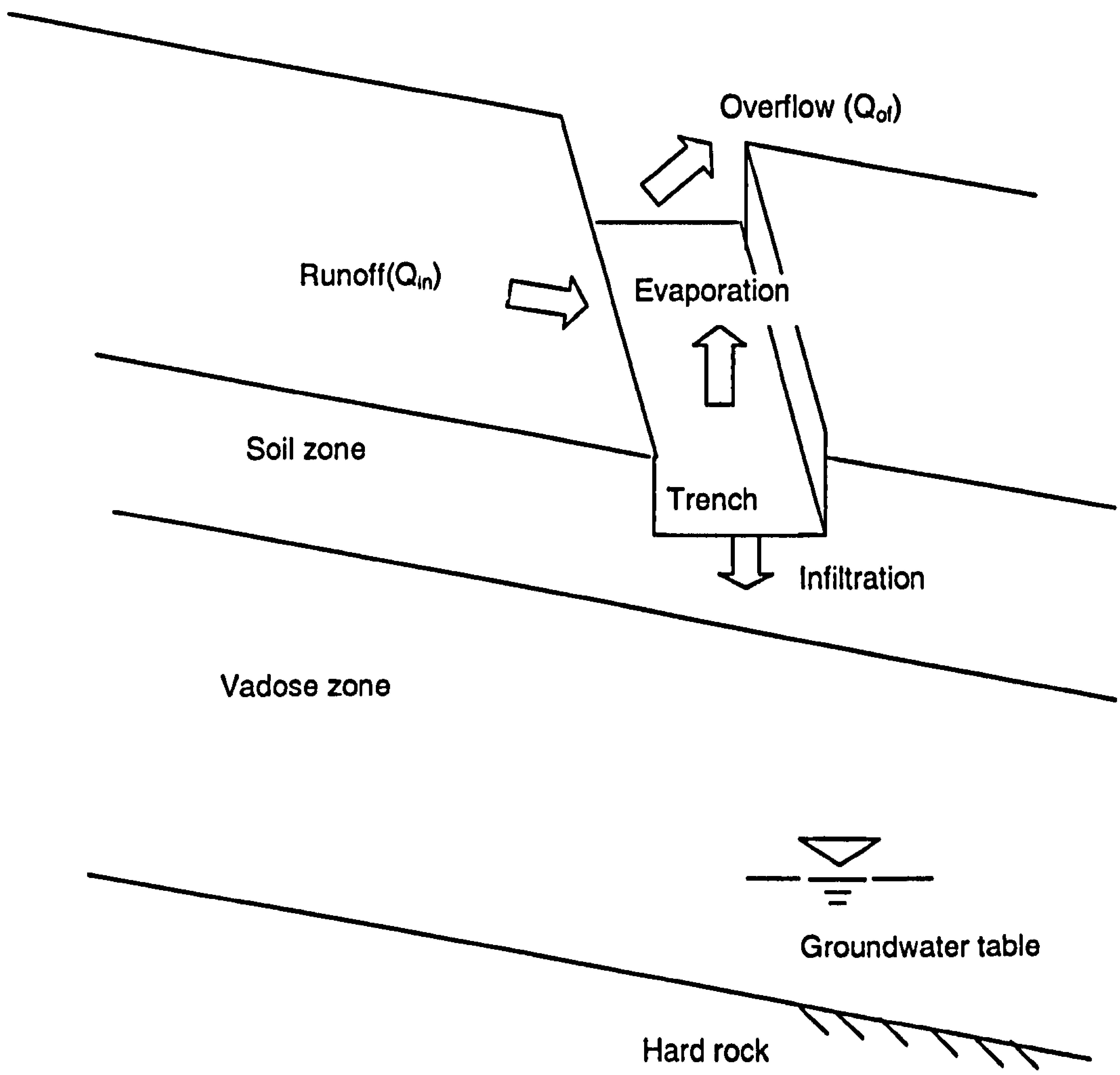


Figure 3.4: Trench water balance components

may be 5 minutes (since infiltration rate is high at the beginning) and for second time step time increment may be 1 hour. Infiltration and evaporation are computed for these time steps and time increments.

Infiltration rate (f) is computed with the help of equations 3.6 and 3.7. Infiltration into the soil for the time increment is estimated with this infiltration rate. Evaporation is estimated by the Penman (1948) method and evaporation rate is considered uniform over the day. After subtracting infiltration and evaporation for the time increment, new trench water level is computed at the end of time interval. Evaporation takes place from the water in the trench and from the saturated soil when the water has infiltrated down the trench. These computations are repeated till the water level in the trench becomes zero. If water in the trench is not infiltrated in 24 hours (as is the case many times), next day rainfall and runoff if any are added to the trench storage and water balance continued.

Trench water balance on daily basis is expressed as

$$Q_i = (E_i + F_i) \cdot A + O_i + S_i \tag{3.3}$$

Where,

Q_i = Inflow on i^{th} day, m^3

E_i = Evaporation on i^{th} day, m

F_i = Infiltration on i^{th} day, m

A = Area of trench (Width x Length), m^2

O_i = Overflow from the trench on i^{th} day, m^3

S_i = Storage in trench on i^{th} day, m^3

3.6.1.2.1 Trench Infiltration

Infiltration rate in the trench is governed by the infiltration capacity of the soil. Infiltration from the trenches is estimated with the Green and Ampt (1911) method (discussed below). The basis of selecting this method was that it is physically based and model parameters can be estimated from the soil textural properties. Infiltration is assumed to occur through the bottom of the trench only. This assumption is based on the experience in the study area that once the soil surrounding the trench is saturated by rainfall or the water from the trench, then hydraulic gradient acts in the vertical direction only. For simplicity it is assumed that the small soil bund on the down slope side of the trench and the vegetation on bund if any do not affect the infiltration rate. The Green Ampt method is described in brief in the following section.

3.6.1.2.2 Green Ampt method

Green Ampt model (Green and Ampt, 1911) is based on a simple conceptualization of an infiltrating front into a dry soil using the sharp interface approximation. The Green and Ampt equation for cumulative infiltration can be expressed as

$$K \cdot t = F(t) - \varphi \Delta\theta \ln(1 + F(t)/\varphi\Delta\theta) \tag{3.4}$$

Where,

K = hydraulic conductivity of the soil, cm/h

$F(t)$ = cumulative infiltration at time t, cm

φ = h_s - h_f Capillary pressure head at the wetting front, cm

$\Delta\theta$ = change in moisture content, cm^3/cm^3

The above equation is implicit in $F(t)$ and needs to be solved iteratively. Once F is found from the above equation, the infiltration rate f can be obtained from

$$f(t) = K(\varphi\Delta\theta / F(t) + 1) \tag{3.5}$$

The explicit version of Green-Ampt model proposed by Salvucci and Entekhabi (1994) was used here to model water infiltration into the unsaturated soil from the trenches. Mathematical formulation of the model is as follows.

$$\frac{q}{K_s} = \frac{\sqrt{2}}{2}\left(\frac{t}{\chi + t}\right)^{-\frac{1}{2}} + \frac{2}{3} - \frac{\sqrt{2}}{6}\left(\frac{t}{\chi + t}\right)^{\frac{1}{2}} + \frac{1 - \sqrt{2}}{3}\left(\frac{t}{\chi + t}\right) \tag{3.6}$$

Where,

$$\chi = \frac{(h_s - h_f)(\theta_s - \theta_o)}{K_s} \tag{3.7}$$

Where,

q = Infiltration rate, cm/h

K_s = Saturated hydraulic conductivity, cm/h

t = Time, h

h_s = Ponding depth or capillary pressure head at the surface, cm

h_f = Capillary pressure head at the wetting front, cm

θ_s = Saturated volumetric water content, cm^3/cm^3

θ_o = Initial volumetric water content, cm^3/cm^3

The output from the model are obtained in the form of Gross and net WHP. Thus model gives these parameters for the existing trench system. It is also possible to suggest suitable design of the trench system to achieve desired WHP, by having repetitive simulations of the model for different trench configurations. The results are discussed in Chapter 8 (see Section 8.3.1.5). As discussed earlier the trench systems are designed based on some empirical rules or experience. Analytical procedure is not adopted for designing the trenches. This modelling approach therefore provides an analytical tool for design and evaluation of the trench system.

The two indicators i.e. Gross WHP and net WHP have significance in this study. According to the first hypothesis proposed in the study, *in situ* RWH systems influence the storages of downstream *ex situ* RWH systems (tanks) and hence they should be considered together in the methodology for optimum design of tank system in the watershed. Gross WHP here indicates the volume of water intercepted by the trenches. This volume never joins the tanks downstream and therefore when included in the methodology of design of tanks, the storage capacities of tanks are obtained for this reduced inflow. Net WHP represents the volume of groundwater recharge due to trenches which can be utilised for irrigation through wells. Therefore Gross WHP affects tank storage and net WHP affects groundwater storage.

3.6.2 Calibration of model parameters

In the Green Ampt method described above, data on two parameters i.e. saturated hydraulic conductivity (K_s) and capillary pressure head (h_f) at the wetting front is needed. These parameters can be determined from soil properties. However it is recommended to determine these equation parameters from field measurements by fitting the measured infiltration data. Field infiltration measurements tend to lump the effects of field heterogeneities into equation parameters. Therefore in this study these parameters were estimated with the measured infiltration rate data at the site for Akola watershed. These parameters are for the infiltration from the soil. However in this study infiltration from trenches is required to be estimated. Hence it is suggested to calibrate these parameters for the trench infiltration.

These parameters for trench infiltration may be calibrated with the observed data on water levels in the trench during the process of infiltration. The observed and model simulated values of trench water level are compared with the RMSE (root mean square error) criteria. The simulated values are obtained by running the model for different calibration parameters in their acceptable range. The calibration parameter data set giving minimum RMSE between simulated and observed water levels is to be accepted for simulation.

The procedure for estimating the parameters from the infiltration test data and the calculations for the case study watershed are given in Appendix A3-2.

3.6.3 Application of the model for case study watershed

The modelling approach for CCT presented here was applied to the Akola case study watershed. The details of the case study watershed are discussed in Chapter 7 and the results of model application are discussed in Chapter 8 (see Section 8.4). As discussed later the modelling approach helped to investigate the fist hypothesis of this research.

The observed infiltration rates used in this study were for soil and not for the trenches, (data on trench water levels were not available). Therefore the model was used without calibration of G-A parameters to demonstrate the applicability of the model and to investigate the first hypothesis.

3.7 Conclusion

Modelling approach and methodology for assessing the performance of continuous contour trenches is discussed in this chapter along with its calibration procedure. It is also possible to design a trench system with this modelling approach. The performance parameter gross WHP is important in the design of tank systems in the watershed which has been included in the design methodology of tank system discussed in Chapter 6. The review on *in situ* RWH systems discussed in Chapter 2 supported partly the first hypothesis of this research. The methodology developed in this chapter for CCT is further helpful to test the hypothesis. The results are discussed in Chapter 8. This closes the discussion on *in situ* RWH systems. Next chapter starts the discussion on *ex situ* RWH systems i.e. tank irrigation systems.

Chapter 4

TANK IRRIGATION SYSTEMS

4.1 Summary

Chapter 2 and 3 discussed the in situ RWH systems that make use of the soil storage. This chapter discusses the ex situ RWH systems that make use of surface storage in the form of small tanks. Different types of tank irrigation systems in India and their evaluation studies are reviewed and discussed. A classification system for tanks as proposed in this research is discussed along with the concept of 'Tank strategy' introduced in the first chapter.

4.2 Introduction

As introduced in Chapter 1, integrated water storage system (IWSS) consists of the integration of three types of storages i.e. soil, surface and groundwater in the watershed. *In situ* RWH systems make use of the soil storage and were reviewed and discussed in Chapter 2 and 3. *Ex situ* RWH systems make use of the surface storage in the form of tanks and are reviewed and discussed in this Chapter. Both *in situ* and *ex situ* RWH practices recharge the groundwater and thus also make use of the aquifer for storage.

A tank is constructed for storage of water for irrigation or groundwater recharge or for both. It varies in size from few hundred cubic metres to a few thousand cubic metres. Tank should be properly located and have sufficient capacity to match the supply and demand of water. The studies on existing tank systems provide useful insights into the performance of the tank systems and for developing guidelines for new tank systems. Hence this chapter reviews and discusses different tank systems in India and proposes a classification system for these tanks in the context of proposed hypothesis (Hypothesis - 2) and proposed methodology for optimizing tank systems in the watershed. The concept of 'tank strategy' introduced in the first Chapter is explained. An investigation is carried out into the relationship of tank system components (i.e. catchment-tank-command) and water balance of tanks with the help of review case studies.

4.3 Tank Irrigation

As discussed earlier, soil storage is the first step in rainwater harvesting. After the soil's capacity to store water is saturated, the excess runoff flows downstream, which is stored in surface tanks. Surface tanks offer far more storage capacity than that of the soil profile. Moreover a tank enables provision of a better water distribution in space and time. These tanks range from a small farm pond of few cubic metres to large tanks of few thousand cubic metres.

Tank, its catchment and command area along with conveyance systems, all constitute a tank irrigation system. Tank irrigation system is also known as supplementary irrigation (SI) water harvesting (Owesis *et al.*, 1999) and small-scale irrigation (SSI) system (Ambler, 1994). It is known as water harvesting irrigation (WHI) system in Mexico (Scott and Silva-Ochoa, 2001). These systems are different from the big reservoir irrigation systems in many aspects. Compared to big irrigation reservoirs, tank irrigation systems have smaller watershed area and low-inflow, smaller storage, larger free-water surface area compared to the command area, and shorter length of the canals (or even absence of canals). Status of community dependent on tank irrigation system is also different. All these constitute a different basis for these tanks (Mayya and Prasad, 1989) and therefore need a different approach for their study.

4.3.1 Tank irrigation systems in India

Tank irrigation is one of the important and oldest sources of irrigation in India. It is the most prominent mode of irrigation in the semiarid regions of India. There are around 120,000 small tanks, irrigating about 4.12 Mha land and account for 37% of the total irrigated area in this region (MOA, 1993 as reported in Anbumozhi, 2001). Tank irrigation systems of Southern India are centuries old. They account for over 30% of total irrigated area of Tamil Nadu, Karnataka and Andhra Pradesh of South India (Palanisami and Flinn, 1988). Tamil Nadu state alone has 39200 tanks of varying sizes (Ranganathan and Palanisami, 2004). Though tanks are highly concentrated in the southern part of India, they are found in almost each state and every district of the country. Before the advent of big reservoirs, tanks were the only sources of water for domestic and irrigation purposes. Even today in many areas the tank is the only source to store rainwater and help farmers through crop growing period and provide stability to agricultural production. Some of the prominent tank systems in India are described below.

4.3.1.1 *Nadi* and *Khadin*

These structures are found in Rajasthan. '*Nadi*' is a dugout village pond in arid Rajasthan, constructed for storing water available from an adjoining catchment during the rainy season. At present, most villages in the region have one or more *nadis*. The capacity of the *nadi* generally ranges from 1200 to 15000 m^3 depending on physiographic conditions, and the rainfall pattern (Khan and Faroda, 2001). The water stored in a *nadi* is generally used for drinking by livestock and human beings. A *nadi* also acts as a source of groundwater recharge through seepage and deep percolation. It is estimated that the recharge from a *nadi* covering 2.25 ha and having a storage capacity of 15000 m^3 in an alluvial area may induce a groundwater recharge of 10,000 m^3 in one rainy season. The economic life of a *nadi* is 25 years with a cost benefit ratio of 1:2.8 (Narain *et al*, 2005). However traditional old *nadis* are more than 50 years old and characterised by high evaporation losses from free water surface, seepage losses through the sides, bottom and heavy sedimentation due to degradation in the catchment.

Khadin is a runoff farming and groundwater recharging system. Runoff from rocky catchments is collected in the adjoining valley against an earthen embankment. Khadin beds are cultivated on receding moisture. Ponding of water in a Khadin induces continuous groundwater recharge. Khan and Narain (2003) reported a water balance study of 10 ha Khadin with a 120 ha rocky catchment in Rajasthan. The study showed that with 250 mm effective rainfall received in 3 spells, the water yield from the catchment was 180,000 m^3 which was harvested and stored in the Khadin. In addition 25000 m^3 rain directly falling on the Khadin increased the total available water to 205,000 m^3. Nearly 62% of this water contributed to groundwater through recharge which resulted in 1.2 m rise in the static water level in wells in a zone of influence of the Khadin of about 10 ha.

4.3.1.2. Water harvesting dams

Water harvesting dams comprise a range of structures on the ephemeral streams, gullies and *nallas*. They take the names as *anicut* (Rajasthan), *nalla* bunds (Maharashtra), check dams (Madhya Pradesh) etc. An earthen or cement embankment is constructed in the stream to store runoff water in the rainy season. The structure may serve the single purpose of controlling the high velocity runoff thereby protecting the streams or recharging the groundwater table or storing water for domestic and animal needs or for irrigation. It may also serve the combination of these purposes. These structures are suitable in hilly and uneven topography where ephemeral streams are available in catchments with good runoff producing characteristics and are widely adopted in hard rock and basaltic terrain of southeast Rajasthan, Gujarat, Maharashtra, and Madhya Pradesh in Deccan plateau. Water harvesting dams have been constructed in many arid and semi-arid states under watershed management programme in India.

4.3.1.3 Percolation tank

A percolation tank is a small tank which stores the runoff during monsoon and allows it to percolate gradually in the ground to recharge groundwater table. The groundwater is exploited through dug wells on the downstream side or area surrounding the tank (Fig 4.1). An ideal percolation tank would fill up in rainy season and dry up by the end of winter and will have adequate cultivable area on the downstream. Selection of suitable sites for the construction of percolation tanks and subsequent maintenance are crucial for their effective functioning. In Maharashtra state the catchment area of these tanks ranges from 250 to 600 ha (Kulkarni and Rasal, 1990). Studies conducted on some percolation tanks constructed in hard rock and alluvium formations in the Pali district of Rajasthan showed a percolation rate of 14-52 mm/day. Percolation accounted for 65-89% losses whereas evaporation loss was 11-35% of the stored water (Narain *et al.*, 2005).

4.3.1.4. Irrigation Tank

The main function of this storage structure is to store water for irrigating the crops. In Tamil Nadu, India, each tank irrigates from 10 to 5000 hectares. Earthen bunds are reinforced with masonry to collect and store rainwater for irrigation. Water from the tanks is normally used to grow paddy crop. These tanks are centuries old and became less efficient due to the problems of siltation, encroachment by farmers in the tank bed and overall neglect from the government due to the advent of big dams. But there is renewed interest and lot of research is going on for the revival of these tanks (Palanisami and Easter, 1987, Palanisami and Flinn, 1988, Sakurai and Palanisami 2001, Ranganathan and Palanisami, 2004).

4.3.1.5. On farm reservoirs (OFR)

These are farm reservoirs often serving a single farm of few hectares, managed by individual farmer. They are also called as farm ponds and are excavated at the down slope side of the farm (Fig 4.2). These systems are small and water yield per unit area from the farm (catchment) is relatively high compared to bigger catchments, which makes these ponds economically viable. But they have poor storage excavation ratio. Many farm reservoirs are found in the country and has attracted the attention of researchers to develop better pond designs and management options.

4.3.1.6 Watershed based tank systems

In India since 80s tanks are constructed as a part of watershed development projects in the semi-arid and sub-humid regions. Tank based water management systems therefore became a whole watershed system with a tank as its central point. Water stored in the tanks is used for supplementary irrigation in dry spells of monsoon season and full irrigation in post monsoon season, if sufficient water is available. Tanks also recharge the groundwater and this groundwater is utilised for irrigating crops through well irrigation. Tanks thus facilitate in providing irrigation water from their own surface storages or subsurface storages that were recharged by the standing water in the tank. In this context it is necessary to understand the functioning of tank system in the watershed.

Tanks in the watershed are located on the main stream (drainage line) and there may be one or series of tanks depending on rainfall, watershed characteristics and cropping pattern in the watershed. They can range in size from a few hundred to few thousand cubic metres. If there is one tank, it is normally located at the lowermost (outlet) point in the watershed. This location offers a good site for the tank and entire watershed contributes runoff to the tank. The water stored in the tank is then pumped for irrigation in the same watershed. When there is larger number of tanks in the watershed, they are spread along the stream forming a tank cascade. First (topmost) tank receives water from its catchment only whereas the lower tanks receive excess flow from upper tanks in addition to the runoff from their own catchments. Irrigation from these tanks is applied by gravity flow to the downstream command or by pumping water to the upstream catchment.

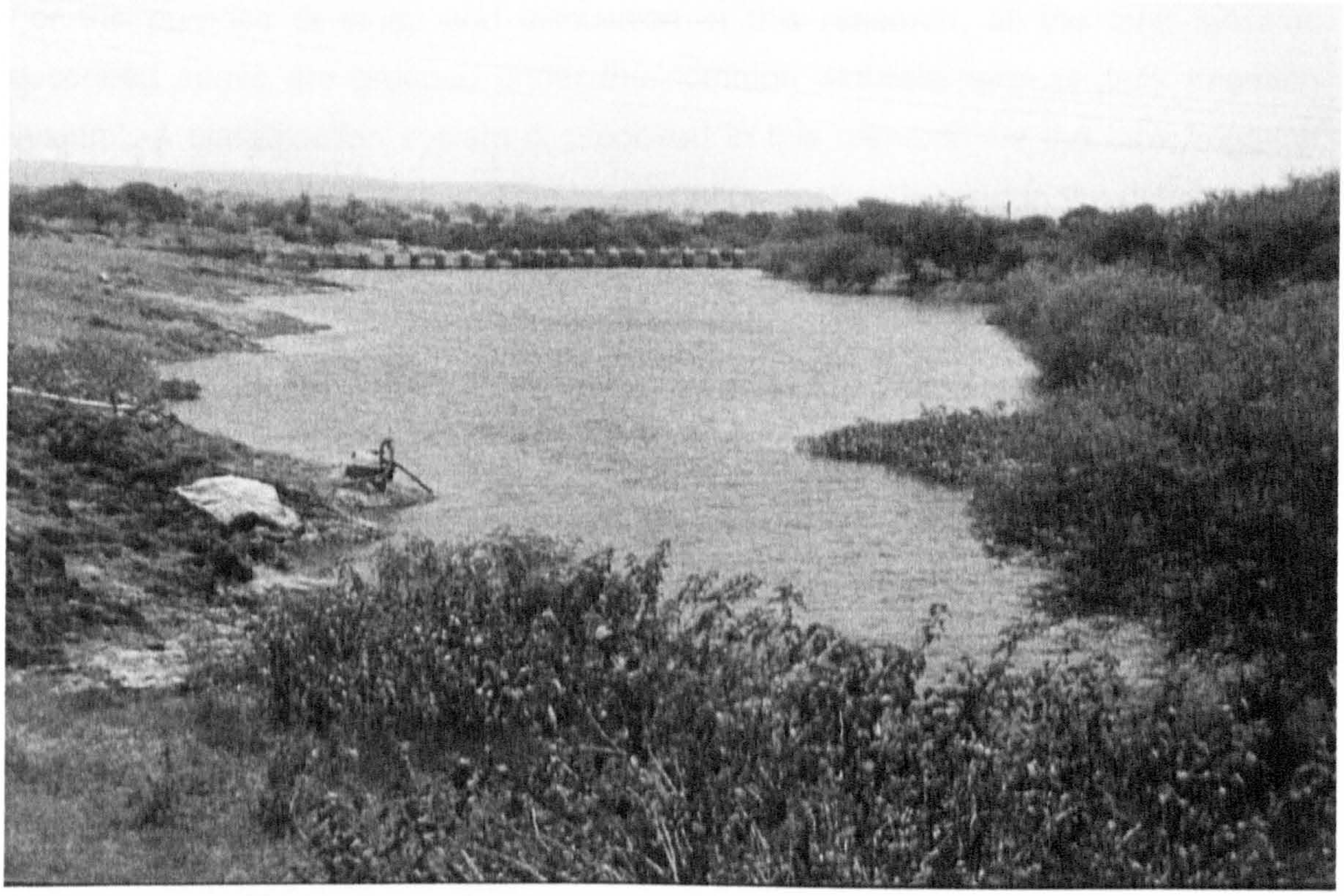


Figure 4.1 An embankment tank for groundwater recharge
(Source: MPKV, 2001)

Figure 4.2 An excavated tank (farm pond) for irrigation
(Source: MPKV, 2001)

For the purpose of study and discussion in this research, all the tank systems described above are grouped under the common umbrella term of 'tank irrigation system'. A classification system is proposed in this research for the tank irrigation systems and discussed below. This classification system is used in the development of methodology for finding the optimum 'tank system for the watershed.

4.3.2 Proposed tank classification

As discussed above water from the tank in the watershed can be used on the downstream or on the upstream side of the tank. This changes the orientation and extent of command area of the tank. Since the methodology proposed for tank design in this research is based on the catchment-tank-command water balance, it becomes imperative to include this aspect of changing command area of the tank in the methodology of tank design. Hence in this study tanks are classified based on the orientation of its command area. Tanks are classified into following three 'tank types'. The term 'tank type' has this specific meaning in this research.

1. Tank with command area on its downstream side (Type-1 tank)
2. Tank with command area on its upstream side (Type-2 tank)
3. Tank with command areas on both upstream and downstream side (Type-3 tank)

4.3.2.1. Tanks with command areas downstream (Type I tanks)

In this type of tank, command area is immediately on the downstream side of the tank (Fig 4.3). Most of the existing embankment type tanks fall into this category. Such tanks are found when sufficient catchment area is available to irrigate the downstream command. The command is normally less than the catchment area and the catchment-command ratio (CCR) may range from 5:1 to 50:1. But sometimes for good yielding catchments this ratio is less than one as in the case of Shiwalik tanks (see Section 4.3.6.2.1). Irrigation from stored water in the tank is normally by gravity flow and/or from groundwater through well irrigation in the downstream of the tank. Size of the tank may range from few hundred to few thousand cubic metres.

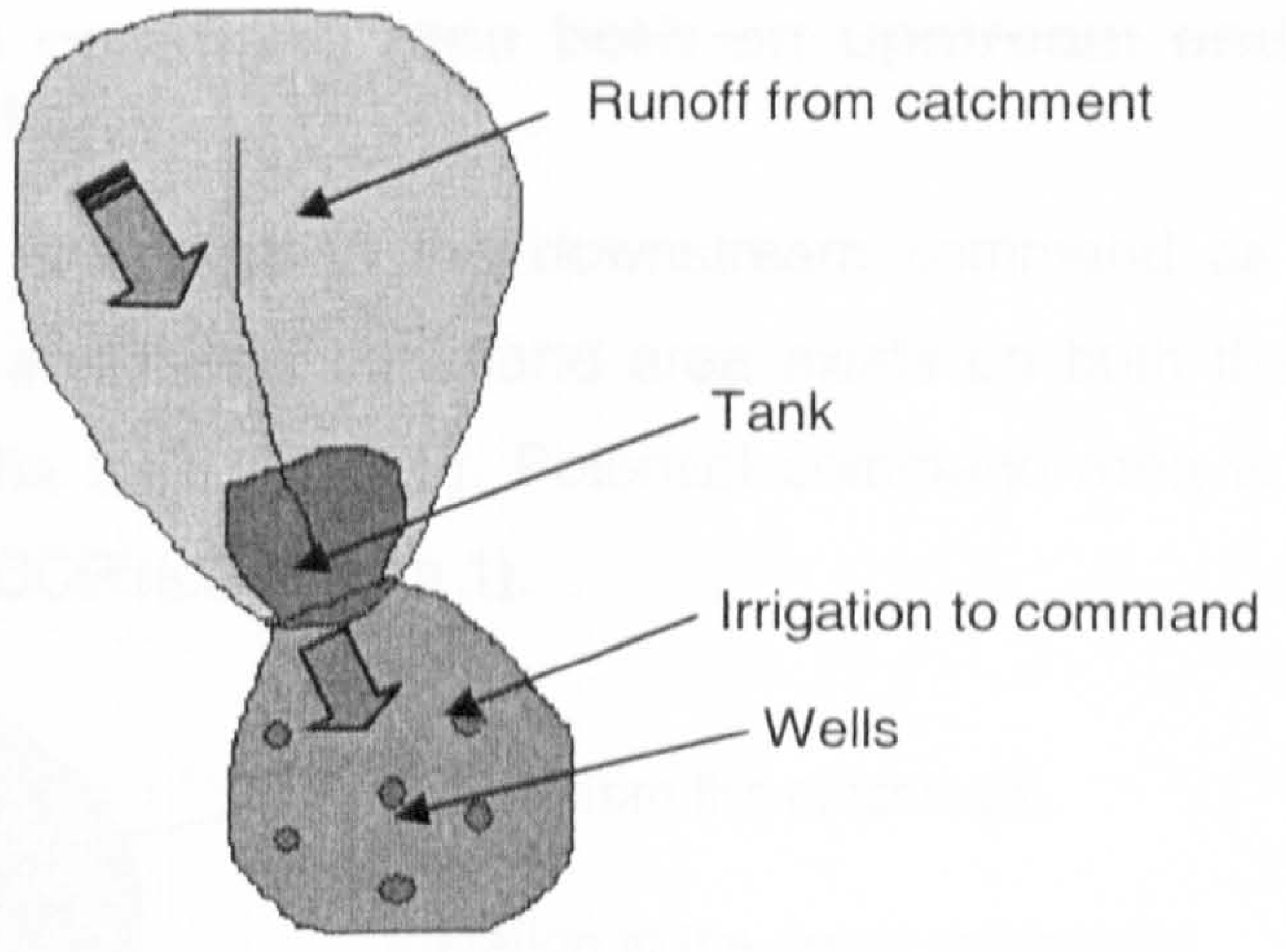


Figure 4.3 Tank with command area on the downstream (Type-1 tank)

4.3.2.2. Tanks with command areas upstream (Type-2 tanks)

In this system part (or whole) of the catchment serves as command area since water is lifted upstream in the catchment area for irrigation (Fig 4.4). Many times suitable site for the tank is available at the outlet of the watershed. Hence tank is constructed at the outlet. In this case there is no downstream command area for such tanks (geographical area exists but due to political or watershed boundary, water is not applied to this area) and water has to be lifted for irrigation in the tank catchment. Hence the potential command area and catchment area are same (CCR is 1). These are normally small systems to harvest more water with the limited catchments. The on farm reservoirs (OFR) fall into this category, where farm reservoirs are dug out at the end of sloping field and the water is lifted to the field for irrigation. This practice is very common in the eastern region of India (Panigrahi *et al.*, 2001), where irrigations to paddy crop are given through farm ponds by pumping water from the OFR.

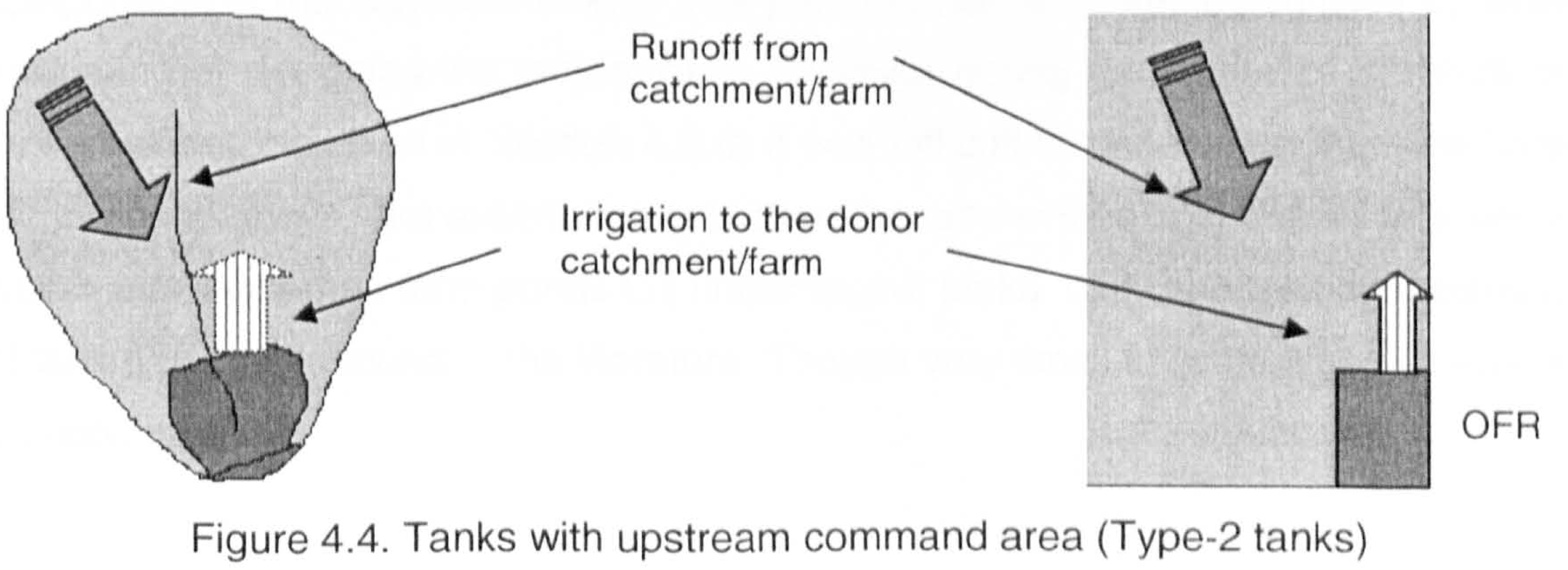


Figure 4.4. Tanks with upstream command area (Type-2 tanks)

4.3.2.3. Tanks with command area both on upstream and downstream (Type-3 tanks)

In this system water is applied to the downstream command as well as to the upstream catchment, and hence command area exists on both the upstream and downstream side of the tank (Fig 4.5). Potential command area is therefore more than catchment area (CCR is less than 1).

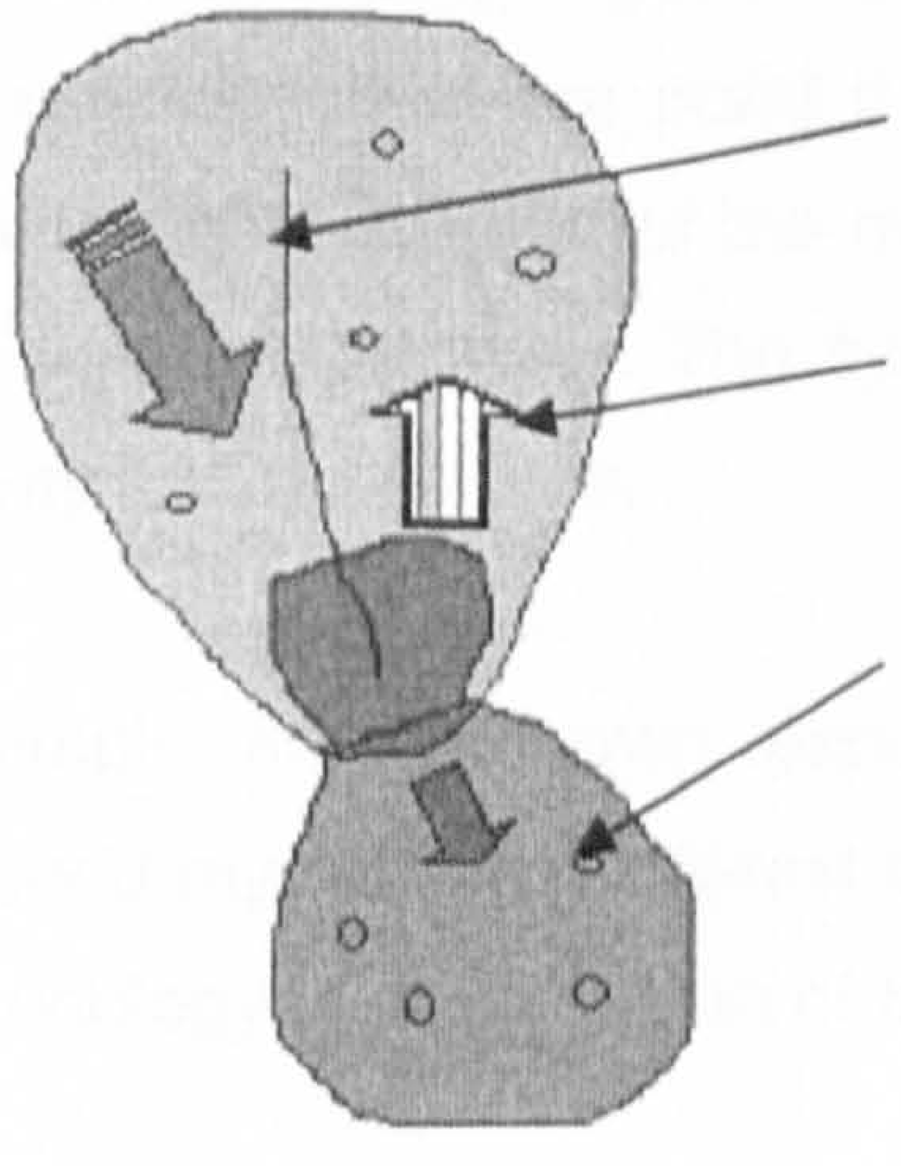


Figure 4.5. Tanks with upstream and downstream command area (Type-3 tanks)

Command area of percolation tanks depends on the 'zone of influence' of the tank which depends on the underground geology. Hence it is difficult to define the 'tank type' for percolation tanks based on the orientation of command area. But normally it is on the downstream side or surrounding the tank. Therefore percolation tank is assumed to come under any of the above tank types depending on the location of the tank and geology of aquifers.

The experience in the study area shows that many tanks designed as type-1 tanks were actually being used as type-3 tanks. Any changes like this in the tank system components or management affects tank performance and must be considered while evaluating or designing the tank system. However during the review of literature on tank studies (discussed in Section 4.3.6) it was difficult to understand the 'tank type' as proposed above. But experience tells that normally embankment tanks falls under type-1 tanks whereas farm ponds fall under type-2 tanks. Only one reported example of tank type-3 was found in the literature. Though very small in scale it needs special mention here.

Rathore *et al.*, (1996) conducted a study for rainwater harvesting in a rice-growing farm in Madhya Pradesh. The farm of 1.05 ha was divided into two fields. One upper field 0.66 ha and other lower field 0.30 ha with a farm pond (0.09 ha in area) at the junction of two fields. Rice was substituted with upland crops viz. soybean, pigeon pea and peanut in the upper field and the lower field was kept for original rice cultivation. Runoff from the upper field was collected in the pond and the water was used as supplementary irrigation to the crops in the upper field and to the lower field. Due to construction of the pond it was possible to take soybean-mustard and rice chickpea cropping system for the micro-catchment and service area (downstream) of the farm pond respectively. The system was found feasible in relation to water use, productivity and net returns.

This example and my own experience of tank water use in the study area strengthened my research interest to propose this tank classification and include it in the methodology of optimization of tank system design for the watershed.

4.3.3 Significance of the proposed tank classification

In watershed development projects tanks are constructed in the watershed. There may be a single tank in the watershed or a series of tanks on the drainage line. When there is single tank it may be of any type depending on its location and requirements. When it is a series of tanks they form cascade on the stream where command area of the upstream tank serves as the catchment area of downstream tank. The different tanks can assume different tank types in the watershed. This gives rise to a number of possible combinations of tanks based on numbers of tanks, their locations and tank types. Each of these combinations is a 'tank strategy' in this research. Hence the tank classification proposed above, helped to formulate the concept of 'tank strategy' for the watershed. The methodology (discussed in Chapter 6) for optimization of tank system for the watershed is based on this concept of 'tank strategy'. The concept is further elaborated in the following section.

4.3.4 Concept of tank strategy

Tank strategy for watershed as proposed in this research is a strategy that defines number of tanks, their locations on the stream and their types. In watershed, there are certain locations on the main drainage line (referred to as 'stream points' in this research) which are suitable for construction of a tank. When these stream points are known next question is "How many tanks and where to place them on these stream points?" For example if only one tank is to be built, it may be located on any of the stream points. The location of the tank has relationship with the tank type discussed above. Hence based on the number of tanks, their locations and types there is a certain number of combinations for the given number of stream points. Each of these combinations is one 'tank strategy'. For illustrative purpose, sample tank strategies are shown in Fig 4.6. The algorithm for generation of tank strategies is discussed in Chapter 6 (Section 6.3.3).

Once the tank strategy is defined each tank has to be assigned the fields in its catchment and command areas. As the tank type changes the command area and its corresponding fields change. As discussed above, catchment fields receive inflows in the form of rain and runoff whereas command fields receive inflows in the form of irrigation in addition to rain and runoff. If the tank is at the outlet of the watershed, it has to be of Type-2. In a series of tanks, the topmost tank will not have excess runoff from the upstream tanks whereas lower tanks will have excess runoff from the upper tanks. The proposed tank classification facilitated this kind of analysis through the concept of tank strategy.

4.3.5 Conclusion

Tank irrigation in India has been playing important role since ages in providing water for domestic use and irrigation. It will continue to play increasingly important role in future due to climatic, ecological and social requirements. Important tank systems in India are reviewed and a new tank classification for the tanks is proposed. This classification laid the foundation for methodology of tank system design in this research.

4.3.6 Evaluation of tank irrigation systems

As mentioned above, India has a long history of storage tanks for community use and irrigation purposes. These systems received less attention after the arrival of big irrigation projects in the country. But due to water scarcity and lowering of the groundwater tables in different parts of the country, there is renewed interest in these tank systems. In spite of their small scale and inherent problems, they are the only source of water for communities and agriculture in dryland areas. As a result, the existing tank systems are being studied for identifying the problems and system indicators to improve their performance. These studies also serve to develop guidelines for new tank systems. In this respect the catchment-storage-command relationships and tank water balance studies need special discussion. Following sections discuss these aspects of tank irrigation systems.

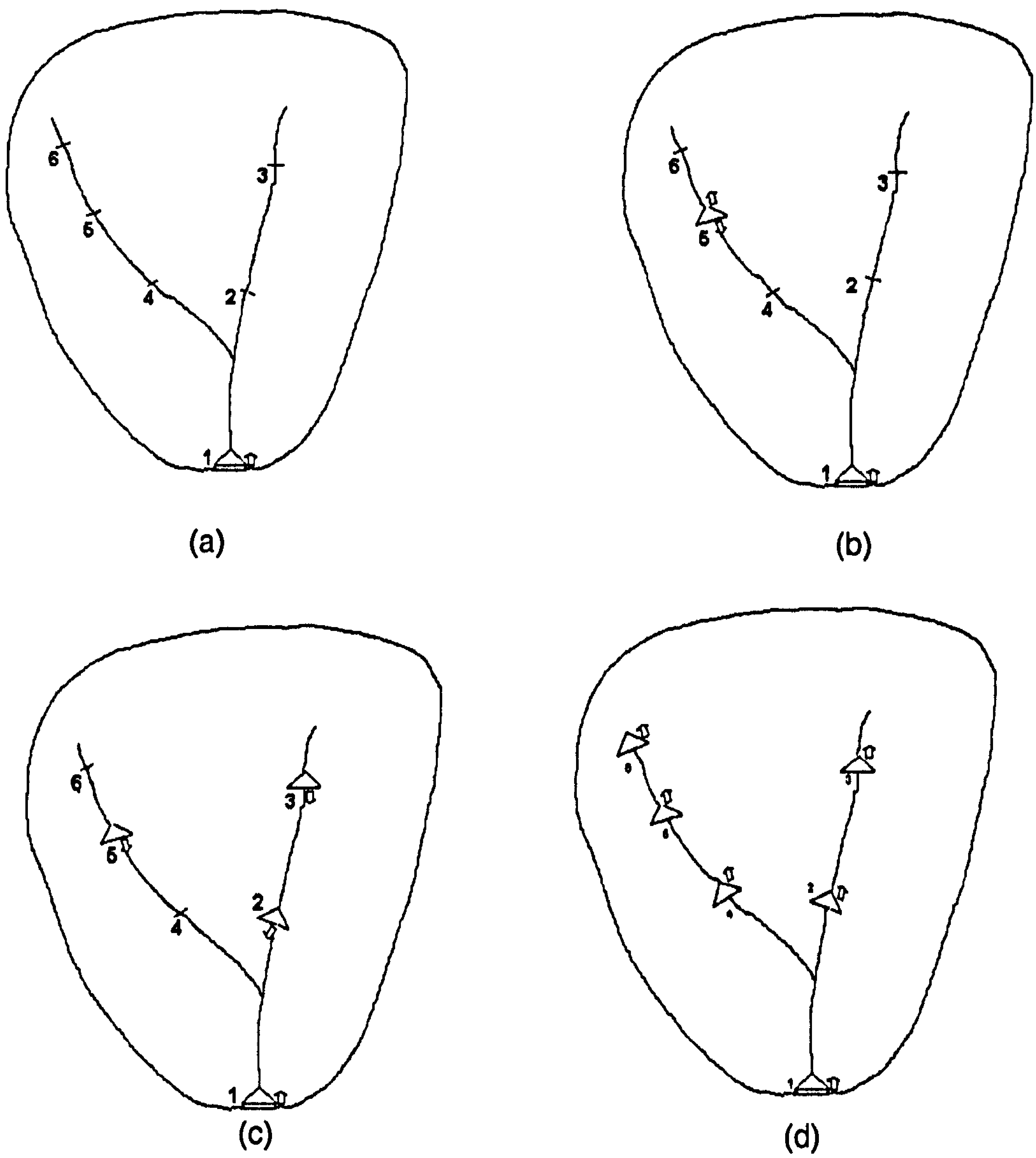


Figure 4.6. Illustration of tank strategy

Fig 4.6 (a) Tank strategy with one tank of type 2 at the outlet (stream point No 1) of the watershed.

Fig 4.6 (b) Tank strategy with two tanks - First tank of type 2 at the outlet of the watershed and second tank of type 3 at stream point No 5.

Fig 4.6 (c) Tank strategy with four tanks - First tank of type 2 at the outlet of the watershed, and all other tanks of type 1 at stream point No 2, 3, and 5.

Fig 4.6 (d) Tank strategy with six tanks – All tanks of type 2 at all the six stream points.

4.3.6.1 Lack of database on tank systems

The major hurdle in studying the existing tanks systems is the availability of data. To study catchment-storage-command relationship, data on as many tanks as possible are necessary. But since these are small-scale systems and often scattered in remote places, many times the data are discarded after the system is constructed (Ambler, 1994). Lack of reliable data on tanks has been a major constraint in planning the rehabilitation of tank systems in South India. Vital statistics like storage capacities of tanks at various periods of time, the number of fillings, figures on receipt of and supply of water and surplus amount of water are lacking (Anbumozhi *et al.*, 2001). With the help of available data from the literature an attempt is made here to investigate these relationships for tank systems for two regions of India.

4.3.6.2 Catchment-storage-command relationship of tank systems

A tank irrigation system has three main components- catchment, tank and command. Catchment yields runoff, which is stored in the tank for subsequent application of irrigation for the crops cultivated in the command area. While designing the tank, first step is always to select a site for a given location. The basic objective in selecting the site for a tank is to irrigate certain fields below it by natural flow (considering type 1 tank). This necessitates the pond to be so located that it has enough excess runoff flowing into it. Too small a catchment may mean that the pond would not have enough water stored up in time to make it available for irrigation. Too large a catchment may result in the quick silting up of the pond thereby shortening its life. Again the nature of the catchment itself has a lot of influence on the excess runoff from it. Storage and catchment depend on the magnitude, number and frequency of rainfall events. Large storage and small catchment combination is suitable for higher events for collection and also disposing runoff. Whereas small storage and large catchment combination is suitable for the maximum and frequent collection during lower events and their recurring usage to keep the storage available while maintaining soil profile moisture at favourable level (Das, 1990).

The relationship between capacity and command area defines how much water would be needed and at what time. This again, is variable factor. So this will vary from region to region as the cropping pattern varies. Conveyance losses are significant in large command areas (as in the case of south Indian tanks). These factors become important while deciding the command area for the tank.

These relationships are often expressed quantitatively as catchment storage ratio (CSR), which is catchment area in ha required to store 1 ha-m of volume of water and catchment-command ratio (CCR), which is catchment area in ha required to irrigate 1 ha of command.

There exists a relationship between these components (catchment, storage and command) of an efficient tank system for a given location. The knowledge of this relationship will help in developing guidelines for designing new systems and also for comparing the performance of different systems. Evidence from literature also confirms this fact. For example in Philippines, Guerra *et al.* (1990) found that minimum catchment area required to support a reservoir of given capacity was nearly five times higher for a grassed catchment than for a catchment under paddy. As mentioned by Das (1990), in South Australia, catchment storage ratio of less than 6 is considered as uneconomical. In Arizona, USA, 10 variable catchment and storage size relations have been examined for providing water to cattle and households. Such relationships need to be developed for Indian conditions.

India has been classified into nine water harvesting regions depending upon the geography, climate, soils and vegetation (Samra *et al.*, 2002). The catchment-storage-command relationship for the tanks in these regions will vary since the supply and demand parameters vary due to climatic changes. Therefore separate norms need to be developed for these regions. Nonetheless this is not an easy task. Though catchment-storage-command components are related with each other, their relationships vary as both supply (catchment) and demand (command) related relationships vary with agroclimatic regions. Sharda and Shrimali (1984) faced this problem of determining the ratio of catchment size to storage capacity in hilly region of Doon valley in northern India. Srivastava (1996b and 2001) designed tanks for which CCR ranged from 3 to 5 but he further observed that in most cases in Orissa there was no linkage between catchment area, size of the tank and area claimed to be irrigated (Srivastava, 2004). But efforts need to be made to study such relationships since they provide valuable information about the system in a nutshell. In this study, these relationships are reviewed for two regions of India for type-1 tanks and are discussed below.

4.3.6.2.1 Catchment-storage-command relationship for Shiwalik foothill region

In the northwest India, there is about 2.45 Mha of land, which falls in the Shiwalik foothills, comprising four states of Punjab, Haryana, Himachal Pradesh and Jammu and Kashmir. The land in the area is undulating and steeply sloping. The whole area is ecologically degraded. Annual rainfall in the region varies from 800 to 1250 mm (Sur *et al.*, 1999).

For Shiwalik foothill region data for 29 tanks were obtained from literature and are given in Table 4.1. Data for tank No. 1 to 10 was obtained from Grewal *et al.* (1989) and for tank No 11 to 29 from Samra *et al.* (2002) Catchment area for tanks in Shiwalik foothills ranged from 1.5 to 190 ha with an average 40 ha and storage capacity of tanks ranged from 0.80 to 62.30 ha-m with an average of 12 ha-m. Catchment per ha-m storage capacity (CSR) ranged from 0.11 to 16.80 ha with an average of 4 ha. The data on the command area were available for tank No 1 to 10 and the average command area was 18 ha with average CCR of 0.67. The relationships of tank storage capacity, CSR, and CCR with catchment area are shown in Fig. 4.7 (a), (b) and (c) respectively. From the figure it is seen that storage capacity of tank shows good linear correlation with catchment area (r^2= 0.93), whereas CSR and CCR do not show good correlation.

4.3.6.2.2. Catchment-storage-command relationship for Bundelkhand region

Bundelkhand region with a total geographical area of 7.01 Mha falls in the semiarid tropical climate. It comprises six districts of Madhya Pradesh and five districts of Uttar Pradesh. The region has undulating topography. Annual rainfall varies from 750-1200 mm.

For Bundelkhand region data on 12 tanks are given in Table 4.2. The tanks in the Bundelkhand region were bigger in size as compared to tanks in Shiwalik foothills. The catchment size ranged from 64 to 805 ha with an average of 262 ha. Storage capacity of tanks ranged from 7.57 to 358.65 ha-m with an average of 70 ha-m. CSR ranged from 1.92 to 28.01 ha with an average of 6 ha. Command area ranged from 45 to 405 ha with an average of 119 ha and CCR ranged from 0.84 to 6.84 ha with an average of 2.3 ha. The relationships of tank storage capacity, CSR, and CCR with catchment area are shown in Fig. 4.8 (a), (b) and (c) respectively. Figures show that tank storage capacity has good linear relation with the catchment area (r^2= 0.68) but CSR and CCR do not show good correlation. This trend is similar to the trend observed for tanks in Shiwalik region. The summary of these relationships for two regions is given in Table 4.3.

Table 4.1: Catchment area, command area, storage capacity, CCR and CSR for different tanks in Shiwalik region *(Source: Grewal et al. 1989 and Samra et al. 2002)*

Sr.No	Tank	Catchment area, ha	Command area, ha	Storage capacity, ha-m	CCR	CSR
1	Sukhomajri I	4.3	6.0	0.8	0.7	7.5
2	Sukhomajri II	9.2	20.0	5.6	0.5	3.6
3	Sukhomajri III	1.5	2.0	0.9	0.8	2.1
4	Sukhomajri IV	2.6	5.0	1.9	0.5	2.6
5	Jatanmajri I	2.9	2.6	1.6	1.1	1.6
6	Jatanmajri II	4.8	4.4	2.3	1.1	1.9
7	Dhamala I	16.0	38.1	6.7	0.4	5.7
8	Dhamala II	3.1	5.3	1.7	0.6	3.2
9	Lohgarh I	9.1	18.3	5.2	0.5	3.5
10	Lohgarh II	42.2	80.2	18.5	0.5	4.3
11	Nada-1	25.0		5.4		4.7
12	Nada II	22.0		3.7		6.0
13	Nada III	11.7		1.9		6.1
14	Dulopur I	72.0		2.8		25.9
15	Prempura	34.0		4.5		7.5
16	Paniwala I	48.0		7.3		6.6
17	Moginand	28.0		3.9		7.2
18	Chowki II	60.0		6.2		9.7
19	Ambwal III	88.0		3.1		28.6
20	Parch II	8.1		2.9		2.8
21	Chott.bari Nangal	10.8		2.8		3.9
22	Fatepur II	20.0		3.6		5.6
23	Majrikahot	27.4		2.4		11.6
24	Hirdapur	54.7		3.6		15.3
25	Nada	125.0		3.6		35.1
26	Karoran III	63.0		4.3		14.7
27	Bardar	190.0		3.1		62.3
28	Majothu	7.0		2.8		2.5
29	Basolan	42.0		5.7		7.4

Table 4.2: Catchment area, command area, storage capacity, CCR and CSR for different tanks in Bundelkhand region *(Source Samra et al. 2002)*

Sr. No	Tank	Catchment area, ha	Command area, ha	Storage capacity, m^3	CCR	CSR
1	Badoni	129	16	42.50	9.20	8.06
2	Agora	805	137	358.65	8.06	2.24
3	Bhadera	362	84	109.19	5.88	3.32
4	Unao	241	55	78.55	4.30	3.07
5	Rawatpura	684	62	98.88	4.38	6.92
6	Raja ka Tal	161	27	55.74	11.03	2.89
7	Parasari	80	18	25.67	5.96	3.11
8	Lallana	80	12	17.00	4.44	4.71
9	Gyarah, Naya	364	53	51.35	6.67	7.09
10	Pipra	212	63	7.57	6.86	28.01
11	Silori	64	49	23.32	3.36	2.74
12	Jignia	233	77	21.51	1.30	10.83

Table 4.3: Summary of catchment area, command area, CCR and CSR for two regions

Region	Average catchment area, ha	Average storage capacity ha-m	Command area, ha	CSR	CCR
Shiwalik	40 (0.7)	12 (2.8)	18	4	0.7
Bundelkhand	262 (2.3)	70 (13.8)	119	6	2.3

(Figures in bracket represent catchment and storage for 1 ha command area)

4.3.6.3 Conclusion

The catchment-storage-command relationships of tanks in the two regions of India were analysed. From the analysis it is observed that the CSR and CCR indices do not show any correlation with the catchment size within the particular region but they do show variation between the regions. In Shiwalik region the CSR is 4 and CCR is 0.7 indicating that 0.7 ha catchment and 2.8 ha-m storage is required to irrigate 1 ha command area. Runoff potential of the area is very high hence catchment area required is less than the command area for the latter's irrigation needs. In the case of tanks for Bundelkhand region the CSR is 6 and CCR is 2.3 indicating that 2.3 ha catchment and 13.8 ha-m storage is required to irrigate 1 ha of command. From the comparison of statistics of tanks of two regions it is observed that more catchment area and storage capacity per ha command area is required for the tanks of Bundelkhand region than the tanks of Shiwalik region. Since other data like water balance and the economics of these systems were not available, it is difficult to conclude whether these relationships could be treated as bench mark for other tank systems. Hence there is the need for the data inventory of these systems.

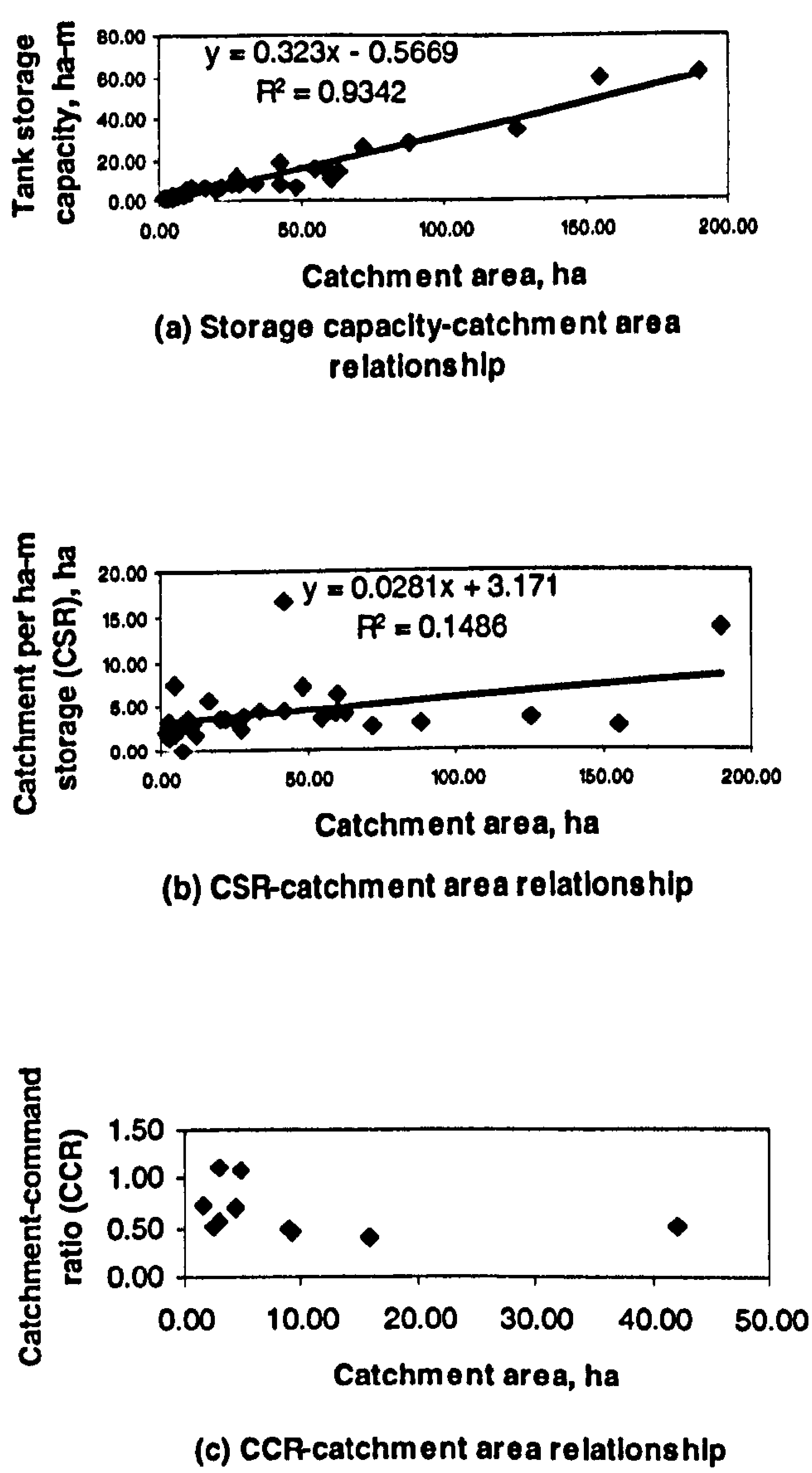


Figure 4.7 Storage capacity, CSR, CCR relationship with catchment area for tanks in Shiwalik foothills regions

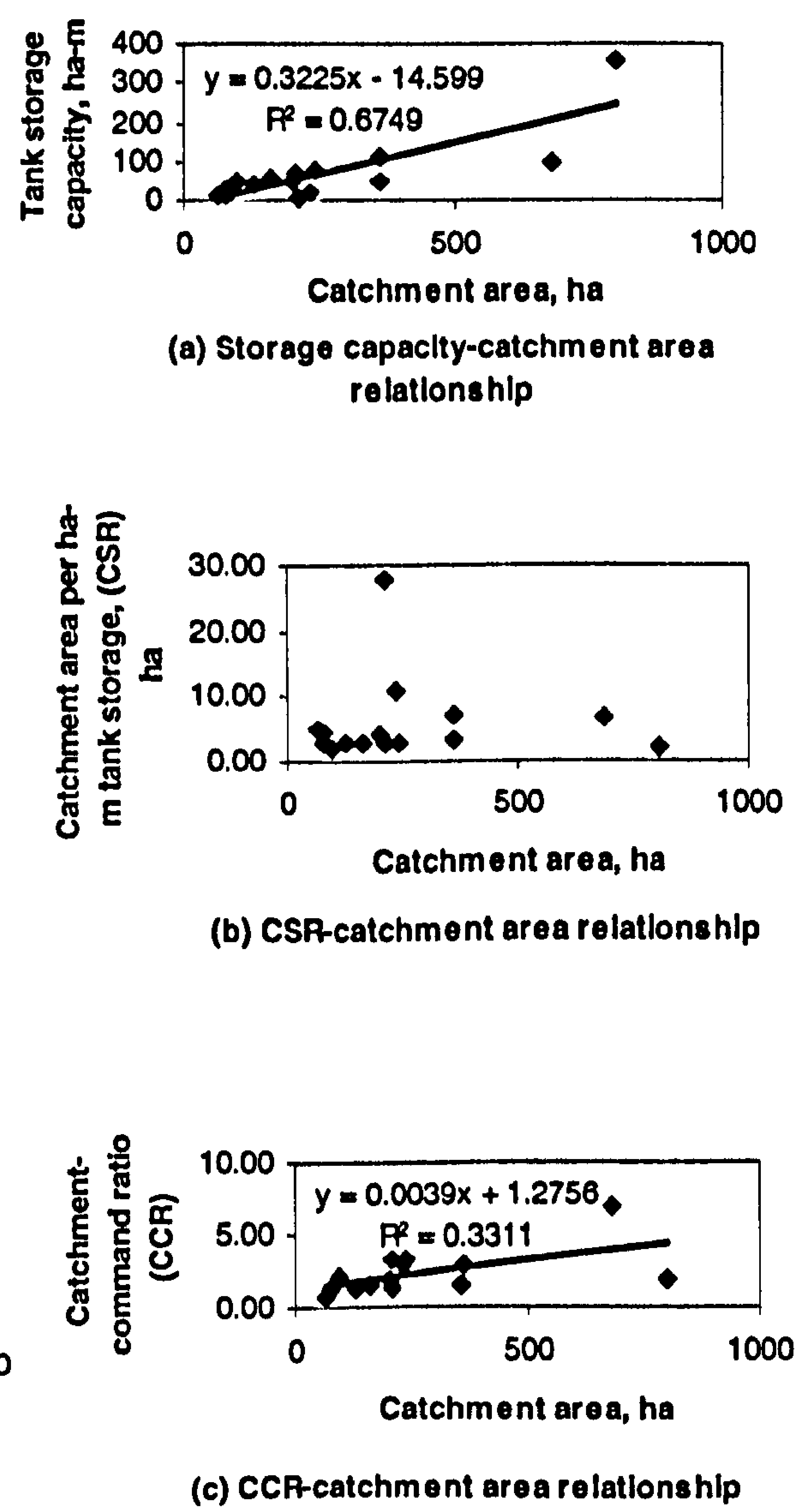


Figure 4.8 Storage capacity, CSR, CCR relationship with catchment area for tanks in Bundelkhand regions

4.3.7 Tank water balance studies

Tank water balance studies involve measurement of water balance components of tanks and investigations on the improvements in the system performance. These studies generate useful information about the water harvested, losses and water use for productive purposes from the tank and thus serve to develop guidelines for the design of new tanks. Water balance studies conducted by a few workers are reviewed and discussed below. The summary of these studies is also given in Table 4.4 (at the end of the Chapter).

Grewal *et al.* (1989) conducted water balance study of a tank in the Shiwalik foothills of India for 10 years. The catchment area, storage capacity and the command area of the tank were 9.2 ha, 5.56 ha-m and 20.0 ha respectively. The quantity of water used from reservoir varied from 0.32 ha-m to 4.79 ha-m and varied with rainfall. The 10 year average of quantity of water utilised and area irrigated were 1.66 ha-m and 9.56 ha (in two crop seasons) respectively. Maximum area irrigated in *rabi* season was 18.5 ha when two irrigations were provided to wheat crop. They reported that system was found economically viable. Productive water use from the system was less due to good monsoon in the area and hence the irrigation requirements of crops were low.

Sur *et al.* (1999) studied water balance for three small water harvesting structures (earthen dams across the seasonal streams) for improving the water availability in the lower Shiwaliks region of Punjab in northern India. The catchment areas of these dams were 77.2, 6.6 and 17.3 ha respectively. The capacities of tanks were 12.35, 1.51 and 4.66 ha-m respectively. On an average 9.3, 1.8 and 4.8 ha-m of water was harvested respectively in these structures. The major mode of the water loss was seepage. The loss of water due to seepage varied from 61% to 86% of the total loss at these sites. They found that pre-sowing irrigation (if required) or a single supplemental irrigation could be provided between October and December during the *rabi* season. Because of high variability in the hydrological parameters of the area in time and space, they suggested more long term, location specific studies.

Guerra *et al.* (1990) quantified the hydrological parameters of four farm reservoirs in Philippines. The reservoir capacities of the farm reservoirs were 3997, 2872, 1139 and 1016 m^3. The average farm size in the region is about 3 ha. The stored water was used to supplement rainfall for wet season rice production and to irrigate a dry season rice crop on approximately one third of the farm area. Farmers without reservoir could not grow a dry season crop. Study indicated that direct rainfall and runoff from the catchment area contributed, respectively, about 36% and 64% to reservoir inflow. Typically, farmer's use of stored water accounted for about 30% of the total water outflow from reservoir. Seepage and percolation losses accounted for about 45% of the outflow volume and evaporation loss of about 25%.

Mugabe *et al.* (2003) conducted study on Mutangi dam, a small reservoir (surface area, 8.7 ha; capacity 111,000 m^3; maximum depth, 2.5 m) in a semi-arid area in southern Zimbabwe during the 1999-2000 and 2000-01 seasons. In these seasons, the Mutangi catchment received 755 and 615 mm of rainfall of which 13% (102 mm) and 10% (62 mm) resulted in runoff, respectively. Of this runoff, 79 and 45 mm spilled over the dam and 24 and 19 mm was stored by the reservoir in 1999-2000 and 2000-01 seasons, respectively. Monthly rates of water loss/use from the dam varied between 3.8 and 8.6 mm/day in November. In volume terms, the highest rate of loss occurred when the dam was full and its surface area was at its maximum. Almost 97% of the loss was through surface evaporation with only 3% used productively. They generated scenarios on how much water could be used for irrigation in years with different rainfall. They claimed to increase water usage by a factor of 5. The later the last spill occurred, the more water was available for productive use. It was suggested to use water earlier in the dry season when volumetric loss rates were highest. The study highlighted that the management approach that matches the quantity of water used to the amount of water in the reservoir for sustainable use of surface water resources was required.

4.3.7.1 Conclusion

The water balance studies by Grewal *et al.* (1989) and Sur *et al.* (1999) indicated low productive use of water due to less irrigation requirement of crops in the former and high seepage rates in the latter case. However in the case of drought years it was possible to grow some crops with the water available in the tank, which recovered the system cost in the case of Grewal *et al.* (1989). Studies on four farm ponds carried out by Guerra *et al.* (1990) in Philippines showed irrigation water use from 8 to 32 %. One case study from Zimbabwe by Mugabe *et al.* (2003) showed in spite of large size of reservoir, the productive use of water was only 3% as most of the water was lost through evaporation. These studies therefore provided insights into the gains and losses of water from the reservoir in a particular region to improve upon the system performance. For example losses due to seepage and evaporation is the major disadvantage of small tank systems and hence while designing the tank system these need to be considered and minimised. These losses can be reduced by locating the tank at appropriate site or optimising the dimensions of tank for minimum seepage and evaporation (as is done in the present investigation). In addition seepage can be reduced by lining the tank. But lining seems to be feasible only for small on farm reservoirs. For other tanks seepage has to be reduced by proper selection of site and optimum dimensioning of tank. It should be mentioned here that with the concept of IWSS (on which tank system design in this study is based) seepage losses contribute to the groundwater storage, which is utilised for irrigation through wells. Hence part of the seepage losses is reused through well irrigation. Hence evaporation will be the major loss through the tanks designed with the concept of IWSS.

4.4 Integrated use of storage system

The success of any RWH project depends on both harvesting of water and its subsequent use for crop production. Hence utilization of water from soil, tank or aquifer becomes equally important. When utilizing these water storages, it is necessary that they be used optimally and in an integrated way. At some places, integrated use is already in practice. For example in South India number of wells in the tank command is increasing. The increasing quantity of groundwater is utilised for irrigation, which is recharged by the storages in the tanks. Wells are mostly used in the post rainy season when there is no water in the tank. These practices should be supported with research to make them sustainable. But literature is lacking on this aspect of integrated use of storages at watershed level. One study on the integrated use of these storages was found in the literature and needs special mention here since the system was designed to integrate tank and groundwater storages.

Srivastava and Satpathy (2005) designed a water harvesting system with tank and wells in the command area of the tank in the high rainfall eastern region of India. The soils in the area are highly permeable. The study showed that the system recharges groundwater significantly to the tune of 1000 m^3 per hectare (additional water to the tune of 8-10 % of monsoon rainfall). This recharge was harvested back through dug wells. Dug wells in the recharge zone provided five times more water than outside the zone. About 37% of the runoff received was lost as seepage (which they considered as recharge to groundwater) out of which 14.1 % was reharvested back through open dug wells. The system made more water available for productive use within watershed by about 32.6%.

4.5 Closure

Different tank irrigation systems that exist in India were reviewed and discussed in this Chapter. These tank systems serve the purpose of groundwater recharge or irrigation or serve both these purposes, in addition to domestic use. Based on the experience and need of this research a tank classification system has been proposed in this study and discussed in the chapter. Though tanks were constructed by considering the aspect of use of water on the upstream or downstream side, they were not classified on this aspect. The proposed classification that classifies tanks according to the relative orientation of command area (responsible for demand) which also influences the catchment area (responsible for supply) is helpful for designing the tank system for its optimum utilisation. The different tank types proposed in the classification were included in the tank strategy that is combination of number of tanks, their locations and types in the watershed for optimum utilisation of water for irrigation. This Chapter therefore fulfils part of the second hypothesis of this research and fulfils the second objective of defining the tank strategy for the watershed.

My observations show that there are numerous studies on tanks but these are not either properly documented or not documented. For example there are more than 10,000 percolation tanks in the region where I work but I could not find any data on their design specifications or on water balance studies. Hence it was difficult to conclude about the catchment-storage-command relationship of these tanks. The recording of these data is helpful for further studies and hence there is need to build inventory of these systems.

The studies on water balance on tanks indicated that the different losses are significant and need to be considered in its design. The methodology developed in this study includes all these losses and also aims at minimising these losses while utilising the water.

Table 4.4: Summary of water balance studies of ponds/tanks

Tank	Location	Catchment area, ha	Storage capacity, ha-m	Water harvested, ha-m	Seepage & Percolation%	Evaporation %	Overflow %	Utilisable water, %
B.S.	Shiwalik foothills, India	77.2	12.35	9.35		79	--	21
Takarala		6.6	1.51	1.79		78	--	22
Karoran		17.3	4.66	4.79		46	--	54
Grewal		9.2	5.56	2.25			--	---
Pond-1	Philippines	2.6	0.40	1.01	34	25	9	32
Pond-2	Philippines	5.8	0.29	0.83	27	26	19	28
Pond-3	Philippines	2.0	0.11	0.24	62	30	--	8
Pond-4	Philippines	0.8	0.10	0.23	50	20	--	30
Tank-1	Zimbabwe	590	11.1	12.98	--	97	--	3

Chapter 5

APPROCHES FOR DESIGN OF TANK IRRIGATION SYSTEMS

5.1 Summary

This chapter discusses different approaches for design of tank systems that have been used in India and abroad. The findings of tank design are also discussed. At the end, merits and limitations of different approaches are discussed and need of a new approach for the present investigation is emphasized.

5.2 Introduction

In India tank irrigation systems have been in operation for centuries. There are different tank irrigation systems in different parts of the country and some systems are discussed in Chapter 4. Each of these tank systems is unique and has been evolved through the socioeconomic needs and climate of that particular region. Small farm ponds for rice based cropping system in Eastern India are entirely different than the south Indian irrigation tank systems. Check dams in Maharashtra are different to tanks in north-eastern hilly region. Tanks in Rajasthan and Gujarat are different to those in Shiwalik region. Whatever may be the tank system, it can be designed for optimum use by studying its supply and demand parameters.

5.3 Design of tank irrigation system

Tank system should be properly designed for its efficient performance and overall system economy. Design of a tank system involves determination of the following parameters. Hydrological analysis of the catchment along with catchment, tank and command water balances are worked out for determining these parameters.

1. Location of tank
2. Storage capacity of tank
3. Type of storage
4. Shape of the storage tank
5. Other system components

5.3.1. Tank location

Tank location depends on number of factors including purpose of the tank, topography, site conditions and social aspects. For example if the tank is to be used for storage, then the location should offer the tank site for maximum storage with surface area exposed to have minimum seepage and evaporation losses. Whereas, if the tank is to be used for groundwater recharge then site should have high seepage rates in addition to suitable aquifer below. Location is also affected by the tank type (as defined in Section 4.3.2). Sometimes value of land can be major consideration in deciding the tank location. Hence OFR may be located on the farm to take advantage of non-productive (or low quality) piece of land. If possible water should be allowed to flow to all points of use by gravity. Many times combinations of these factors decide the tank location and it is difficult to find a location that simultaneously meets all the criteria.

5.3.2. Storage capacity of tank

Storage capacity is the most important factor since it decides the availability of water for crop production and/or domestic use. This depends on runoff volume from the catchment, its temporal distribution and pattern of water withdrawal including losses through seepage and evaporation. Where the siltation in tanks is excessive as observed in the Shiwalik foothills (Sur *et al.,* 1999), tank capacity should also consider this aspect. In the case of small tanks, silt is excavated from the tank bed after every 3-5 years and provision for silt deposition is not made in designing the tank storage capacity. In the case of large tanks a provision of dead storage is made when deciding the tank storage capacity.

5.3.3. Type of storage

Storage type refers to the way tank is constructed. Storage type depends on the site conditions. If the tank is on the stream, tank is constructed by putting an embankment on the stream (see Fig. 4.1). The tank on flat lands is of excavated type as in on farm reservoir (OFR) (see Fig. 4.2). Sometimes excavation and embankment are combined to increase the storage excavation (S/E) ratio of tanks. S/E ratio is discussed in Chapter 6. (Section 6.3.7.2).

5.3.4. Shape of the storage tank

Normally the embankment type of tanks has irregular shapes whereas the tanks of excavated type have regular shape. All of the studies described below consider the regular shape of tanks. Irregular shapes can be approximated to the regular shapes as discussed in Section 6.3.7. For excavated tanks shape can be square prism, rectangular prism, inverted truncated pyramid, inverted truncated cone, cylindrical, parabolic or hemi-spherical. These different shapes have been considered in developing the methodology of tank design and are discussed in Section 6.3.7. Once the shape is fixed, tank dimensions can be optimised for the specified volume of tank.

5.3.5. Other system components

Other tank system components include mainly the spillway, sluices, irrigation channels, gates etc. Spillway is used for disposing the excess runoff and for satisfying the downstream release requirements. It is designed with the estimate of peak rate of runoff for the location. Sluices and irrigation channels are designed for satisfying the peak irrigation requirement.

5.4. Approaches for design of tank storage capacity

Out of different tank system components discussed above, tank storage capacity is the most important and its determination involves lot of complexities. Hence it has attracted the attention of many researchers. Since the aim of this research is to design a optimum tank system for watershed which includes number of tanks, their locations and types along with their storage capacities, following paragraphs discuss the different approaches for estimating the storage capacity (or size) of tanks along with the findings of their studies. These approaches are broadly discussed under the following categories.

1. Empirical studies
2. Optimization modelling
3. Simulation-optimisation modelling

5.4.1. Empirical studies

People have been using thumb rules, empirical equations and local experience in the absence of any reliable information for the design of tank systems. Many times these approaches are based on the understanding of local hydrology. Guidelines for tank sizes are also determined based on the experiments with existing tank systems. Many times these studies relate storage capacity with the catchment area in terms of CSR as presented in Table 5.1. In the absence of more analytical approach, these studies have been serving as valuable guidelines for designing tank systems in different regions. Some of these approaches are described below.

In the early stages of pond design in the Damodar valley in India no data were available for pond design. Hakim (1952) reported that therefore 200 mm of runoff from each ha during the first period of the monsoon i.e. up to middle of July was assumed for deciding storage capacity of ponds. During this period the average total rainfall amounted to about 350 to 450 mm Therefore for the ponds with assumed average depth of 120 to 150 cm, the area of their water spread would be between $1/6^{th}$ to $1/8^{th}$ of the catchment area. This assumption was adhered to as far as possible in the various ponds that were constructed. No consideration was given to the nature of the catchments in the earlier designs.

At Karnal in Haryana, Gupta and Narayana (1974) considered a typical heavy storm to design storage capacity of three ponds. The storm of 239 mm occurred from July 7 to 11, 1972 (3 and half day duration). The corresponding storage capacities were 1.44 ha-m for 30 ha catchment, 0.22 ha-m for 6 ha catchment and 0.80 ha-m for 26 ha catchment. However they did not report the return period of this storm.

Singh (1991) recommended that the pond volume should be half or less than half of the total amount of annual runoff expected from the catchment whereas Sivanappan (2005) estimated tank capacity as $1/3^{rd}$ of the annual yield of the catchment.

Juyal and Katiyar (1991) reported that in Doon valley 0.20 ha-m capacity farm pond could be constructed for every 1 ha of catchment area (giving CSR of 5). In another study in Doon valley, Sastry and Singh (1993) worked out the relationship between the catchment area-pond size to 1 ha-m capacity for every 6 and 9 ha of catchment area for lined and unlined ponds respectively.

The thumb rules were also used for design of percolation tanks. For example as reported by Selvarajan *et al.* (1995) in Tamil Nadu state of India the effective zone of pond recharge (i.e. the zone of influence) is considered as the area within 945 m radius from the centre of the pond and for design purposes, 50% of the gross storage was taken as the annual recharge from ponds.

Regional studies on the design of tank systems are being conducted in India and Samra *et al.* (2002) compiled this information for different regions of the country. Some tank capacity recommendations as compiled by them are given in Table 5.1.

Table 5.1: Tank capacities for different regions based on catchment area

Region	Rainfall, mm	Topography	CSR*
Shiwalik region	1100	Steep slopes, sparse vegetation	4 to 7
Southern hill region	500-6000	Rolling topography	8-20
Bundelkhand region	750-1200	Undulating topography	12 Hilly areas 25 Flat lands
Doon valley	1250	Steep slopes	6 for lined pond and 9 for unlined pond
Black soil region	750-1250	Varying	30-40
Ravine region	700-800	Network of deep gullies	10-20
Red soil region	550-1250	Varying	40

*(*CSR: Catchment area in ha required per ha-m storage capacity)*

5.4.2 Optimization modelling

Mathematical modelling involves representing various relationships about the tank system parameters in the form of mathematical equations. These systems of equations are then solved by optimisation techniques. In optimization, the problem consists of an objective function and constraints. The objective function represents the quantity to be maximized (or minimized) and the constraint equations represent the restrictions imposed by the resources or system boundary conditions. An objective function in tank irrigation system may be maximization of storage volume or net benefits from tank system or minimization of storage losses or system costs. The constraints equations may include the restrictions on catchment and command area, conservation equations etc. Simononovic (1992) reported that optimisation techniques can be classified as linear programming (LP); dynamic programming (DP) and non-linear programming (NLP). Each of these techniques can be applied in a

deterministic and stochastic environment. Following paragraphs describe some studies by mathematical modelling for designing the storage capacity of tanks.
Sharma and Helweg (1982) analysed the optimal small reservoir problems as constrained or unconstrained. The constrained problem was formulated when the size of the catchment limited the reservoir (tank) volume. They described the constrained tank capacity and dimensions optimisation problem where they formulated the objective function of maximization of net benefits in terms of tank capacity. Constraints included catchment area, location of tank from the outlet of the catchment, and non-negativity constraints on the dimensions of the tank. They developed the functions for runoff volume and irrigation volume as a function of distance from the outlet of the watershed. Helweg and Sharma (1983) discussed the unconstrained tank capacity and dimensions optimization problem when unlimited runoff (supply) and command area (demand) were available. Tank volume was optimized for maximum net benefits. They derived the equation for objective function in terms of tank capacity and solved by nonlinear optimisation algorithm.

Srivastava (1996a) designed a tank system for hilly terrain of north-eastern India. He solved the design problem by the method of decomposition and multilevel optimisation. The problem was formulated at two levels. The first level comprised optimisation programmes corresponding to a set of number of tanks and a conveyance system. An optimal cropping pattern was selected on the basis of the benefits of agricultural production and the costs associated with the irrigation water allocation. The technical constraints defined the feasible set of the decisions for the command area of each tank. The first level optimisation was carried out by linear programming to achieve the single objective and by goal programming to achieve the multiple objectives for each set of number of tanks and conveyance system combinations. The input to the first level was the coefficients of the constraints and the objective function. The second level involved the mathematical representation of catchment and command area characteristics, estimation of tank size, optimisation of tank dimensions, estimation of cost of tank, estimation of weighted investment cost of storage of water, estimation of dimensions of conveyance and application. The model was run for four individual objectives of i) maximizing net returns, ii) maximizing increase in production due to irrigation per unit investment in water resources development, iii) maximizing gross irrigated area per unit investment in water resources development, iv) maximizing runoff retardation per unit investment in water resources development and for multiobjective function combining the above four objectives. Thus the model gave a detail optimal design of a multitank irrigation system entailing a number of tanks, their locations, size, dimensions, type of conveyance system, type of application system and area under various crops and their irrigation levels by accounting for all the interacting factors in an integrated manner.

Srivastava (1997) optimised the design parameters for a runoff recycling based irrigation system for vegetable farming in hills of northern India. The design criteria included the size of tank and catchment-command area ratio (CCR). The objective function consisted of equation relating tank capacity with command area, CCR, gross irrigation requirement and evaporation losses (seepage losses were not considered since the pond was lined). The equation was solved for the constraints relating runoff potential with the irrigation needs. As the catchment-command area ratio increased from 0.1 to 0.5, the size of the tank decreased from 39 m^3 to 15 m^3. The system was designed with a view to get round the year vegetable production on fields nearby farmstead (a farm house surrounded by cultivable farm) with the runoff harvested from impermeable surfaces of farmstead such as rooftops etc.

5.4.3. Simulation-optimization modelling

A simulation model is usually characterised by a representation of a physical system used to predict the response of the system under a given set of conditions. Simulation models of tank system include simulation of tank and cropped area water balance. They may also include economics, irrigation benefits and other similar characteristics. Simulation models are often used with historical period of record. The simulation model is not able to generate an optimal solution to a reservoir problem directly. However when making numerous runs of a model with alternative decision policies it can detect an optimal or near-optimal solution (Simononovic, 1992). It is an appropriate technique to study the performance of a tank irrigation system since it embodies the variables and relationships that characterise an irrigation system and permits the evaluation of alternatives which may not be possible in real world systems (Palanisami and Flinn, 1988). Following paragraphs describe the simulation-optimisation approaches for designing the tank system. These are mainly simulation approaches and the optimum tank size is derived by taking a repetitive simulation runs. The optimum tank size is derived based on net benefits.

Palmer *et al.* (1982a) proposed a simulation approach for designing size of small reservoir in USA. This approach involved simultaneous simulation of crop water balance and tank water balance and formed the basis for many later studies in India and hence needs detail description.

Palmer *et al.* (1982a) developed a simulation model combining a watershed runoff model and a corn grain model to determine the reservoir size necessary to ensure the availability of water on a probability basis for irrigation. Model consisted of five components viz. i) crop growth-soil water function, ii) water supply function, iii) reservoir water balance-reservoir sizing routine, iv) site characterisation function and v) climatic simulation model. Crop growth-soil water function simulated the yields of maize as a function of soil water. Water supply function simulated the inflow to the reservoir. Reservoir water balance simulated the size of reservoir. Site characterisation function gave the site-specific inputs to the model and climatic simulation model simulated the climatic parameters with Monte Carlo techniques. Of these functions the reservoir water balance function is relevant to be discussed further here.

In order to size the reservoir Palmer *et al.* (1982a) assumed initial dam height and daily reservoir water balances were calculated starting from the beginning of the simulation period. If the reservoir became dry during any year of the data set being analysed, the dam height was incremented, thereby increasing the volume of reservoir. Simulation was then continued after returning to beginning of that year's data set. The model continued to increase the reservoir size until a size was reached that supplied irrigation water at all times for the period under study. They referred to this size as the maximum reservoir size. Later this reservoir size was reduced and corresponding risk of crop failure was estimated. Return period calculations were made on yields to obtain probability curves of yield as a function of reservoir size for the simulation period. Such information enabled the user to make better decisions regarding selection and design of irrigation water supply reservoirs.

Palmer *et al.* (1982b) in the second part of their study, conducted the economic analysis of the reservoir system to determine the optimum reservoir size based on maximum net returns. Procedures were presented to determine the optimum reservoir size as well as the information about whether or not supplemental irrigation was economically feasible. Grain yields and irrigation expenses were calculated for each reservoir size. The factors considered were the increased income from grain yield, additional expenses from irrigation and reservoir construction cost. A family of curves was generated at different risk levels, which indicated the amount of capital which could be justified for investment in the irrigation systems as a function of reservoir size. These curves were recommended as a guide in deciding if irrigation was economically feasible as well as sizing the water supply reservoir.

Verma and Sarma (1990) developed a model to design a tank for water harvesting for a *Kandi* dry farming region of northern Punjab in India. The main criterion for determining the volume of tanks was taken as the lowest assured runoff occurring during 24th to 35th week (periodical runoff) for irrigation to maize and during the 24th to 39th week (seasonal runoff) for irrigation to wheat. Thus the tanks would be completely filled during the 35th and 39th week in the first and second case, respectively. It was observed that total cost of tank per unit of capacity decreased with increasing tank capacity. Tanks designed on the basis of seasonal runoff and used for presowing irrigation of wheat, were the most beneficial with benefit-cost ratio ranging from 1.60 to 4.56 for catchment areas varying from 1 to 100 ha. They determined the reservoir size for assured runoff corresponding to probability levels, 10 to 100%. The probability level of the lowest assured runoff corresponding to the lowest annual cost per unit of available water increased with increasing tank capacity and varied from 40 to 80%.

Arnold and Stockle (1991) used the Simulator for Water Resources in Rural Basins (SWRRB) model to determine the optimum pond size and irrigation strategies for supplemental irrigation systems. The original model was modified to simulate crop yield, supplemental irrigation, furrow diking (similar to tied ridges described in Section 2.5.1.2) and economics. Individual components such as water yield, ET, and crop yields were validated with measured data to ensure proper model operation. The model was then linked with a golden-section search algorithm to determine the pond size that optimizes average annual return to management. Golden-section search is an algorithm for finding the extremum of an unimodal function. The new interval point is found with golden ratio. The model also developed frequency distributions for risk assessment.

Srivastava (1996b and 2001) developed a simulation model of tank and cropped area water balance for rice based cropping system in India to determine the catchment command area ratio and size of the tank. Model was run for different catchment-command area ratio (CCR) varying from 1.0 to 6.0 for different years of climatological data. It was found that the catchment command ratio of 5.0 or more and tank of storage capacity of 1326 m^3/ha would be sufficient at a return period of five years for

UP midhills of India. For eastern India, a catchment-command ratio of 3.0 and tank size of 1750 m^3/ha command area was required. With the same model he (Srivastava 2003) determined the tank sizes for different seepage rates for a site in the eastern India. Tank capacities per ha command area as determined by him were 1750 m^3 for seepage rate less than 6mm/day, 2500 m^3 for seepage rate more than 6 but less than 10 mm/day. And when seepage rate was more than 10 mm/day, tank lining was must and tank capacity was 1650 m^3.

Ambast and Sen (1998) developed a soil water balance model to determine the optimal size of on farm reservoir (OFR) in rainfed rice lowlands of Sunderbans delta of east India. Weekly rainfall values at 2 years return period were used to optimise the size of OFR. All the computations were on weekly basis. They recommended to convert 20 per cent of the watershed area into OFR to harness the excess rain in the region.

Panigrahi and Panda (2003) adopted the approach of Palmer *et al.* (1982a) and developed a simulation model for prediction of the optimal size of an OFR to provide supplemental irrigation to rice in monsoon season and presowing irrigation to mustard in winter for rainfed farming system of eastern India. Irrigation management practices, a water balance model of both cropped field and OFR, as well as an economic analysis were used for finding the optimum size of the OFR. A family of curves was generated at different probability of exceedence levels that indicated the net profit of OFR irrigation system as function of OFR size. From the developed curves, an OFR of depth 2 m requiring 12% of the 800 m^2 farm area with a volume of 61 m^3 was found to be the optimum size. Based on simulation results field experiments were conducted with rice-mustard cropping system in both irrigated and rainfed conditions. The above-mentioned OFR size gave a benefit-cost ratio of 1.22, internal rate of return (IRR) of 15% and pay back period (PBP) of 15 years. Simulated results were verified by conducting three years of field experiments to justify the investment in the OFR irrigation system. The observed BCR, IRR and PBP from the experimental study were 1.17, 14.6% and 16 years, respectively. There was an increase of 39 and 15% in the yield of rice grain and mustard seed over rainfed conditions because of application of 84 and 45 mm of supplemental irrigation, respectively.

Agrawal *et al.* (2004) added the physically based soil water balance model to the above model of Panigrahi and Panda (2003). The general 1-D equation for steadystate flow of water through porous media was solved numerically using the finite-difference approach to predict percolation under the ponded phase of rice.

Following studies were conducted for simulating the performance of tank based irrigation systems in Sri Lanka. Though tank design was not the purpose of these studies, they were based on the same principle of simulation of tank and cropped area water balance and hence found relevant for discussion.

Jayatilka *et al.* (2003) presented a water balance model *'Cascade'* for studying the dynamic components of an irrigation tank cascade system in Sri Lanka. The model was designed to estimate tank water availability on a daily basis, for the purpose of improving productive use of water resources in the tank cascade system. It represented the physical system using a node-link system configuration, and included water balance components of irrigation tanks including rainfall, runoff, rainfall on tank, evaporation of tank water, tank seepage and percolation, irrigation water release, spillway discharge and return flow from upstream tanks. The model employed a modified runoff coefficient method for estimating runoff from rainfall, which incorporated a modified antecedent precipitation index as an indicator of catchment wetness. This provided a simplified method for representing the non-linear runoff generation process. The model calculated tank seepage and percolation based on functions derived from an analysis of the observed tank water reduction during time periods without rainfall. The model was calibrated using field data collected at four tanks over a period of 21 months, which represented different agrometeorologic conditions encountered under both *Maha* and *Yala* growing seasons at the Thirappane tank cascade system in Sri Lanka.

Li and Gowing (2005) presented a daily catchment-tank-command water balance model, which simulated tank water level and crop water requirements, runoff, deep percolation on daily basis. They modelled the non-irrigated and irrigated areas within tank catchment separately, whereas command area needed modelling only as irrigated area. For all irrigated land (command and catchment), modelling for paddy and non-paddy fields was conducted by using a daily field water balance approach and soil moisture status was tracked on daily basis to determine the runoff response to rainfall and applied irrigation water. Non-irrigated areas were modelled using the Curve Number method based on average soil moisture condition. Runoff from irrigated paddy fields was modelled by setting maximum water depth that could be retained in the bunded paddy fields. Water in excess of this depth was considered as runoff. In the case of irrigated non-paddy fields, two runoff processes were considered one from rainfall and other from irrigation. Runoff from rainfall was computed using the Curve Number method, whereas runoff from irrigation was estimated by multiplying applied irrigation water and its runoff contribution ratio. The modelling of the tank was performed through a water balance approach, which takes inflow, and outflow components into account.

5.5 Summary of the modelling approaches

Summary of modelling approaches discussed in the Chapter is given in Table 5.2 (at the end of Chapter). Most studies involved simulation approach wherein simultaneous simulation of cropped area water balance and tank water balance was carried out. Reservoir size was incremented/decremented to match the supply of water with its demand. The studies varied in the representation of different component processes like runoff, evapotranspiration etc. The optimal tank size was derived through repetitive runs of simulation model. Optimization criterion mainly involved the maximization of net benefits from the system. All the studies used lumped modelling approach except that of Agrawal *et al.* (2004) who simulated the soil water balance by numerical modelling. Verma and Sarma (1990) and Ambast and Sen (1998) applied probability to the input data (rainfall) to the model for designing the tank system whereas Palmer *et al.* (1982a) and Panigrahi and Panda (2003) applied probability analysis to the output (tank size) of the model. There were a few studies on tank design by mathematical modelling approach and they optimised the tank dimensions by non-linear optimization algorithm (Sharma and Helweg, 1982).

5.6 Merits of existing approaches

The simulation-optimization studies for single tank system discussed above provided detail and insight in to the modelling approach for tank design. Moreover they provided the validity of the approach for tank design for Indian conditions. They also provided the basis for simulation of cropped area water balance and tank water balance in the present investigation. Suggestion by Palmer *et al.* (1982 a) about simulation of different irrigation management practices was found helpful. Runoff computation with soil moisture accounting as reported in Panigrahi and Panda (2003) was found more appropriate than AMC conditions as proposed in the original SCS-CN method. The catchment-tank-command water balance model reported by Li and Gowing (2005) was found helpful in the modelling of irrigated and non irrigated areas in the catchments. Moreover it also considers multi-tank systems. The above modelling studies thus showed the ways to solve the problem of tank design.

5.7 Limitations of existing approaches

The list of modelling approaches under different categories is given in Table 5.3. From the table, it is seen that most of the modelling studies in the literature were found for design of single tank systems with the approach of simulation or simulation-optimization modelling. The studies by Jayatilka *et al.* (2003) and Li and Gowing (2005) adopted the simulation of catchment, tank and command water balance for evaluating the performance of multi-tank systems in Sri Lanka. These studies did not optimise the tank dimensions since they were for evaluation purpose only. Moreover they did not consider the tank system as a part of watershed. There was no consideration for groundwater storage and effect of catchment treatments like *in-situ* water harvesting methods on the tank water balance. Srivastava (1996 a) studied the multitank system by mathematical modelling approach. The mathematical approach adopted by him was quite complex (and would have become more complex for the present investigation). It was also not possible to test different scenarios with his approach. Moreover most of these studies were for rice based cropping systems. The irrigation and hydrology characteristics of rice based cropping system are quite different from other cereal, pulse and oilseed crops which are common in the arid and semiarid regions of India. These limitations of the existing approaches initiated the process of developing new approach of tank design in the present investigation.

The present investigation attempts to design multi-tank system in the watershed. From table 5.3 it is seen that information was lacking on the simulation-optimization of multi tank system (shaded box in Table 5.3). This research fills this gap by developing simulation-optimization methodology for the watershed based multi-tank system.

Table 5.3: Modelling approaches for the design of tank systems under different categories

Approach	Single tank system	Multitank system
Empirical	Samra *et al.* (2002), Juyal and Katiyar (1991), Singh (1991), Gupta and Narayana (1974), Hakim (1952)	
Simulation modelling	Srivastava (1996b and 2001), Agrawal *et al.* (2004), Panigrahi and Panda (2003). Panigrahi *et al.* (2001), Arnold and Stockle (1991), Verma and Sarma (1990), Ambast and Sen (1998), Palmer *et al.* (1982a), Palmer *et al.* (1982b)	Li and Gowing (2005), Jayatilka *et al.* (2003),
Simulation-optimisation modelling		
Mathematical modelling	Sharma and Helweg (1982), Helweg and Sharma (1983). Srivastava (1997)	Srivastava (1996a),

5.8 Need of new approach

The studies reviewed in this Chapter focussed on the optimization of design parameters for a single tank. However the watershed management concept involves the integration of different water harvesting techniques and storage systems – Integrated Water Storage System as proposed in this study along with the specified downstream requirements for downstream users and/or environmental reasons. The earlier studies reviewed in the Chapter showed that different systems and their individual components influence each other and hence the optimization of storages focussed on individual tank does not represent the philosophy of watershed management. Therefore there is a need to optimize all the storages together by optimally matching supply and demand parameters.

In my investigation, the methodology of tank system design for watershed starts from the generation of tank strategies for the watershed based on the number of stream points. Each tank strategy is unique and therefore supply and demand parameters of the tank system vary from one tank strategy to the other. For each tank strategy three water balances i.e. field, tank and groundwater balance need to be simulated. In addition the effect of *in situ* RWH practices (taken in the catchments of these tanks), needs to be simulated through the water balance of these practices. Moreover simulation is also governed by the downstream release requirement from the watershed. All these factors were missing in the earlier approaches. Therefore a new methodology is needed and proposed wherein these aspects are included for deriving the optimum tank system for the watershed. The approach is based on the simulation of watershed water balance.

Since the problem becomes too complex to be solved by optimization modelling, the approach of simulation-optimization was preferred over that of optimization modelling. This approach is also suitable to test the different hypotheses proposed in the research.

5.9 Conclusion

The existing approaches for design of tanks have number of limitations when considered in the context of IWSS for the watershed. Hence a new approach is proposed. The proposed approach is an integrated approach that considers different aspects for the design of tank irrigation system in a watershed as discussed earlier and makes maximum volume of water available for utilisation in a watershed under consideration and a specified proportion of harvested water available for downstream water requirement. There are numerous watersheds in developing countries wherein the decisions are required to be taken at planning stage to design the tank system or to upgrade the system in watersheds wherein the tanks are already constructed. It is important that these decisions are optimal i.e. the selected tank system should maximise the use of water at minimum cost and also satisfy other requirements. Therefore it is necessary to convert the methodology appropriately into a computer model that has utility in developing countries. The detailed discussion of the methodology of the proposed approach and the developed model forms the contents of the next Chapter.

Table 5.2: Summary of modelling approaches for tank design

Source	Country	Time scale	Tank system	Study parameters	Calibration parameters	Characteristics	Cropping system
Simulation-optimization approach							
Ambast and Sen (1998)	India	Weekly	Single OFR	Tank size	Not reported	2 –yr weekly rainfall	Rice
Verma and Sarma (1990)	India	Weekly	Single tank	Tank size	Not reported	Probable weekly rainfall. Tank to be full in 35^{th} or 39^{th} week	Maize, Wheat
Arnold and Stockle (1991)	USA	Daily	Single OFR	Tank size	Catchment yield, ET, Crop yield	Considered the effect of furrow dikes on pond storage	Rice, cereals, pulses, oilseeds
Srivastava (1996b &2001)	India	Daily	Single tank	Tank size CCR	Not reported	Time series of simulation output subjected to probability analysis	Rice
Palmer *et al.* (1982a & 1982b)	USA	Daily	Single OFR	Tank size	Not reported	Only one irrigation management practice considered	Maize
Panigrahi *et al.* (2001)	India	Daily	Single OFR	Tank size	Not reported	WHP match with tank size	Rice
Panigrahi and Panda (2003)	India	Daily	Single OFR	Tank size	Economic indicators	Model results validated with field experiments	Rice, mustard
Agrawal *et al.* (2004)	India	Daily	Single OFR	Tank size	Not reported	Numerical modelling of soil water balance	Rice
Mathematical modelling approach							
Srivastava (1997)	India	--	Single tank	Tank size CCR	--	Small roof top RWH for hilly areas	Vegetables
Sharma & Helweg (1982), Helweg & Sharma (1983).	India	--	Single tank	Tank volume, Dimensions, Location	--	Analysed the unconstrained and constrained cases of tank design	Sorghum
Simulation approach (Evaluation studies)							
Li and Gowing (2005)	Sri Lanka	Daily	Multiple tanks	Tank hydrology	Tank water level,	Simulation of irrigated and non-irrigated areas in tank catchment	Rice and non-rice crops
Jayatilka *et al.* (2003)	Sri Lanka	Daily	Multiple tanks	Tank hydrology	Tank water level	ST, NT, CT tank types considered	
Mathematical modelling approach							
Srivastava (1996a)	India	--	Multiple tanks	Tank size, location, CCR	--	Tank system for hilly areas	Rice

Chapter-6

METHODOLOGY AND MODEL DEVELOPMENT

6.1 Summary

This chapter discusses the details of the methodology for the optimum design of tank system in the watershed. The methodology is based on the concept of IWSS and integrates soil, tank and aquifer water balances. The methodology is converted into a computer model and the resulting model named ***SOFTANK*** *(Simulation Optimisation For* ***TANKs****) is discussed at the end of the Chapter.*

6.2 Introduction

The efficient utilisation of water resources at micro level of agricultural watersheds has long been a concern of policy makers in developing countries. Development of water resources on watershed basis involves integration of *in situ* and *ex situ* rainwater harvesting (RWH) techniques reviewed and discussed in Chapter 2, 3 and 4. When these different RWH techniques are adopted in the watershed, they influence each other's storages as discussed earlier. The watersheds, for which this study is undertaken, range in size from 500 to 2000 ha and their hydrology differs from that of bigger river basins. Overland flow is a major component of hydrologic cycle in small watersheds as against the stream flow in river basins. Small watersheds are more sensitive to the catchment treatment than the river basins. Hence the *in situ* RWH techniques adopted in the catchment of the tanks in the watershed need to be considered in the design of storage capacity of tank system. In this study one such *in situ* RWH technique i.e. continuous contour trenches (CCT) has been considered to demonstrate the effect. Moreover the methodology should also consider the groundwater storage as a part of the tank system since tanks are the source of seepage for water, which recharges groundwater and this groundwater being used for crop production in the watershed. In watershed development there is always a concern about the downstream release of water to avoid upstream-downstream conflict. Therefore the methodology of watershed based tank system design should consider upstream receipt (USR) of flow coming into the watershed and downstream release (DSR) requirement from the watershed. Besides these major considerations, the system should also consider cropping pattern of command area, return flows, conveyance and water application methods. All these factors are interrelated and should be considered while designing the optimum tank system in the watershed. The methodology is therefore developed on the concept of IWSS introduced in the first Chapter which takes into account all these factors. It is expected that such a methodology could provide a basis for the development of a useful tool, which could provide a valuable means to the utilisation and management of surface and groundwater resources in the watershed. The detail discussion of methodology follows in this Chapter.

6.3 Methodology

Since the tanks are constructed as a part of watershed development projects, tank based water management systems become a whole watershed system with a tank as its central point. Design of tanks therefore assumes importance since tanks create new water resources for crop production in the watershed and involves major share of total financial outlay of the watershed project. However planning the construction of tanks in the watershed poses technical questions on their numbers, locations and capacities. Studies conducted earlier by many researchers (Ambast and Sen, 1998; Panigrahi *et al.* 2001; Panigrahi and Panda, 2003; Panigrahi *et al.*, 2005; Srivastava, 1996a; Srivastava, 2001; Srivastava *et al.*, 2003) on tanks relate mostly to isolated small on farm reservoirs (OFR) for rice based cropping systems in India. These studies are discussed in detail in Chapter 5. Most of these studies follow the approach of simultaneous simulation of cropped area water balance and tank water balance as demonstrated by Palmer *et al.* (1982a). They do not consider tanks as component part of the watershed.

This study therefore introduces a new approach of watershed based tank system design that addresses the questions on the number, location, types and capacities of tanks in the watershed in a scientific manner. The study involves development of a methodology with the capability to account for the dynamic hydrologic components in the watershed on daily basis for different tank strategies. The developed methodology of tank system design takes into account all factors affecting inflows to and outflows from the watershed by considering the three important water balances: field water balance, tank water balance and groundwater balance in the watershed. The conceptual flowchart of the methodology is shown in Fig 6.1. At the beginning fields are allocated to 'stream points'. As defined earlier stream point is a point on the stream at which tank location is preferred. Tank strategies are generated based on the number of stream points (This is discussed in detail below in Section 6.3.3). Catchment and command field allocation is performed for each tank strategy. Initial tank capacity is determined with the design runoff depth (DRD). Simulation then starts from the first (or selected) tank strategy. A DSR criterion is given before the simulation. The DSR criterion in this research is the annual volume of water that passes the watershed outlet as per cent of annual volume of runoff generated in the watershed. For example a DSR of 30% means tanks will harvest 70% of the runoff generated in the watershed and remaining 30% will go downstream out of the watershed. Tank system is designed for this DSR. In simulation field, tank and groundwater balances are simulated simultaneously on daily basis. At the end of simulation, output DSR is obtained. This DSR is compared with the input DSR ± deviation (e.g. 30 ± 10). Since the output DSR is the result of simulation and depends upon many factors like tank size, water use, climate etc., this DSR may or may not match with the input DSR. If DSR criterion is not met, tank capacity is increased (or decreased) and simulation performed again. The procedure is repeated till the DSR criterion is met. When the DSR criterion is met, project economics for the tank strategy is performed. In this way all tank strategies are simulated.

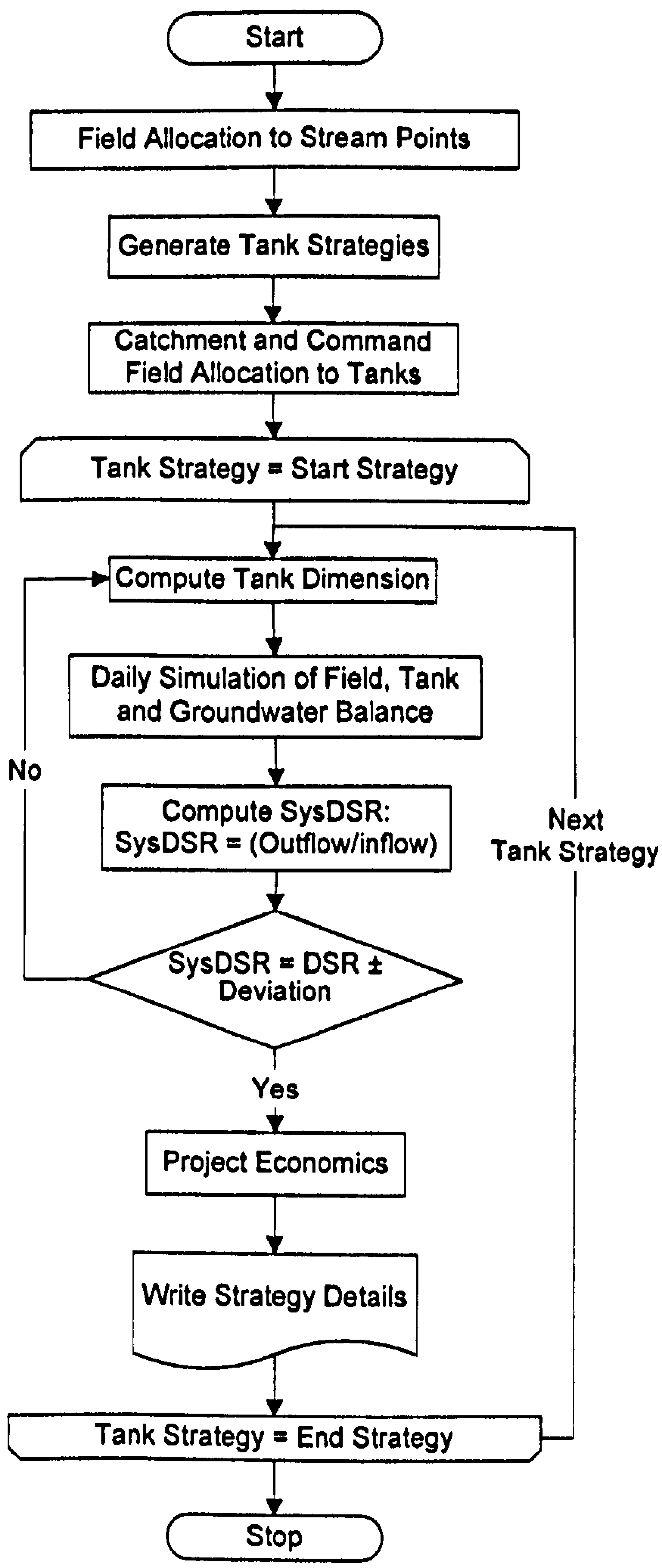


Figure 6.1 Conceptual flowchart of the methodology for finding optimum tank strategy

6.3.1 Field allocation to stream points

Once stream points are defined, different fields in the watershed are allocated to different stream points based on the elevation of the stream point and that of the field (Z-coordinate). The flowchart of field allocation to stream points is shown in Fig. 6.2.

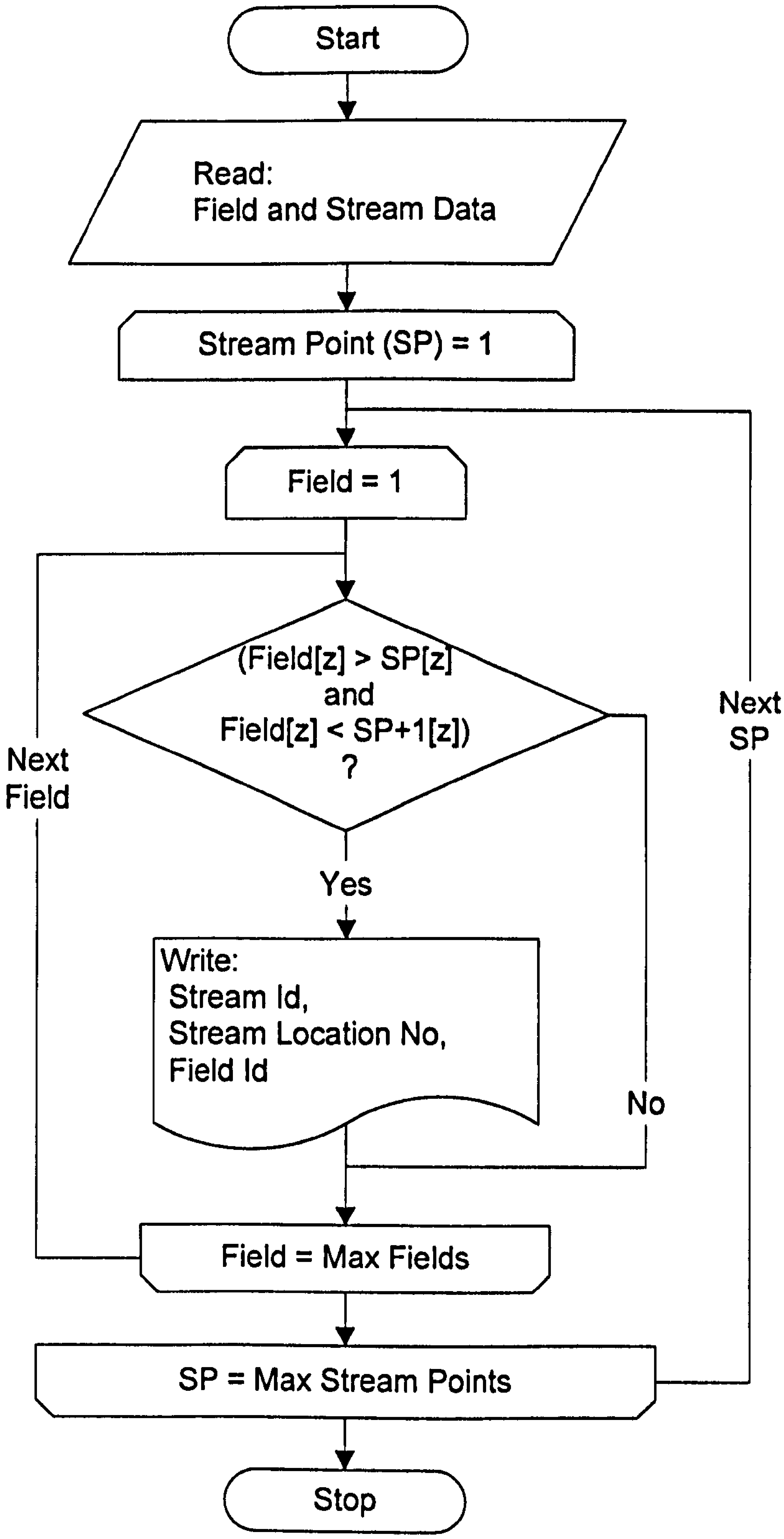


Figure 6.2 Flowchart of field allocation to stream points

6.3.2 Tank strategy

Tank strategy for the watershed is defined as the strategy describing the number of tanks, their locations on the stream and their types. The concept of tank strategy has already been discussed in Section 4.3.4. Different components of tank strategy are discussed below.

6.3.2.1 Number of tanks

A watershed may have any convenient number of tanks. This number depends on many factors like suitability of site for tanks, the purpose of tanks, supply and demand parameters of the tank, socioeconomic requirements etc. A typical watershed of say 1000 ha may have 1 to 5 numbers of tanks. Hence it becomes necessary to evaluate different number of tanks in the watershed for maximum net benefits. Therefore in the generation of tank strategies number of tanks varies from 1 to number of stream points in the watershed.

6.3.3.2 Tank location

Tank location is the position of tank on the stream in the watershed. It is defined by the stream point. These stream points are spaced at some interval on the main stream in the watershed. It is assumed that these stream points provide good sites for tanks. Once the stream points are finalised, tanks in the watershed will take any location on these stream points. If there are say five stream points in the watershed and one tank is to be constructed, this tank can take any location on these five stream points. Each of these locations generates a new tank strategy. Theoretically any point on the stream can be a stream point (or possible location for a tank) but as the number of stream point increases the number of tank strategies increases exponentially (as shown in Table 6.1) increasing the computational efforts exponentially. Hence it is suggested to keep number of stream points minimum. This can be done by actual site study in the watershed and having the interaction with the stake holders in the watershed for favourable tank locations.

6.3.3.3 Tank type

Tank type has been defined and elaborated in detail in Section 4.3.2. The particular tank taking on any of the three tank types depends upon the agro climatic region, topography and the supply and demand for water. For example Type-1 tanks are preferred in the semi-arid regions where supply is always less than the demand and therefore command area of these tanks is far less than catchment area (CCR may range from 5 to 50). Type-2 tanks may be constructed in small areas in semi-arid region to have more runoff to meet crop water requirements in the catchment like on farm reservoirs (OFR) (CCR is 1). Whereas Type-3 tanks will be more appropriate in the sub-humid and humid regions where there is abundant supply of water (CCR is less than 1). Moreover stream points in the watershed may have restriction on the tank type. For example a stream point at the outlet of the watershed will have tank type-2 only since there is no command area below this stream point. Similarly a stream point in the upper reaches of watershed may have tank type-1 only if the catchment of the tank at this stream point has non arable lands. A percolation tank may assume any tank type depending on its 'zone of influence' which ultimately depends upon the underground geology. In the proposed methodology the restrictions on tank type are assigned to the stream points.

6.3.3 Tank strategy generation

Based on the different possible combinations of numbers of tanks, their locations and tank type, tank strategies are generated for a particular number of stream points. Thus the number of tank strategies generated is a function of number of stream points. These strategies were generated by developing an algorithm for the purpose (The flowchart is shown in Fig 6.3). The concept of generation of tank strategy is explained with the following example.

For example say there are only two stream points in the watershed as shown in Fig 6.4. Now since stream point number 1 is at the outlet of the watershed it can have only type-2 tank whereas the stream point number 2 can have any type tank. The watershed may have one tank at any of these two stream points or it may have two tanks on two stream points. Hence total 7 number of tank strategies are generated for these 2 stream points as listed below in Table 6.1.

Table 6.1: Generation of tank strategies for two number of stream points

Tank strategy No	Description of tank strategy
1	One tank of type-2 at stream point No 1
2	One tank of type-1 at stream point No 2
3	One tank of type-2 at stream point No 2
4	One tank of type-3 at stream point No 2
5	Two tanks with one tank of type-2 at stream point No 1 and other tank of type-1 at stream point No 2
6	Two tanks with one tank of type-2 at stream point No 1 and other tank of type-2 at stream point No 2
7	Two tanks with one tank of type-2 at stream point No 1 and other tank of type-3 at stream point No 2

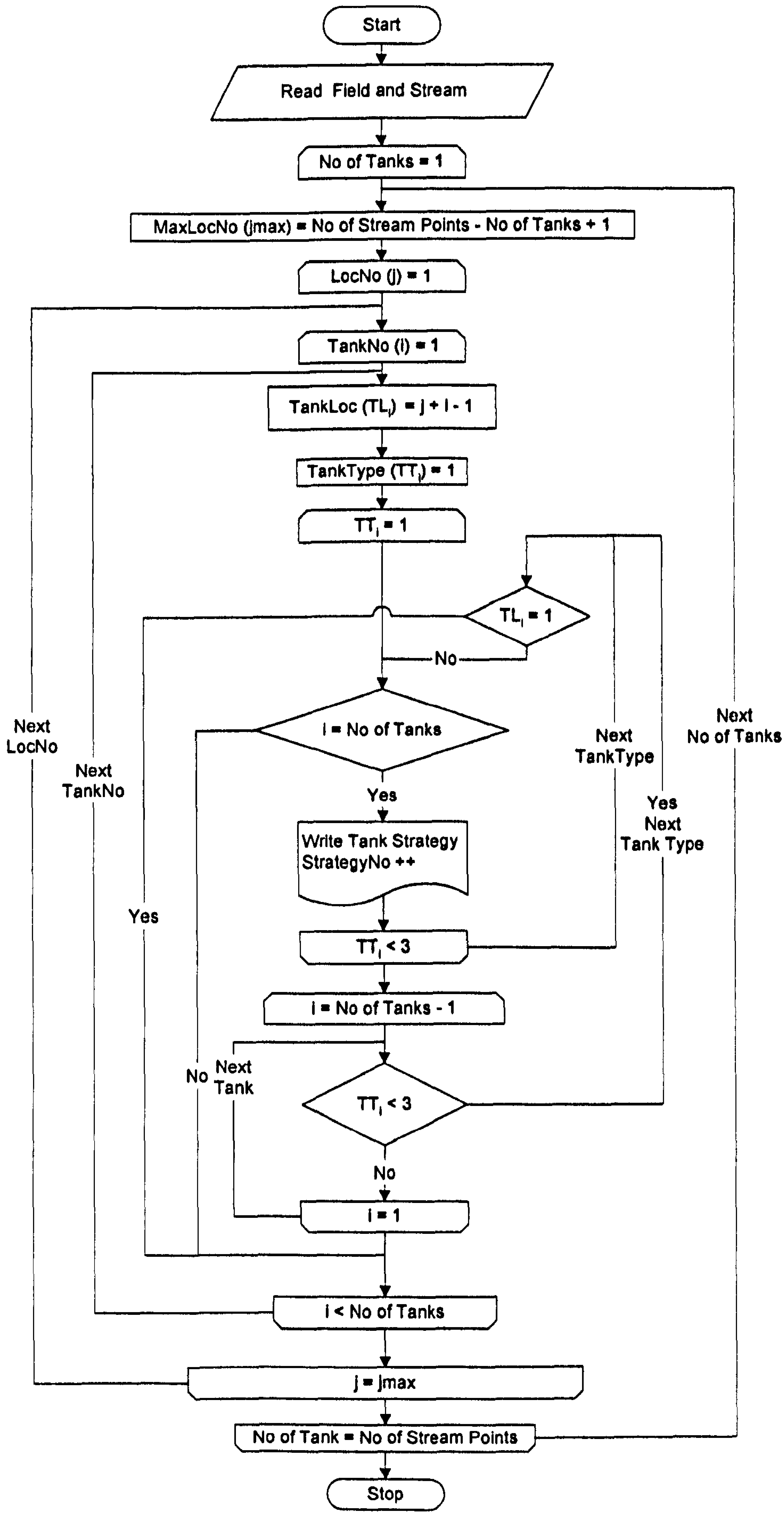


Figure 6.3 Flowchart for generation of tank strategies for 2 number of stream points

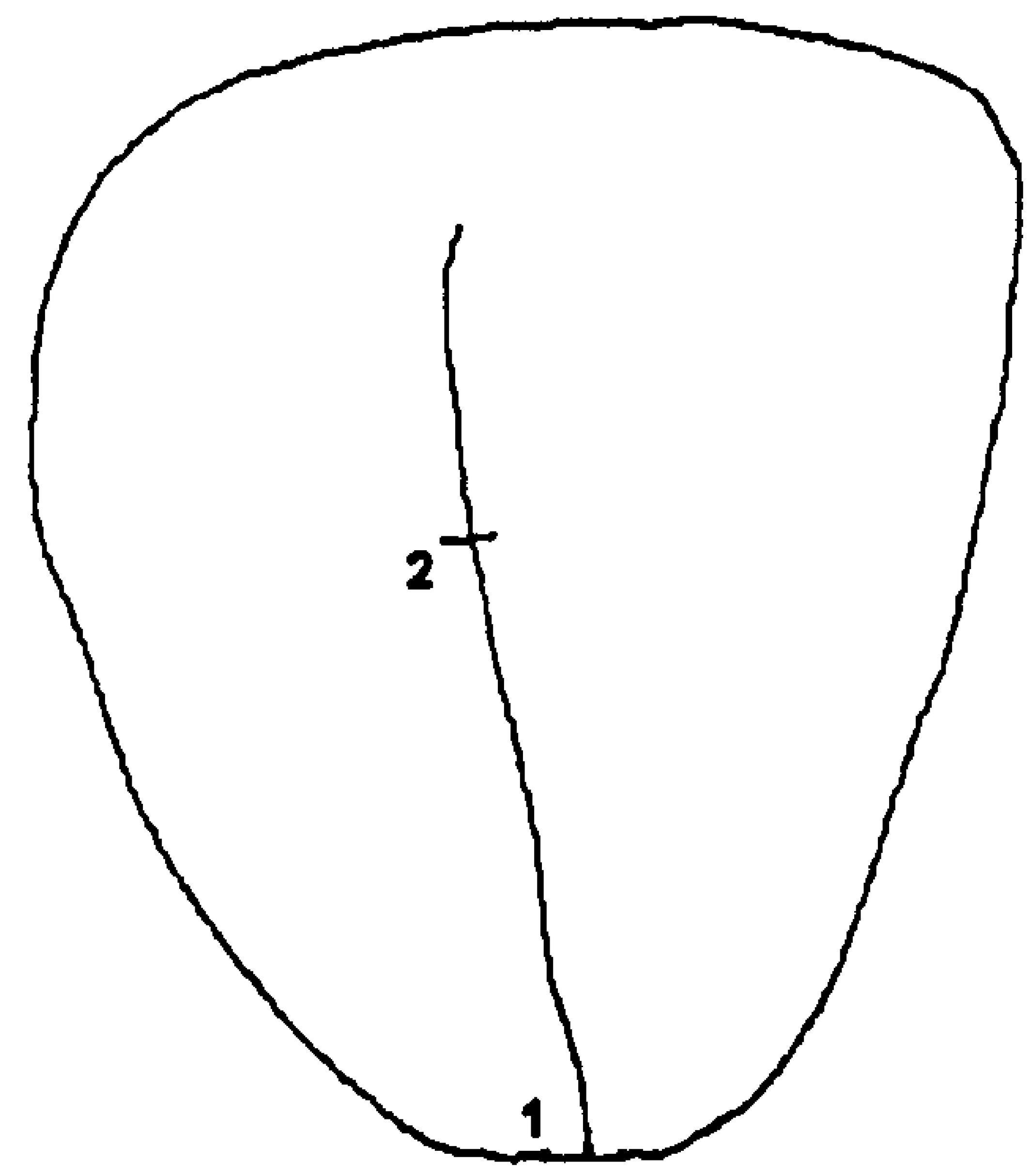


Figure 6.4 A watershed with 2 stream points

Like this, if there are three stream points, 31 tank strategies are generated consisting of 7 strategies for 1 No of tanks, 15 strategies for 2 No of tanks and 9 strategies for 3 No. of tanks. The possible numbers of tank strategies for 1 to 6 number of stream points are given in Table 6.2.

Table 6.2 Tank strategies generated for different number of stream points

Stream points	Total number of tank strategies
1	1
2	7
3	31
4	127
5	511
6	2047

6.3.4 'Tank strategy' and 'tank system'

These two terms 'tank strategy' and 'tank system' are used more frequently in this research and need some elaboration. Tank strategy as defined earlier is the combination of number of tanks, their locations and types. In this methodology simulation-optimization is carried out for a tank strategy and the output of the simulation- optimization process is the tank system. In addition to the number of tanks, their locations, and types tank system consists of storage capacities and tank dimensions. Tank system is a physical entity while tank strategy is conceptual. 'Tank system' and 'tank irrigation system' are used synonymously.

6.3.5 Catchment and command field allocation to tanks

Watershed comprises of number of fields. Each field has unique spatial Cartesian coordinates (x,y,z). These fields contribute runoff to the tanks. These fields also need water for irrigation from nearest tank or groundwater depending upon crop and soil conditions. Therefore it is necessary that each field is assigned to a specific tank for runoff contribution (catchment) and irrigation (command) purpose. However this is not the one time process. As stated earlier tanks in different tank strategies may have different stream points or coordinates. Hence for a particular tank strategy if a specified field is assigned to a tank on stream point say 2 for runoff contribution purpose, in another tank strategy the same field may be assigned to a tank on stream point 3 as the tank strategy may not have tank at stream point 2. Again as the tank type changes field assignment in the command areas of the tank changes. For example say there is 1 tank at the middle of the watershed and there are 10 fields (1-10) in the catchment of the tank and 5 fields (11-15) on the downstream command area. When the tank is of type-1, command area fields will be 5 (11-15); when the tank is of type-2, command area fields will be 10 (1-10); and when the tank is of type-3 command area fields will be 15 (1-15) i.e. 10 fields from upstream and 5 fields from downstream of the tank.

Thus the field assignment is a dynamic procedure and changes with tank strategy. Hence a procedure is developed that assigns a particular field to a tank's catchment and command area depending on the relative elevation of the field and different tanks. The flowchart for allocation of fields to tank strategies is shown in Fig 6.5.

Field allocation is performed on the basis of Z-coordinate of fields and stream points. Sometimes due to special topographic features (e.g. depression or hills) the fields may not be allocated to the correct stream point on the basis of Z-coordinate. In such cases fields are allocated manually to the respective stream points.

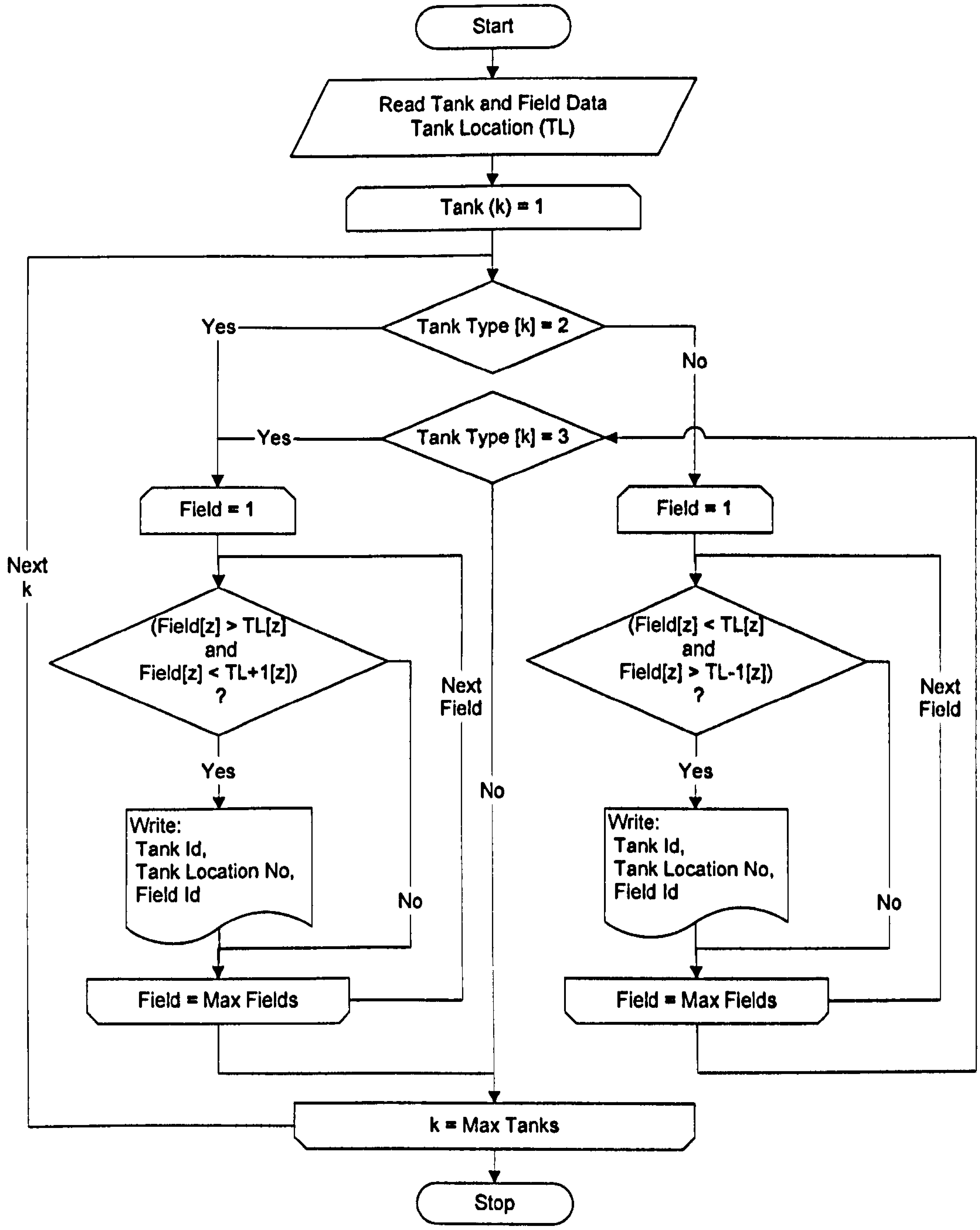


Figure 6.5 Flowchart of allocation of command fields to different tank strategies

6.3.6 Upstream receipt (USR) and downstream release (DSR) criteria

Watersheds may be nested or in series one below (downstream) the other. Therefore a watershed under consideration may receive water from the upstream source (either from watershed or some other source like canal as in the case of system tanks in south India). In the proposed methodology, provision is made to include this upstream flow to the watershed. In semi-arid and arid regions where, water supply is always less than water demand, attempts are made while developing the watershed that almost all the rainfall and runoff (considering the average rainfall year) is harvested in the watershed, leaving no water to flow out of the watershed for downstream use or ecological reasons. It gives rise to upstream-downstream conflict about the water use. It thus necessitates giving consideration to downstream water release when designing the tank system in the watershed. Hence in this study a downstream release (DSR) criterion is defined as "the amount of water (expressed as some fraction of the runoff generated in the watershed) that must be allowed to go out of the watershed for downstream use or ecological conservation". A specified value of DSR gives the per cent of watershed runoff to be allowed to go to downstream. This is referred to as input or target DSR. As the computations may not permit to follow the exact value of DSR, in this study DSR is specified with deviation that can be allowed in DSR. For example if downstream release (DSR) is 30%, and the deviation allowed is 5%, then the computations will result in the tank sizes for harvesting runoff in the range of 65 to 75% of the total runoff generated in the watershed and remaining 25 to 35% will go as downstream release. Computations are repeated with increased/decreased tank size till the DSR criterion is met. It needs to be mentioned here that computation efforts for arriving at the design tank size increases as the deviation in DSR decreases.

6.3.7 Tank dimensions

In the watershed, tanks are constructed on the main drainage line (or stream). Tanks may be constructed either by putting an embankment on the stream and creating a pool of water behind the embankment or by excavation of soil and putting it on all sides to create storage. The former is called an embankment tank and the latter is called an excavated tank. Embankment tanks do not have well defined shape of the reservoir and hence general methodology for estimating storage is not possible. On the contrary excavated tanks have regular well defined shape and stage-area-storage relationships can be developed. Currently in the developed methodology the irregular shaped embankments tanks are represented with the regular shaped tanks as shown in Fig. 6.6.

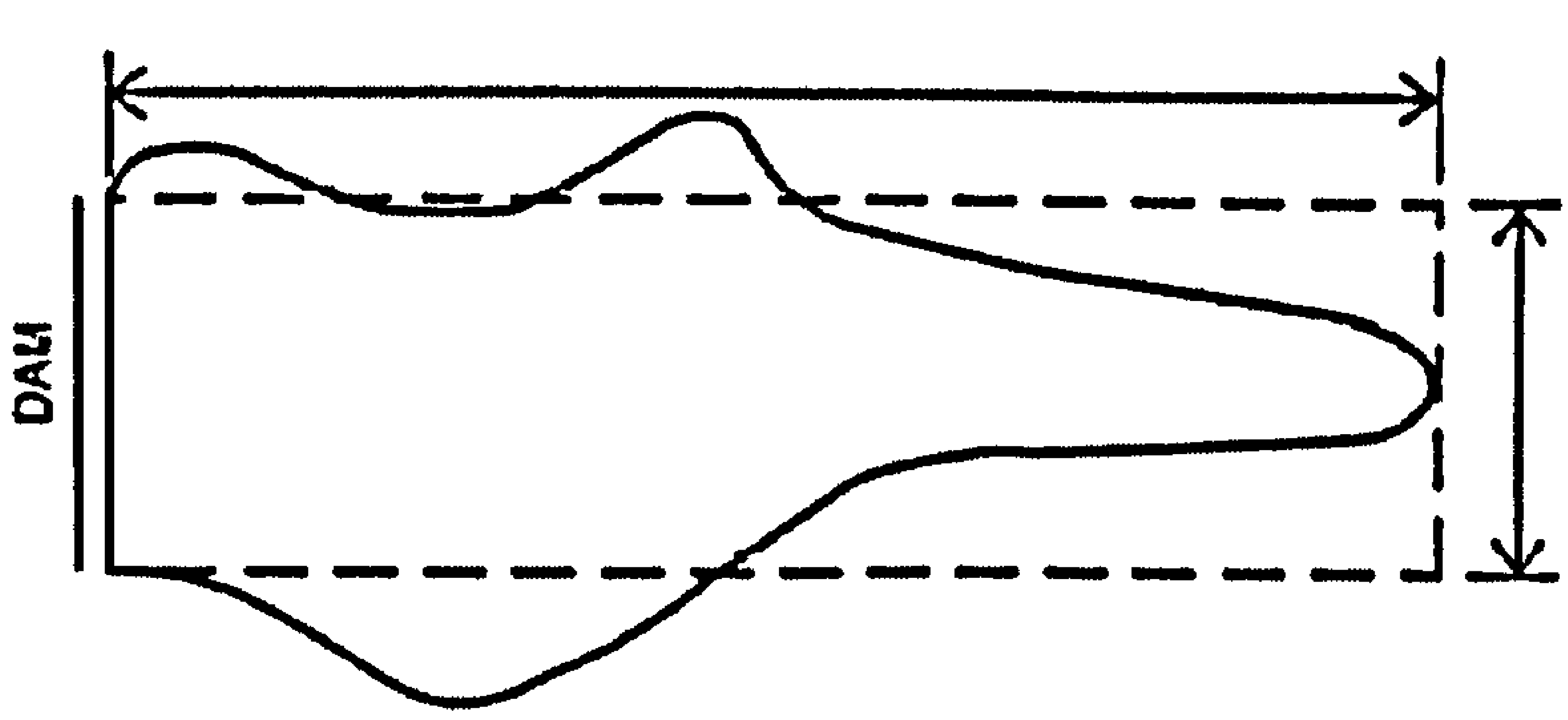


Fig 6.6 Converting the irregular shaped tank into regular (rectangular) shape

Excavated tanks may be constructed in various shapes. In this study following five shapes are considered.

1. Square prism
2. Rectangular prism
3. Inverted truncated pyramid (trapezoidal)
4. Cylindrical and
5. Hemi-spherical

Dimensions to be decided for rectangular and square prism shaped tanks are length, width and depth. For truncated pyramid, the dimensions are bottom length, bottom width, depth and side slopes. These are depth and diameter for cylindrical shaped tank and diameter for hemi-spherical tanks.

Water is lost from the tank in the process of evaporation and seepage. Hence, it is essential to give proper consideration while deciding these dimensions. The dimensions of the tank should be such that both evaporation and seepage losses are kept to the minimum. The method of Lagrange Multipliers is used to decide the optimum dimensions of the tank for minimum seepage and evaporation losses.

6.3.7.1 Method of Lagrange multipliers

This method consists of the function of variables, which is to be minimized (equation 6.1) subject to the set of constraints (equation 6.2).

$$Minimize \quad f(\ ) \qquad (6.1)$$
$$= x_i, \quad i = 1, n$$

Subject to

$$g_j(\ ) = 0, \qquad j = 1,2,\ldots\ldots,m \qquad (6.2)$$

The Lagrange function, L, is defined by introducing one Lagrange multiplier λ_j for each constraint $g_j(\mathbf{X})$ as (equation 6.3)

$$L(x_1, x_2, \ldots\ldots, x_n, \lambda_1, \lambda_2, \ldots\ldots, \lambda_m) = f(\ ) + \lambda_1 g_1(\ ) + \lambda_2 g_2(\ ) + \ldots.. + \lambda_m g_m(\ ) \qquad (6.3)$$

By treating L as a function of the n+m unknowns, $x_1, x_2, \ldots\ldots\ldots, x_n$, $\lambda_1, \lambda_2, \ldots.., \lambda_n$, the necessary conditions for the extreme of L, which also corresponds to the solution of the original problem stated in equations (6.1) and (6.2) are given by equations (6.4) and (6.5).

$$\frac{\partial L}{\partial x_i} = \frac{\partial f}{\partial x_i} + \sum_{j=1}^{m} \lambda_j \frac{\partial g_j}{\partial x_i} = 0, \qquad i = 1,2,......,n \tag{6.4}$$

$$\frac{\partial L}{\partial \lambda_j} = g_j(\;) = 0, \qquad j = 1,2,.....,m \tag{6.5}$$

Equations (6.4) and (6.5) represent $(n+m)$ equations in terms of $(n+m)$ unknowns, x_i and λ_j

In the present study, the function to be minimized is seepage and evaporation area of the tank such that the required quantity of water is stored in the tank. The estimation of the dimensions for square shape is described in this section. The estimation of the dimensions for other shapes is presented in Appendix-A6-1.

Square prism

$$\begin{aligned} &Min \;\; \left(2l^2 + 4ld\right) \\ &subject \;\; to \\ &dl^2 = V \end{aligned} \tag{6.6}$$

where,

l = the base length, m
b = the base width, m (for square prism b = l)
d = the depth, m
V = the required quantity to be stored in the tank, m^3

The Lagrange function L is given as:

$$L = 2l^2 + 4ld - \lambda\left(dl^2 - V\right) \tag{6.7}$$

After solving

$$\begin{aligned} &d = \sqrt[3]{V} \\ &b = d \\ &l = b \end{aligned} \tag{6.8}$$

6.3.7.2 Storage excavation ratio

In the design of tank system the cost of tank is determined by the amount of earthwork required for creating the tank storage. Therefore many times tank sites are selected such that they will offer high storage excavation ratio. The criterion for selection of tank site becomes more stringent as the tank size increases. This is due to the high cost involved in these structures. Normally for large tanks, the sites are selected such that high storage is obtained with minimum excavation. This aspect of tank design is expressed as the storage excavation ratio. Storage excavation ratio (S/E) is defined as the ratio of the capacity of a reservoir to the volume of excavation required to build it (Helweg and Sharma, 1983).

Normally farm ponds have poor storage excavation ratio whereas gully dams (as in the case of tanks in the watershed in this study) have high storage excavation ratio. The storage excavation ratio depends on the nature of gully and S/E values may range from 1 to as high as 20 for different gully shapes and site conditions (Gupta and Dhruva Narayana, 1974). In this study storage excavation ratio was related to the tank capacity and increased with tank capacity. Accordingly S/E ratios were assigned to the corresponding tank capacities. The storage excavations ratios used in this study are given in Appendix A6-2. This is based on the understanding that as the tank storage requirement increases, tank site locations that offer higher S/E ratios are preferred.

6.3.8 Crops

Since tank strategy for a watershed will be designed for giving irrigations during dry spells of rainy season and during post rainy season, crops of both seasons need to be considered while developing the methodology for tank design. The crops comprise common cereal crops, pulses, oilseeds, vegetables and horticultural crops in the region. The crop details are given in Appendix A7-1. The crops like rice and sugarcane are not cultivated in the dryland areas as they are more water demanding crops and hence not considered in the study. Field balance computations start from 1st June of the year and the soil is assumed to be at wilting point on the first day of the computations. Monsoon (rainy season) in the study area starts from 7th June and hence this assumption is valid. Crop sowing is activated as per the following three criteria.

6.3.8.1 Crop sowing criteria

Following crop sowing criteria have been included in the methodology.

i) Criteria- I:

Sowing is activated when soil attains field capacity.

According to this criterion, farmers will sow their fields of different soils at different times even though the fields are adjacent to each other. But in practice farmers sow all their fields (considering there are no other constraints) when sufficient rainfall is received. Hence following criteria are also included.

ii) Criteria- II:

Sowing is activated if 2 –day rainfall is equal to or greater than water available at minimum field capacity of soil in the watershed.

ii) Criteria- III:

If one day rainfall is greater than 20 mm crop sowing is initiated.

If the above criteria are met in the first 60 days from 1^{st} June then 1^{st} crop (rainy-season) is sown else if these criteria are met from 100-150 days then 2^{nd} crop (post rainy-season) is sown. If these criteria are not met then crop sowing is not initiated and field remains bare. All these criteria are based on the knowledge of sowing and harvesting dates and crop growth duration of rainy season and post rainy season crops in the study area. The rainfall depth of 20 mm is estimated from the knowledge of soil properties in the case study watersheds and the calculations are given in Appendix A6-3.

6.3.8.2 Estimation of crop root growth

In field water balance, when the fields are cultivated with crops, the knowledge about the crop root growth is essential for computing water consumed due to evapotranspiration. The field water balance is discussed in detail in section 6.3.12. Crop root growth is estimated by the following root growth model.

Linear root growth model (Fereres *et al.*, 1981)

$$Z_t = Z_0 + (Z_m - Z_0)\left(t/t_m \right) \qquad (6.9)$$

Where,

Z_t = Depth of root zone on t^{th} day, mm
Z_m = Maximum depth of root zone during crop growth period, mm
Z_0 = Initial depth of root zone (depth of sowing), mm
t_m = Day at which crop attains Z_m since sowing
t = Total crop period, days

6.3.8.3 Estimation of crop yield

Crop yields are calculated assuming a weighted linear relationship between actual and potential transpiration, with weight or yield response factors Ky varying between crops and development stages of the crop considered. The yield response factors, rooting depth and growing stages for the crops considered are given in Appendix A7-2. To compute the actual crop yield (Ya) as a function of actual evapotranspiration (ETa), the water production functions of crops are used. The following crop production function (or yield model) is used to estimate the crop yields.

Stewart *et al.*(1976): Crop production function in additive form

$$\frac{Ya}{Ym} = 1-\sum_{s=1}^{ns} Ky_s \left(\frac{ETm_s - ETa_s}{ETm}\right) \tag{6.10}$$

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} growth stage

ns = Number of growth stages

ETm_s = Maximum crop ET of s^{th} growth stage (mm)

ETa_s = Actual crop ET of s^{th} growth stage (mm)

ETm = Maximum crop ET of entire crop growth period (mm)

Potential crop yields for different crops are obtained from literature. Yield response factors for different growth stages are given in Allen (1998). Reference crop ET is estimated by Penman-Monteith method. Maximum crop ET and actual crop ET are obtained as discussed in Section 6.3.10.6.1.

6.3.9 Irrigation management practice

Irrigation management affects all the three storages in the watershed i.e. soil, tank and aquifer. Irrigations can be scheduled to make optimum use of available water resources in the watershed. Normally irrigations are scheduled such that full irrigation depth is applied when soil moisture is depleted to 50% of the available soil moisture capacity of the soil. Another common practice is to provide irrigations of fixed amount and at fixed interval. When water supplies are less, deficit irrigations can be practiced. Gorantiwar and Smout (2003) have shown that by practicing deficit irrigations irrigated area and total crop production in the region can be increased. In semiarid regions water is always short of demand for crop production. Hence this finding of deficit irrigation will be useful for increasing the benefits of watershed based tank irrigation systems.

By adopting the methodology of tank system design for different irrigation strategies it is possible to derive the optimum tank system for a particular irrigation strategy.

It is assumed here that irrigation to fields will be given by lifting the water from tank, irrespective of the position of the field. This assumption is based on the fact that these tanks are located on the stream, which are always at lower elevations from adjoining fields. Sometimes water may be lifted for shorter distances and then taken to fields by gravity flow. But here it is assumed that water is lifted for giving irrigations to all fields. Water is conveyed through the underground pipeline and an empirical value for the length of pipeline i.e. 125 m per ha of command area is assumed. Fields close to the tank are given priority for irrigation over the fields, which are away from the tank when water is limited in the tank. Irrigation application efficiencies are considered in estimating the water to be lifted from tank or groundwater.

6.3.10 Estimation of different components of water balance in the watershed

As discussed earlier, all the processes influencing the supply of water and demand for water in the watershed need to be considered while designing the tank system. Different processes like surface runoff, infiltration from field and trench, evapotranspiration from cropped field, evaporation from bare soil and evaporation from open water bodies have been estimated by appropriate methods and are discussed below.

6.3.10.1 Surface runoff

Inflow to the tanks comes through streamflow. Streamflow consists of overland flow, interflow and base flow (groundwater flow).

The watersheds for which this study is being undertaken comes in semi arid and dry sub humid regions. The watersheds are of 2^{nd} or 3^{rd} order where the streams are shallow. Groundwater is sufficiently deep. Therefore there is no groundwater flow contribution to the streams. Interflow occurs as immediate subsurface runoff occurring in a few hours after the storms. Therefore interflow is considered included in the overland flow and hence not estimated separately. Overland flow occurs by two mechanisms.

1. Hortonian overland flow (when rainfall intensity exceeds infiltration capacity of soil)
2. Saturation overland flow

In semi-arid areas overland flow takes place as Hortonian overland flow and hence only this form of overland flow is considered in the study.

Runoff (which is combination of overland flow and interflow) is simulated with the help of SCS Curve Number (CN) method. The choice of the method was influenced by easy availability of the parameters of the CN method and the wide applicability of the method for Indian conditions (Bhatnagar *et al.*, 1996, Sahu, 1996, Srivastava, 2001, Panigrahi and Panda, 2003). Another obvious advantage of the method is that it does not require the use of historical streamflow data and can be used for determining runoff from ungauged watersheds. The major input parameters are rainfall and CN values published by USDA (1986) and are used in the model to estimate daily runoff unless the locally modified CN values are available as used by Khandelwal *et al.* (2002).

For estimating surface runoff SCS CN method is combined with the soil moisture accounting procedure as suggested by Sharpley and Williams (1990). Value of surface runoff under Indian condition is estimated as

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \quad \text{if} \quad P > 0.2S \qquad (6.11)$$

$$Q = 0 \quad \text{if} \quad P \leq 0.2S \qquad (6.12)$$

Where,

S is the maximum potential retention (mm).
The parameter S is related to the curve number (CN) as

$$S = 254\left(\frac{100}{CN} - 1\right) \qquad (6.13)$$

The curve number for average antecedent moisture condition (CN for AMC II = CN_2) is given by USDA (1972). The corresponding values of CN for dry (CN for AMC I = CN_1) and wet (CN for AMC III = CN_3) conditions are given by Sharpley and Williams (1990) as

$$CN_1 = CN_2 - \frac{20(100-CN_2)}{100-CN_2+\exp[2.533-0.0636(100-CN_2)]} \qquad (6.14)$$

$$CN_3 = CN_2 * \exp[0.0673(100-CN_2)] \qquad (6.15)$$

and S given by them is

$$S = S_1 \left[1 - \frac{FFC}{FFC + \exp(W_1 - W_2\, FFC)} \right] \tag{6.16}$$

Where S_1 is the value of S associated with CN_1; W_1 and W_2 are the weighted parameters; and FFC is the availability of soil water expressed as fraction of field capacity given as

$$FFC = \frac{SWC_l - WP}{FC - WP} \tag{6.17}$$

Where WP is the wilting point (mm/mm)

W_1 and W_2 are given as

$$W_1 = \ln\left(\frac{S_3}{S_1 - S_3} \right) + W_2 \tag{6.18}$$

$$W_2 = \ln\left(\frac{0.5 S_2 (S_1 - S_3)}{S_3 (S_1 - S_2)} \right)^2 \tag{6.19}$$

Where S1, S2 and S_3 are the values of S when FFC = 0, 0.5 and 1 respectively. S_1, S_2 and S_3 are the retention parameters corresponding to CN_1, CN_2, and CN_3 respectively. Once parameters W_1, W_2 and FFC are estimated, value of S can be obtained from equation 6.16. Runoff from individual field is estimated on daily basis and the inflow to the tank is estimated as the sum of runoff values from all fields in the catchment of the tank (as defined by the tank strategy). It is assumed that volume of runoff entering a field from upstream field joins to the downstream field without any loss. Runoff routing through fields and streams is not performed as runoff joins the tanks immediately after a few hours of the storm.

Peak runoff rates are required to design the spillways for the tanks. The aim of the study is to determine tank capacities (volumes). Spillway design is not considered and hence peak runoff rates are not estimated.

6.3.10.2 Field Infiltration

In this study, field infiltration is estimated with the SCS CN method. Rainfall minus runoff gives infiltration which is used as infiltration from the field. This infiltration volume is subjected to the soil water balance estimation. In these estimation procedures (Arora *et al*

1987; Rao, 1987; Cambell and Diaz, 1988) the soil is divided into layers and each layer is assumed to fill to its capacity and then pass on any remaining water to the layer below. Such methods assume that both infiltration and redistribution of water are instantaneous. The assumption is more nearly satisfied for lighter soils as redistribution in such soils occurs within 24 hours. In heavier soils, this may take 2 to 3 days. The book keeping models require data of only two soil parameters, field capacity and permanent wilting point. These data of soil storage limits are relatively easier to determine than the hydraulic characteristics data required for the physics-based models. The data are available from soil survey reports or can be estimated from the soil textural data or directly measured in the field. The approach is described later in field water balance (Section 6.3.12).

6.3.10.3 Trench Infiltration

Infiltration takes place when water is stored in the trenches and behind the terraces in the watershed. The infiltration from the trenches along with complete trench water balance is discussed in Chapter 3 (see Section 3.6.1.2.1).

6.3.10.4 Deep percolation

Deep percolation occurs from root zone and underlying soil zone when soil contains water in excess of its capacity. Deep percolation can be estimated with the physics-based models, empirical equations or simple book keeping approach. In this study the piston flow concept of the book keeping models of infiltration and redistribution is extended to estimate deep percolation. By this procedure, the moisture in excess of field capacity in the last layer of the soil root zone is considered to be lost from the soil reservoir as deep percolation. This is discussed in field water balance (Section 6.3.12).

6.3.10.5 Upward flow from the water table by capillary rise

In the present analysis considering the situation in the case study area, groundwater table remains at more than 2 m depth below the ground surface during most of the part of the year and hence contribution to soil reservoir through capillary rise is considered to be negligible and hence not considered in the analysis.

6.3.10.6 Evapotranspiration

Fields in the watershed may have any land use i.e. row crops, horticultural crops, or a silvipasture system. The estimates of evapotranspiration will be different for these land uses.

6.3.10.6.1 Row crops

The rate of evapotranspiration from a crop depends on three factors: i) atmospheric evaporative demand, ii) extent of crop cover and iii) available soil water in the root zone. When soil water is freely available, the atmospheric evaporative demand is estimated for a reference crop, 15 cm green grass completely covering the soil. This evapotranspiration (ET) is termed as reference evapotranspiration (ET_o) This evapotranspiration is estimated with Penman-Monteith method. Field crops do not cover the ground completely throughout the growing season. Even when soil water is freely available, the ET is less than ET_o when crop cover is incomplete. This ET is termed as maximum crop evapotranspiration (ET_m). This determines the upper limit on ET from a specified crop. ET_m is estimated from ET_o and crop coefficients (K_c) as

$$ET_m = K_c \cdot ET_o \qquad (6.20)$$

Where

K_c = crop coefficient

ET_o = reference crop evapotranspiration (mm/day)

K_c is derived empirically for each crop, location and irrigation management condition (Allen *et al.*, 1998).

Under water stress conditions, actual evapotranspiration (AET) is given as

$$AET = \frac{(SWC - WP)}{(1-p)(FC - WP)} ET_m \qquad \text{if } WP < SWC < (1-p)(FC-WP) \qquad (6.21)$$

$$AET = ET_m \qquad \text{if } (SWC - WP) > (1-p)(FC-WP) \qquad (6.22)$$

Where p is the soil moisture depletion factor, which depends on the type of the crop and potential evapotranspiration in the interval under consideration. Values of these depletion factors for different crops and potential evapotranspiration rates are reported in Doorenbos and Kassam (1979).

6.3.10.6.2 Horticultural plants

In close growing crops, the entire area is considered for irrigation while computing the water requirement. But fruit crops are widely spaced and the roots are not developed in the entire area. The roots are spread over the area approximately equivalent to the area shaded by the crop. Therefore only shaded area is considered for the computation of the water requirement (ET) of the fruit crops. This shaded area is initially less but goes on increasing with the age of tree and stabilizes after some years. Thus water requirement of the fruit crops is computed by the following equation.

$$WR = ET_0 \cdot K_c \cdot F_a \qquad (6.23)$$

Where

F_a = shaded area factor

6.3.10.6.3 Bare soil evaporation

Field can be kept as bare or it may remain bare if crop sowing is not effected as per the crop sowing criteria discussed in section 6.3.8.1. The water loss from this field will be from deep percolation and soil evaporation. Bare soil evaporation on these fields is estimated with Penman (1948) method.

6.3.10.6.4 Evaporation from open water surface

Evaporation takes places from open water surface in the trenches, behind the terraces and in the tanks. This evaporation of water from these structures is estimated with the Penman (1948) method.

6.3.11 Soil erosion

Soil erosion takes place whenever there is rainfall and runoff. Erosion can take place in different forms such as raindrop splash erosion, overland flow sheet erosion, rill erosion, gully erosion or stream bank erosion. Combination of all these erosion forms results in silt load being carried away downstream normally settling where the velocity of flowing water decreases or becomes zero as in detention or retention structures. In this analysis it is assumed that the watershed is treated with different *in situ* soil and water conservation treatments like trenches and terraces and hence soil is trapped in these structures due to erosion in the upstream reaches. Whatever silt is deposited in these structures and downstream tanks, is excavated after every 2-3 years as is practiced in the study area. Hence soil erosion is not considered while designing the tank system for the watershed.

6.3.12 Field water balance

The 'field water balance', 'soil water balance' and 'crop water balance' are synonymous terms used by researchers to describe water balance in a cropped field. Soil acts as storage reservoir for water in this balance. The water balance in the soil reservoir plays an important role in both the runoff production and irrigation requirement.

There are two basic approaches to study soil water balance:

1. Dynamic models and
2. Volume balance models

Detailed dynamic soil water balance models which are based on the Richard's equation of unsaturated flow depend on the hydraulic or transport characteristics of soil. Their time steps are small (less than 1 day), require computer based numerical techniques for their solution and involve many parameters. Further for the theory to be applicable, the soil has to confirm to the basic assumptions of the Richard's equation, namely isothermal conditions and uniformity and homogeneity of the soil. Therefore this distributed soil water modelling approach is criticized as too sophisticated for the real world. The simple soil water volume balance models are often preferred for field applications.

As reported by Rao (1987), and Panigrahi and Panda (2003) volume balance models are more popular than the dynamic models since they are relatively simple, require few parameters (i.e. field capacity and wilting point) and can be easily used at the field scale level. The data on soil parameters are available directly or can be deduced from other soil data normally provided in soil survey reports. The basis of these models is the piston flow concept. Each soil layer fills to field capacity and passes on the remaining water to the next lower layer. Volume balance model is essentially based on the principle of conservation of mass applied to the soil reservoir that is limited by the maximum root zone depth of the crop. Since the root growth varies with time, the soil reservoir is divided into an active root layer where roots are present at any given time from which both moisture extraction and percolation would occur and a passive layer (soil layer) from which only percolation would occur. Soil water balance in the upper layer is governed by daily values of rainfall, runoff, supplemental irrigation, actual evapotranspiration and percolation to the lower soil layer. Soil water balance in the soil zone is governed by percolation reaching from upper active layer and deep percolation out of the layer. Two layered soil water balance models have been reported by many researchers.

In this analysis volume balance approach is used to estimate the different components of the soil water balance as discussed below.

The conceptual model of the field water balance is shown in Fig. 6.7. The soil profile is divided into 3 zones (or layers). Root zone, soil zone and vadose zone. The soil in the vadose zone is assumed to be at field capacity. Moisture extraction by plant roots and drainage occurs from root zone whereas only drainage occurs from the soil zone.

The size of the soil water reservoir inside which the different processes of the water balance occur is not constant. It varies with crop growth and is determined by the depth of the active soil reservoir from which crops extract water, that is, on the effective rooting depth. This depth increases with crop growth and attains a maximum value by the end of flowering period for most crops. Roots go down to such layers if there are no impending soil layers. During initial period of crop growth these two zones exist separately with their relative dimensions being determined by the rate of root growth. When root zone becomes equal to soil zone, water balance is carried out for only one zone that is root zone. If root zone becomes greater than soil zone it is equated with the soil zone (i.e. root growth is restricted to the soil zone). In soil water balance estimation it is necessary to know the rate of root growth to determine the incremental availability of soil water to crops which is determined by the equation presented in Section 6.3.8.2.

The daily field soil water balance in the root zone is estimated as

$$SMCr_i RZD_i = SMCr_{i-1} RZD_{i-1} + P_i + SI_i + \Delta RZD_i SMCs_{i-1} - SR_i - D\Pr_i - AET_i \qquad (6.24)$$

Where,

$SMCr_i$	= Soil moisture content of root zone on i^{th} day, mm/mm
$SMCr_{i-1}$	= Soil moisture content of root zone on $(i-1)^{th}$ day, mm/mm
RZD_{i-1}	= Root zone depth on $(i-1)^{th}$ day, mm
P_i	= Rainfall on i^{th} day, mm
SI_i	= Irrigation on i^{th} day, mm
ΔRZD_i	= Incremental root zone depth on i^{th} day, mm
$SMCs_{i-1}$	= Soil moisture content of soil zone on $(i-1)^{th}$ day, mm/mm
SR_i	= Runoff on i^{th} day, mm
$D\Pr_i$	= Deep percolation from root zone on i^{th} day, mm
AET_i	= Actual evapotranspiration from root zone on i^{th} day, mm

i = Time index taken as days after sowing

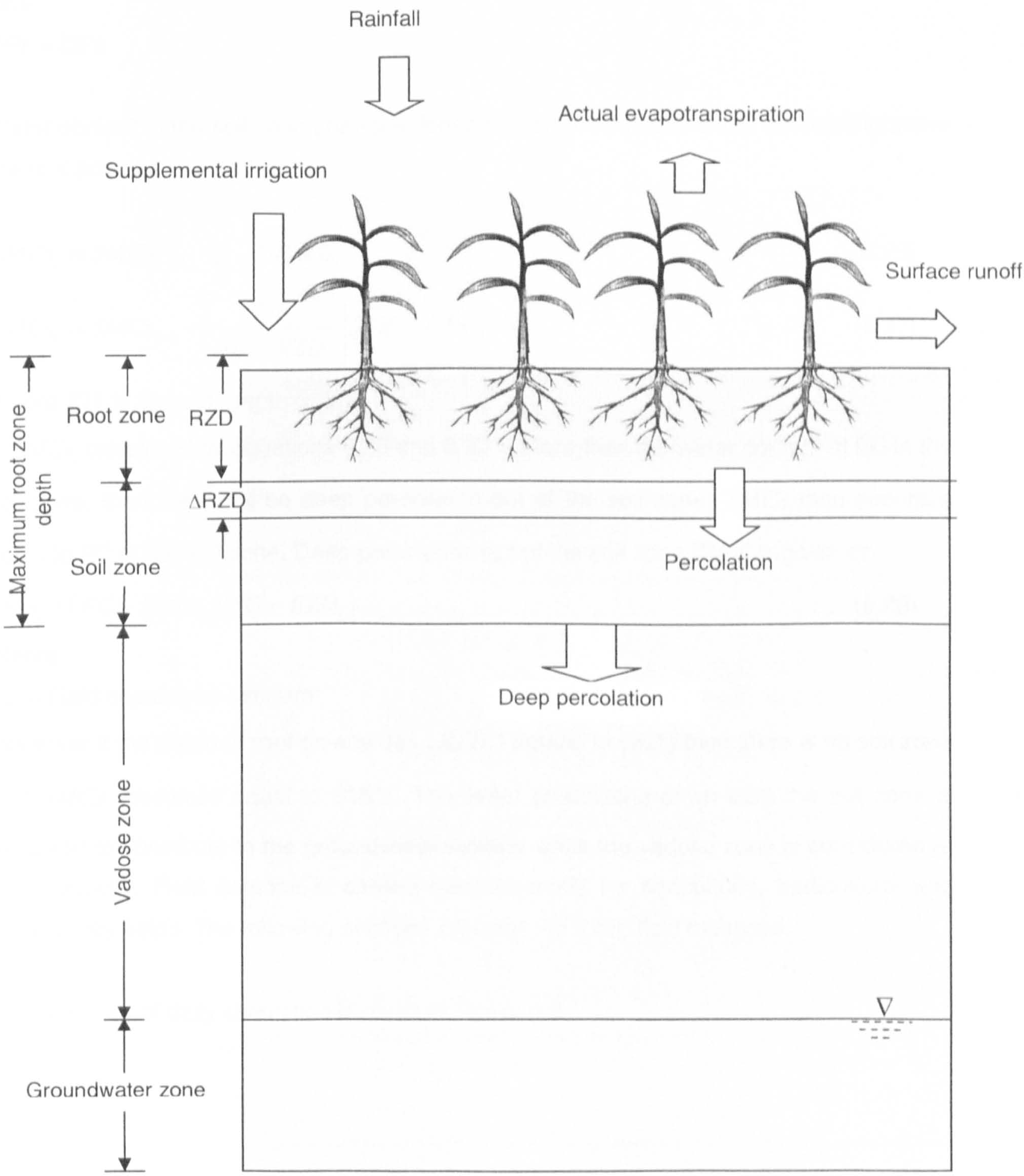


Figure 6.7: Conceptual field water balance model

Deep percolation occurs from root zone to soil zone and from soil zone to vadose zone. The amount of water percolating below root zone is given as

$$D\Pr_i = [SMCr_{i-1}RZD_{i-1} + \Delta RZD_i SMCs_{i-1}] + [P_i + SI_i - SR_i] - FC \cdot RZD_i - AET_i \quad (6.25)$$

if $D\Pr_i < 0 =$ then $D\Pr_i = 0$

else

$DPr_i = DPr_i$

Water content in the soil zone changes depending on the value of water percolating below the root zone as

$$SMCs_i = SMCs_{i-1}, \quad if \quad DP_i \leq 0 \quad (6.26)$$

$$SMCs_i = SMCs_{i-1} + \left[\frac{DP_i}{SD - RZD_i}\right], \quad if \quad D\Pr_i > 0 \quad (6.27)$$

Where SD is the soil 'depth (mm).

If $SMCs_i$ calculated by equations 6.26 and 6.27 is more than the water content at FC in the soil zone, then there will be deep percolation out of the soil zone. $SMCs_i$ then becomes equal to FC of the soil zone. Deep percolation out of the soil zone DPs_i is given as

$$DPs_i = (FC - SMCs_i)(SD - RZD_i) \quad (6.28)$$

Where

FC = Field capacity in mm/mm

Moreover if the depth of root on any day (RZD_i) equals to (SD) then there is no soil zone and $SMCs_i$ becomes equal to $SMCr_i$. The water percolating down from the soil zone is assumed to contribute to the groundwater storage since the vadose zone is considered at field capacity. Field balance is carried out separately for agricultural, horticultural and agroforestry fields. The following sections describe the three field balances.

The flowchart of daily simulation is given in Figure 6.8.

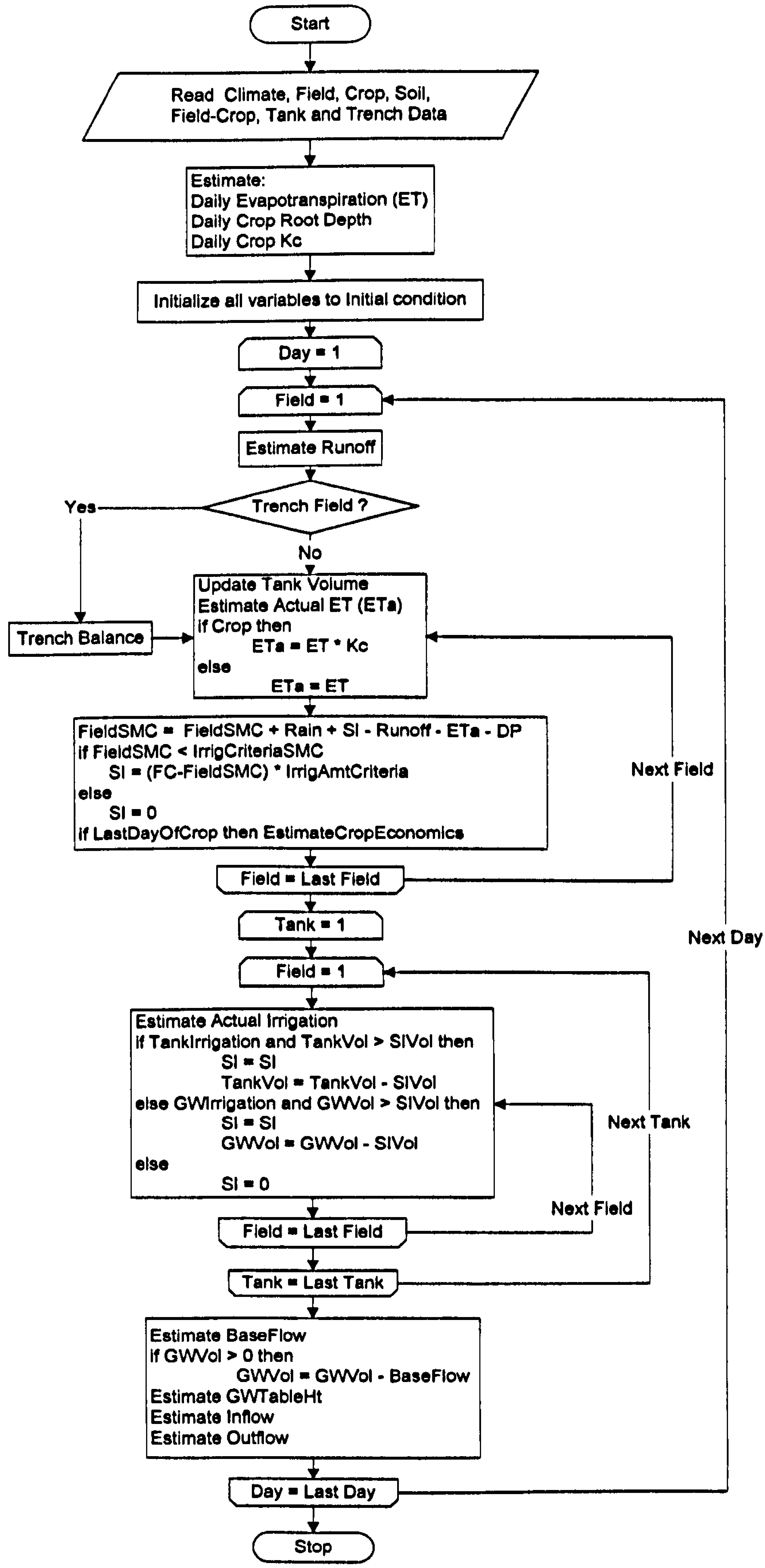


Figure 6.8 Flowchart of daily simulation

Assumptions in the soil water balance model

1. The total depth of effective rainfall (rainfall minus runoff) from different storms occurring daily and irrigation applied if any are lumped and assumed as input to the soil reservoir at the beginning of the day and that the entire water infiltrates into the soil reservoir.
2. The infiltrated water is redistributed uniformly and instantly over the effective crop root zone and the water remaining in excess of the corresponding soil storage capacity percolates out of the root zone.
3. The groundwater table in the study area is considered to be sufficiently deep and contribution from capillary rise negligible.

6.3.12.1 Agricultural field balance

In agricultural field, where the fields contain row crops, water balance is computed for common cereal, pulses, oilseeds, vegetables and fodder crops. Crops like rice and sugarcane have entirely different hydrological and irrigation characteristics. Rice and sugarcane being high water requirement crops are not grown in the dryland watersheds. Hence these crops are not considered in the present analysis. The field balance starts from 1st of June of each year. The soil in the soil zone is assumed at wilting point on the first day. Crop sowing takes place according to the criteria discussed in section 6.3.8.1. If crop sowing doesn't take place, bare field water balance is computed. First runoff is computed by the SCS CN method (Section 6.3.10.1). The difference between the rainfall and runoff is taken as water infiltrated into the soil. Soil moisture in the root zone is updated with this infiltrated water. At the beginning of the crop period the crop root zone is small and the water in excess of the field capacity of the soil goes down to the soil zone as deep percolation. As the crop reaches maturity, crop root zone increases. If the crop root zone becomes equal to the soil zone, both zones are combined into one zone that is root zone. Water in excess of field capacity of this entire root zone goes below to the vadose zone. Since vadose zone is assumed to be at field capacity, the water percolating to this zone gets added to the groundwater storage. In daily soil moisture computations, when the soil moisture of any field falls below the irrigation criteria set at the beginning, irrigation is activated. If water is available in the tank, irrigation is given from the tank else irrigation is given from the groundwater. Evapotranspiration is estimated as discussed in section 6.3.10.6.

6.3.12.2 Horticultural field balance

Horticultural field consists of rows of plants and bare soil not covered by the plant rows. Separate field balance is carried out for the plant and bare areas. Horticulture fields may contain trenches. If trenches are present runoff from the inter-trench areas as computed by SCS-CN method is the inflow to the trench. Trench water balance is computed separately. Overflow from the trench system is considered as runoff from the field (This runoff later joins the streams and tanks). If trenches are not present then the SCS-CN runoff is taken as field runoff. Runoff is computed separately for bare soil and plant areas and added together to get the field runoff. For estimating field balance plants are considered as mature (i.e. fully grown). Irrigation may be either by surface or drip irrigation method. When surface irrigation is considered irrigation is applied to the entire field and when drip irrigation is considered irrigation is given near the plants. Evapotranspiration from plant areas is computed as discussed in section 6.3.10.6.2. Soil evaporation is computed from bare field by Penman (1948) method. Since plants are considered as mature, root growth computations are not done and maximum plant root depth is considered for computations. Moisture in excess of field capacity of root zone, joins the groundwater table.

6.3.12.3 Silvipasture field balance

In silvipasture system of land use, fields contain rows of forest trees with grass cover in between the rows of the trees. Irrigation is not given to this system. If trenches are present in the field, separate trench water balance is carried out and the excess overflow from the trench system is considered as field runoff. The difficulty in this field balance is the estimation of ET since the crop coefficient values are not available for silvipasture systems. In the present analysis crop coefficient values of dryland fruit trees are considered for silvipasture trees.

6.3.13 Trench water balance

This is discussed in detail in Chapter-3 (Section 3.6.1.2).

6.3.14 Tank water balance

Tank strategy generated at the beginning give number of tanks their locations and types in the watershed. Tank water balance is carried out with the help of these tank strategies generated to arrive at the tank sizes and the best tank strategy. Tank water balance consists of applying the continuity equation to the tank system in the watershed on daily basis. The excess overflow from the upstream tanks joins as inflow to the downstream tanks. Tank balance includes all inflows to and outflows from the tank. The inflows are the direct rainfall on the tank and surface runoff coming from the fields in the catchment of the tank and overflows from the upstream tanks if any. The outflows are evaporation, seepage, excess overflows and supplementary irrigation given to crops from the tank. The schematic of tank water balance is shown in Fig. 6.9. The tank water balance is carried out on daily basis with the following balance equation.

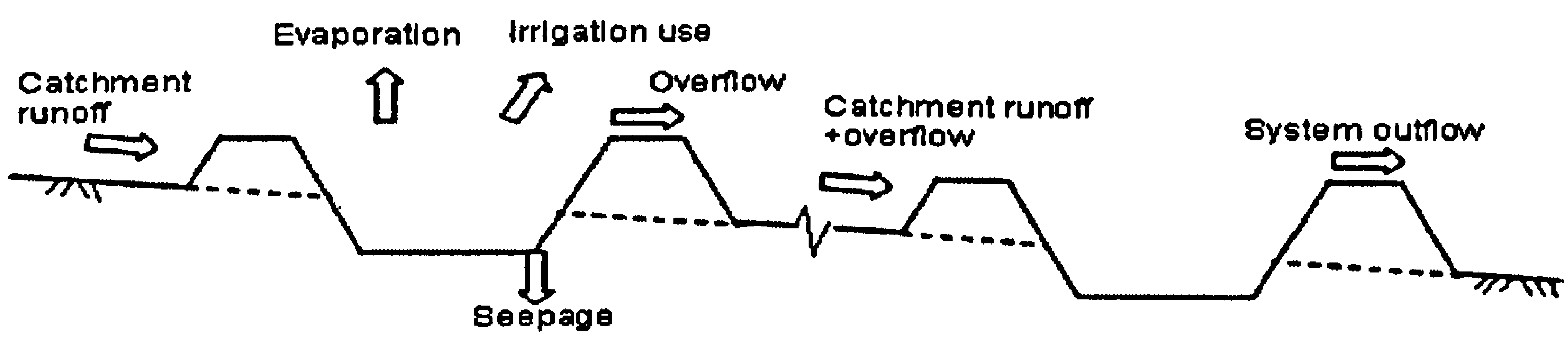


Figure 6.9. Components of tank water balance

$$S_i^j = S_{i-1}^j + P_i * A_{surf}^j + R_i^j * A_{cat}^j + O_i^{j-1} - I_i^j * Ai_i^j - DP_i^j - E_i^j * A_i^j - O_i^j \quad (6.29)$$

Where,

S_i^j = Tank storage of j^{th} tank on i^{th} day, m^3

S_{i-1}^j = Tank storage of j^{th} tank on $(i-1)^{th}$ day, m^3

P_i = Rain on i^{th} day , m

A_{surf}^j = Tank top surface area of j^{th} tank, m^2

R_i^j = Runoff to the j^{th} tank on i^{th} day, m

A_{cat}^j = Catchment area of j^{th} tank, m^2

O_i^{j-1} = Overflow from $(j-1)^{th}$ tank on i^{th} day, m^3

I_i^j = Supplementary irrigation from j^{th} tank on i^{th} day, m

Ai_i^j = Area for which irrigation is applied from j^{th} tank on i^{th} day, m^2

DP_i^j = Deep percolation from j^{th} tank on i^{th} day, m^3

E_i^j = Evaporation from j^{th} tank on i^{th} day, m

A_i^j = Water surface area of j^{th} tank on i^{th} day, m^2

O_i^j = Overflow volume from j^{th} tank on i^{th} day, m^3

For estimating tank water balance some initial tank capacity is required. This initial tank capacity is computed by giving some empirical design runoff depth over the catchment.

Note that this value is used to set off initial tank capacity only. This runoff depth multiplied by the catchment area gives the initial tank capacity. Simulation then starts from 1st June of each year and the storage in the tank at the start of the simulation is considered zero. The volume of direct rainfall contributing to the tank is calculated as the product of the top area of the tank and daily rainfall depth. Sum total of runoff values (as computed with SCS-CN method) from all fields in the catchment of the tank is taken as inflow to the tank. Overflow occurs when inflow exceeds the available capacity of the tank. The storage is then adjusted with daily losses from evaporation and seepage. Evaporation from tank is estimated by the Penman (1948) method and seepage varies as per the soil condition at the tank site. Evaporation volume is the product of the evaporation rate (as computed with Penman (1948) method) and the water surface area on that day. Seepage is considered constant for a particular tank site. Seepage from the tank contributes to the groundwater storage. Seepage rate is multiplied by the wetted area of the tank on that day to get the seepage volume. Tank water surface area and wetted area are upgraded daily to estimate the evaporation and seepage losses. It is assumed that the groundwater flow from tank catchments has no impact on tank water balance since all tanks have shallow depths. Also there is no upward flow from the groundwater to the tanks. Irrigation time and volume are activated as per the user defined depletion i.e management allowed deficit (MAD) and volume criteria and the irrigation is applied if water is available in the tank. This irrigation volume is subtracted from the tank storage. While deciding the fields for irrigation, the fields close to the tanks are given priority for irrigation. If sufficient water is not available in the tank, irrigation is given from the groundwater storage. Excess water from supplementary irrigation contributes to lower zone recharge. The dimensions of the tank are optimised with Lagrange method as discussed in section 6.3.7.1. The general topography of the catchment is sloping, but for simplification the land under tank is considered flat. The flowchart for tank water balance is shown in Fig 6.10.

For each tank strategy the tank sizes are determined after the simulation for the entire year is run. The outflow from the watershed is compared with the input DSR. (as defined in the DSR criteria discussed in section 6.3.6). If the criterion is not met, tank sizes are increased (or decreased) with some percent of the tank capacity in the earlier iteration and simulation run again for the year. Thus the tank water balance gives tank sizes for the tank strategy for each year after satisfying the irrigation and DSR criteria with some percentage deviation allowed to meet the DSR criteria (e.g. ±10%). It needs to be mentioned that as the deviation in meeting the DSR criteria decreases, the computation efforts in converging the solution for tank sizes increase. In the case of more than one number of tanks computations are performed from the most upstream tank to the lower most tank. Tank shape and the seepage rate are the two site specific parameters that are required for the tank water balance estimation.

6.3.15 Groundwater balance

Groundwater is used for irrigating the crops in the watershed. A simple bucket type approach is adopted in this study to represent the groundwater balance which is coupled with the field and tank water balance. Groundwater is stored in underground aquifers. Aquifers can be either unconfined or confined. In this study only shallow unconfined aquifers have been considered. Deep percolation from the soil zone (including the infiltration as a results of micro level activities) of field water balance and seepage from the tank water balance are the daily inflow parameters of the groundwater balance. Outflow from the groundwater comprise irrigation through wells, water for domestic, livestock, industrial use (termed as other use) and any groundwater flow (described below) coming to or going out of the aquifer. The outflow parameter 'irrigation' is the inflow parameter of field water balance and inflow parameters 'deep percolation' and 'seepage' are outflow parameters of field water balance, and tank water balance, respectively. The groundwater balance is performed by equation 6.30.

$$AqBq_i\phi = AqBq_{i-1}\phi + DPf_i + DPt_i + DPtr_i - GI_i - OU_i \pm BF_i \qquad (6.30)$$

Where

Aq = Areal extent of aquifer, m^2
Bq_i = Thickness of aquifer on i^{th} day, m
ϕ = Drainable porosity of the aquifer
DPf_{i-1} = Field deep percolation on $(i-1)^{th}$ day, m^3
DPt_{i-1} = Tank deep percolation on $(i-1)^{th}$ day, m^3
$DPtr_{i-1}$ = Trench deep percolation on $(i-1)^{th}$ day, m^3
GI_{i-1} = Groundwater irrigation on $(i-1)^{th}$ day, m^3
OU_{i-1} = Other use on $(i-1)^{th}$ th day, m^3 3
BF_{i-1} = Groundwater flow on $(i-1)^{th}$ day, m^3

For groundwater balance, it is assumed that the groundwater (aquifer) boundaries match with the watershed boundaries. It is also assumed that groundwater do not enter the soil zone since during most of the part of the year groundwater table is at more than 2 m depth below the ground surface.

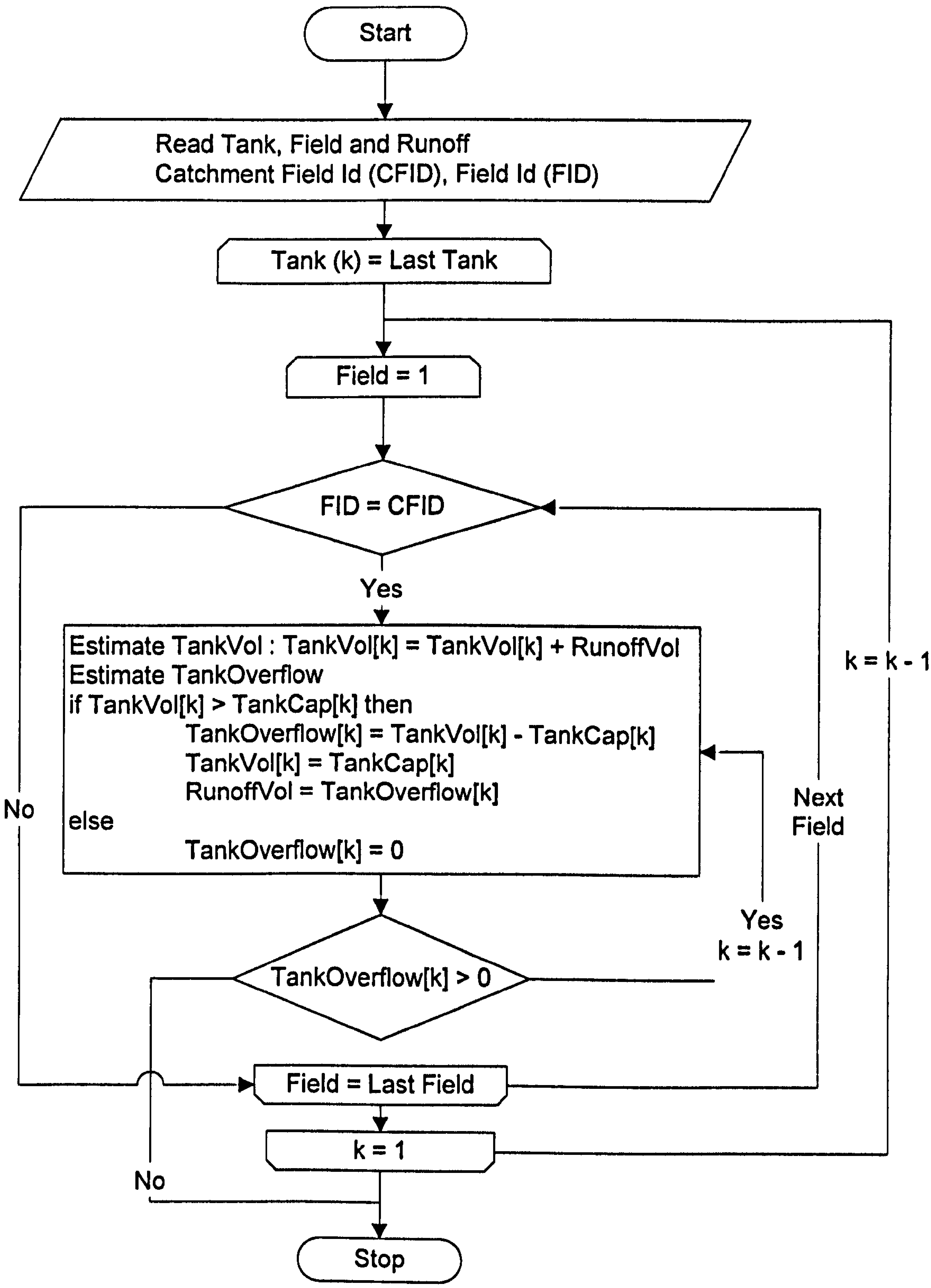


Figure 6.10 Flowchart of tank water balance

6.3.16 Estimation of groundwater flow

When watershed development takes place groundwater recharge is enhanced and groundwater gradients are changed in the underground aquifer to include this effect an empirical equation has been introduced as presented below:

$$BaseFlow = \frac{GWVol_i^{\alpha}}{1000} \tag{6.31}$$

Where

$BaseFlow$ = Volume of water leaving watershed as groundwater flow, m^3
$GWVol_i$ = Groundwater volume on i^{th} day, m^3
α = Groundwater flow exponent

6.3.17 Integration of water balances in the watershed (Watershed water balance)

The three water balances discussed above are integrated to decide the optimum tank system for the watershed. The runoff from the field water balance or the overflow from the trench system (if the trenches are present) goes as inflow to the tank water balance (in addition to any USR from the upper watershed), whereas infiltration from field and trench and seepage from tank goes to groundwater balance. Irrigation to fields reduces the tank and groundwater storage and increases the soil moisture in the catchment fields, which again influences the runoff generation.

6.3.18 Economics

The optimum tank strategy is selected on the basis of maximum net benefits and hence economics of each tank strategy is worked out.

Economic analysis for simulating a particular tank strategy or finding the optimum tank strategy is carried out by considering each climatic year as independent. All initial costs are converted to their annualised values. Total costs consisted of initial cost, maintenance cost, and crop cultivation cost. Initial costs comprised cost of tanks, tank pumps, wells, well pumps, pipeline, trenches, horticultural plantations etc. Benefits are from the crop produce in the watershed. Benefit cost ratio is obtained for each year considering the life of project 30 years.

Economic analysis for evaluating a particular tank strategy is carried out for the available climatic series (1975-76 to 2003-04). Average annual costs of cultivation and average annual benefits are considered for the analysis. Benefit cost ratio is obtained for the available climatic series.

The cost of cultivation of crops has been taken as cost of land preparation, sowing, weeding, pesticide application, harvesting and threshing. Irrigation costs are added separately. For horticultural crops, average annual net benefits for the area are considered.

For estimating the net benefits for a tank strategy all the benefits from the crops grown for a tank strategy are summed. This includes the value of the main and bye produce. The variable cost (cost of cultivation) and the fixed cost (cost of tanks, pumps, pipelines and drip system) are subtracted from benefits to obtain net benefits. Following formula is used to compute the annualised value of fixed costs.

$$A = P\frac{i\,(1+i)^n}{(1+i)^n - 1} \qquad (6.32)$$

Interest rate in the equation 6.32 is modified for inflation rate as below.

$$i = \frac{(1+im)}{(1+if)} - 1 \qquad (6.33)$$

Where

A = annual value
i = interest rate (fraction)
P = present value
n = number of years or life of the project
im =market interest rate (fraction)
if = inflation rate (fraction)

6.4 Simulation optimization model - SOFTANK

The methodology developed and described in this chapter has been converted into a computer simulation and optimization model – SOFTANK (Simulation Optimization For Tanks). Simulation is a modelling technique that is used to approximate the behaviour of a system on the computer, representing all the characteristics of the system by mathematical relationships. In the present case simulation was thus found to be appropriate methodology to represent the different water balances in the watershed for different tank strategies

6.4.1 Optimization approach

In the present study the approach adopted for optimisation is by repetitive simulation i.e. to perform the simulation of different alternatives and select the alternative that is optimum by certain criteria. For example in the present study the different alternatives are 'tank strategies' and one of the criteria for optimisation is to obtain 'maximum net benefits'. In this case, the simulation model of 'SOFTANK' is run for all the possible tank strategies and then the tank strategy that gives maximum net benefits is selected as the optimum tank strategy. The possibility of using the proper optimisation techniques such as conventional optimization methods of linear programming, non-linear programming and dynamic programming and the evolutionary methods such as genetic algorithm was investigated prior to proposing optimization by repetitive simulation. However those were not found suitable for this study due to the peculiar nature of the optimisation. This is explained below.

The optimisation problem consists of obtaining the tanks strategy by matching supply and demand parameters to decide irrigation water deliveries to different fields of watershed from different sources of water for maximization of the net benefits. These sources are groundwater and/or tanks. Depending on the relative location of the tanks and fields, field may get water from one or more tanks. In addition to this, different land treatments in fields, for example trenching and bunding, enhance the soil water storage that alter the irrigation water deliveries. The rainfall and resulting runoff are the sources for groundwater, tank and soil water storages. The relationships that govern the different processes of supply and demand are complex and nonlinear (e.g. relationship between evapotranspiration and crop yield, rainfall and runoff). Therefore use of linear programming that needs the linear relations among the decision variables, both in the objective function and in the functions forming the constraints is not possible. The stepped linear programming that helps to solve the problem of non-linear nature by discretising non-linear relationships into several linear relations (Gorantiwar, 1995) could not be used due to over million combinations of the decision variables.

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. In the present study, the number of variables influencing the decision (state variables) are so large that it becomes computationally impossible to consider all of them simultaneously. On the other hand, a coarse discretisation of the state variables may result in trapping states (same states being successively visited many times). A good criterion would be to choose the number of class intervals for the different state variables that avoid trapping states in operation while ensuring computational tractability. However this is time consuming and needs trial and error method. Again due to large number of relationships, the use of non-linear programming is unfeasible.

As such the scene is well set for using the evolutionary algorithms such as genetic algorithm, a random search algorithm that is considered to provide the optimum solution to complex problems (Goldberg 1989, Wardlaw and Bhaktikul. 2004). In genetic algorithms, the problem is represented by a string (or chromosome) of number of blocks (or genes). This is also a representation of the solution. In this study these genes are all possible locations of the tanks. The genetic algorithm then creates a population of strings or solutions. In the present study the population is the combination of number of tanks, tank locations and tank type, and capacity. The variables represented in the string can be processed in an evaluation function or fitness function by applying genetic operators such as mutation and crossover to obtain the optimum solution. In the present study the evaluation function will be the simulation model of SOFTANK. However embodied within this optimization problem are the two constraints that are difficult to include in GA formulations even by the use of penalty functions. These are optimisation of the tank dimensions for the optimised tank capacity and minimisation of losses (seepage and evaporation); and a specified downstream release requirement.

In the methodology proposed in this study, the initial tank capacity is estimated for given design runoff depth (DRD). DRD times the catchment area of tank gives volume of runoff for which tank dimensions are optimized by the Langrange method. Simulation is then carried out for the entire year. If the output DSR (sum total of daily outflow for the year) is within the range of input DSR the tank capacity is considered to be optimised otherwise tank capacities are altered and tank dimensions are optimised again. This process is repeated till the output DSR matches with input DSR within the certain given range. This was envisaged infeasible in classical optimisation techniques and evolutionary algorithms and hence the optimisation by repetitive simulation is proposed in this study.

Computer programme for the methodology is written in 'C' language and the model is named as **Simulation Optimization For Tanks (SOFTANK)**

6.4.2 Different modes of SOFTANK

SOFTANK can be run in the following four modes

1. Calibration mode
2. Evaluation mode
3. Simulation mode
4. Optimisation mode

The flowchart of the model showing different modes is depicted in Fig. 6.11.

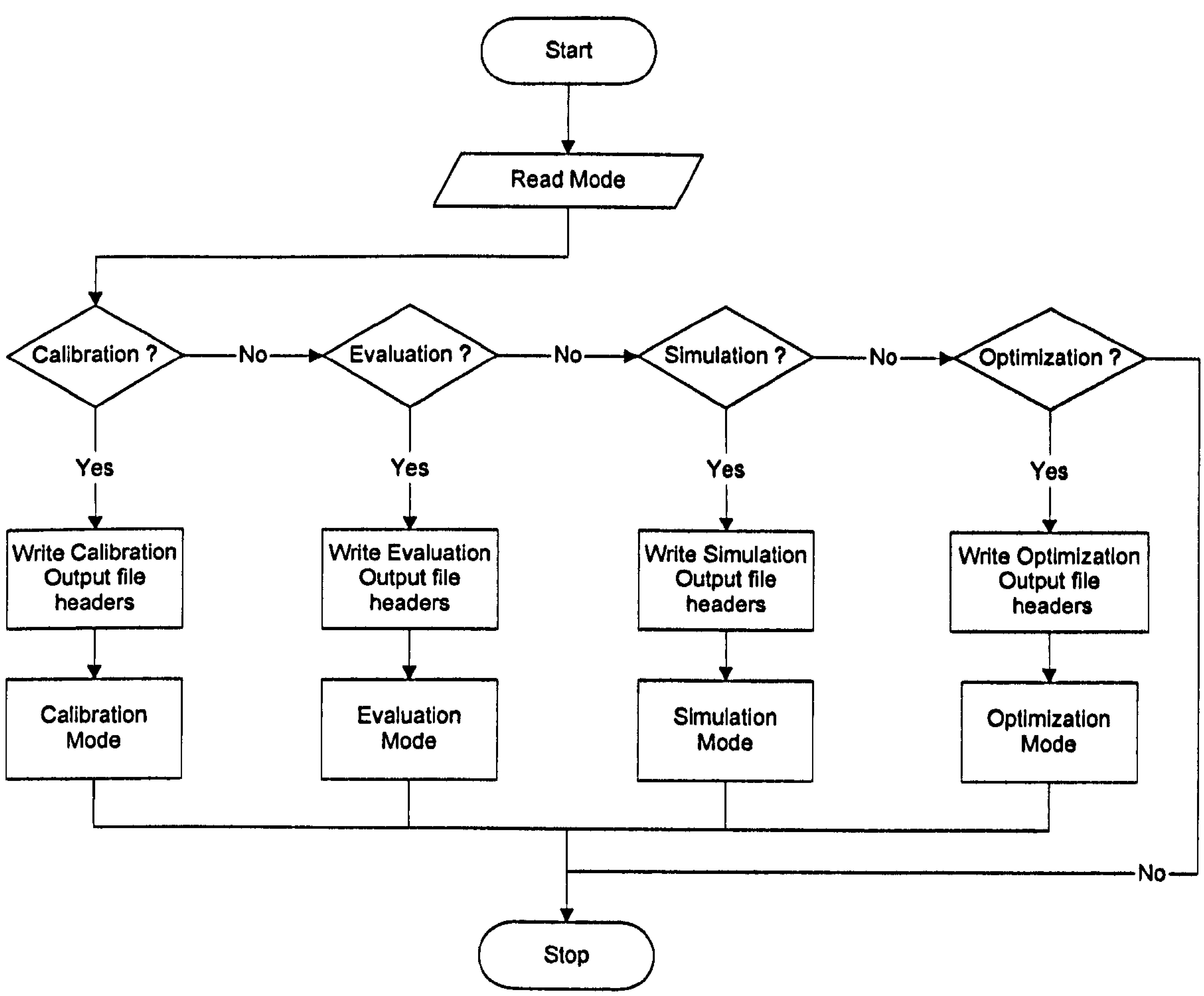


Figure 6.11 Flowchart of SOFTANK with different modes

6.4.2.1 Calibration mode

In calibration mode the existing watershed data are used for running the model. Calibration can be performed for infiltration; runoff and groundwater level. Estimated values of these parameters are compared with the observed values. If the values deviate, estimated values are modified by a adjusting a calibration parameter till the observed and estimated values agree. This is done with root mean square error (RMSE). Flowchart of SOFTANK in calibration mode is presented in Fig 6.12. This mode is used to obtain the results in Chapter 7.

6.4.2.2 Evaluation mode

In evaluation mode the model is used to evaluate the existing tank strategy for its performance assessment. The changes in the tank strategy or irrigation strategy can be suggested to improve the performance of the existing tank system in the watershed. In evaluation mode the model reads the existing tank dimensions and hence tank dimensions are not optimised. Existing irrigation and crop practices are input to the model. Flowchart of SOFTANK in evaluation mode is presented in Fig 6.13. This mode is used to obtain the results in Chapter 8.

6.4.2.3 Simulation mode

SOFTANK can be used in simulation mode to simulate a particular tank strategy or all the tank strategies for the watershed. In this mode, tank dimensions are optimised for the given watershed data and DSR criterion. Model gives one optimum tank strategy for each year in this mode. Different management options can be simulated and compared in the simulation mode. The flowchart for SOFTANK in simulation mode is shown is shown in Fig.6.14. This mode is used to obtain the results in Chapter 9.

6.4.2.4 Optimisation mode

Simulation mode gives the best tank strategy for each year based on the maximum net benefits. In optimisation mode, the model selects these best tank strategies generated in the simulation mode and evaluates this strategy for other climatic data years. The tank strategy giving maximum net benefits with output DSR within the range of input DSR is selected as the stable 'optimum tank strategy' for the watershed. Flowchart of SOFTANK in optimization mode is presented in Fig 6.15. This mode is used to obtain the results in Chapter 10.

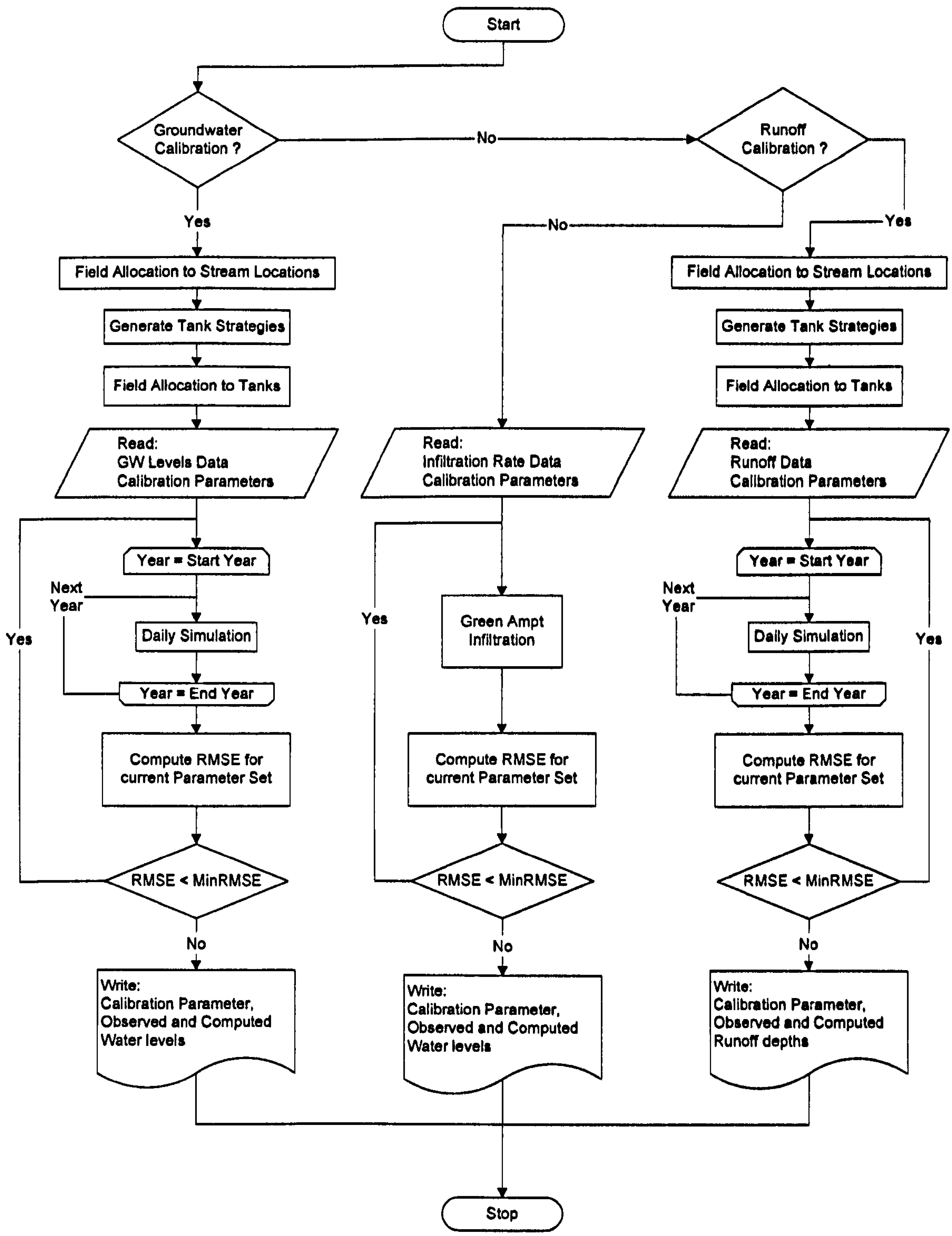


Figure 6.12 Flowchart of SOFTANK in calibration mode

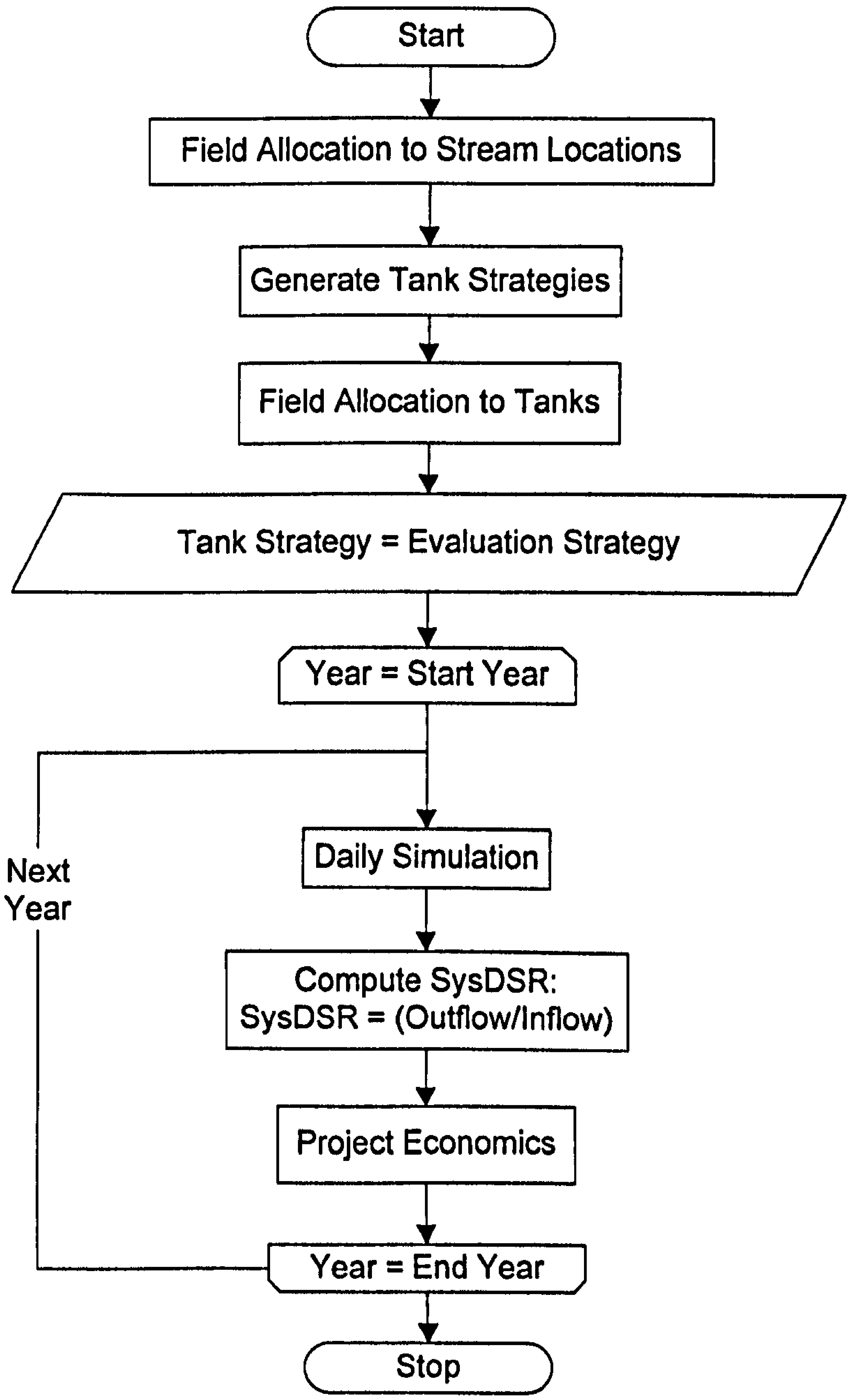


Figure 6.13 Flowchart of SOFTANK in evaluation mode

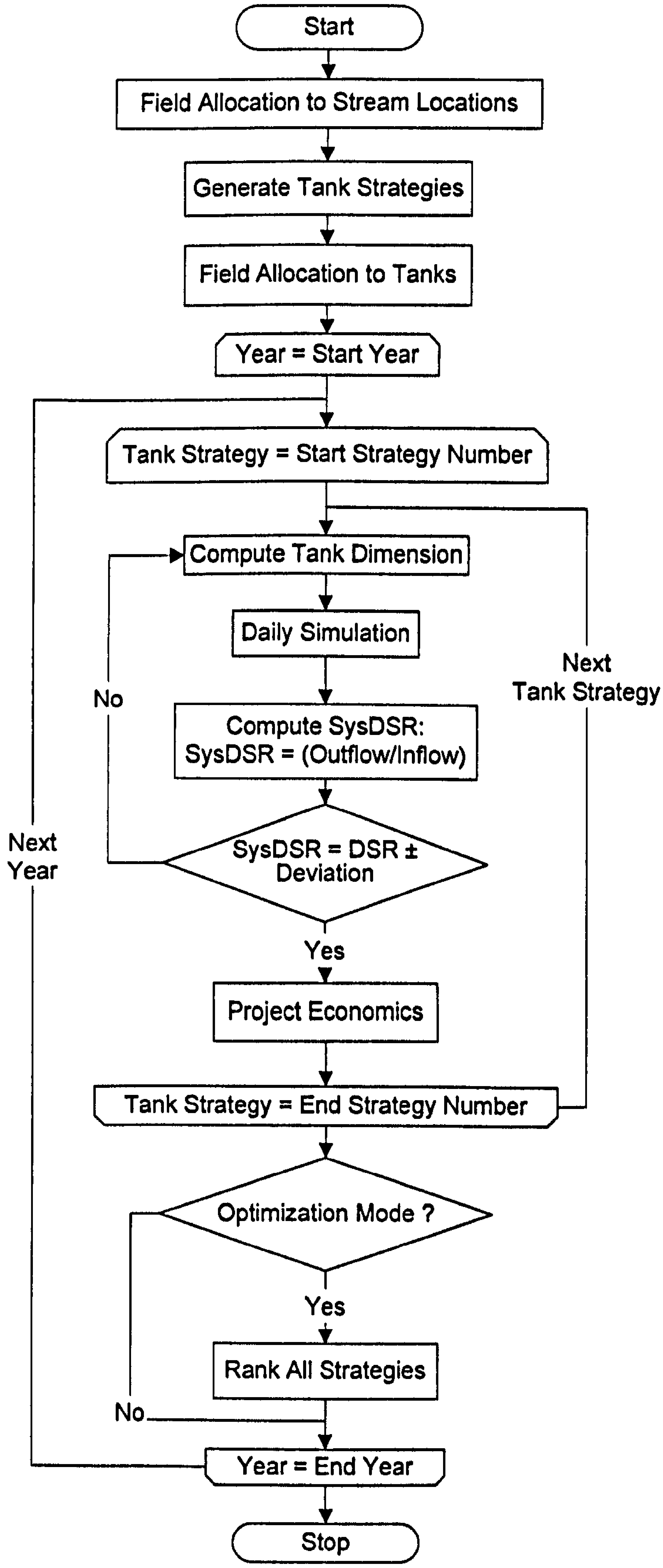


Figure 6.14 Flowchart of SOFTANK in simulation mode

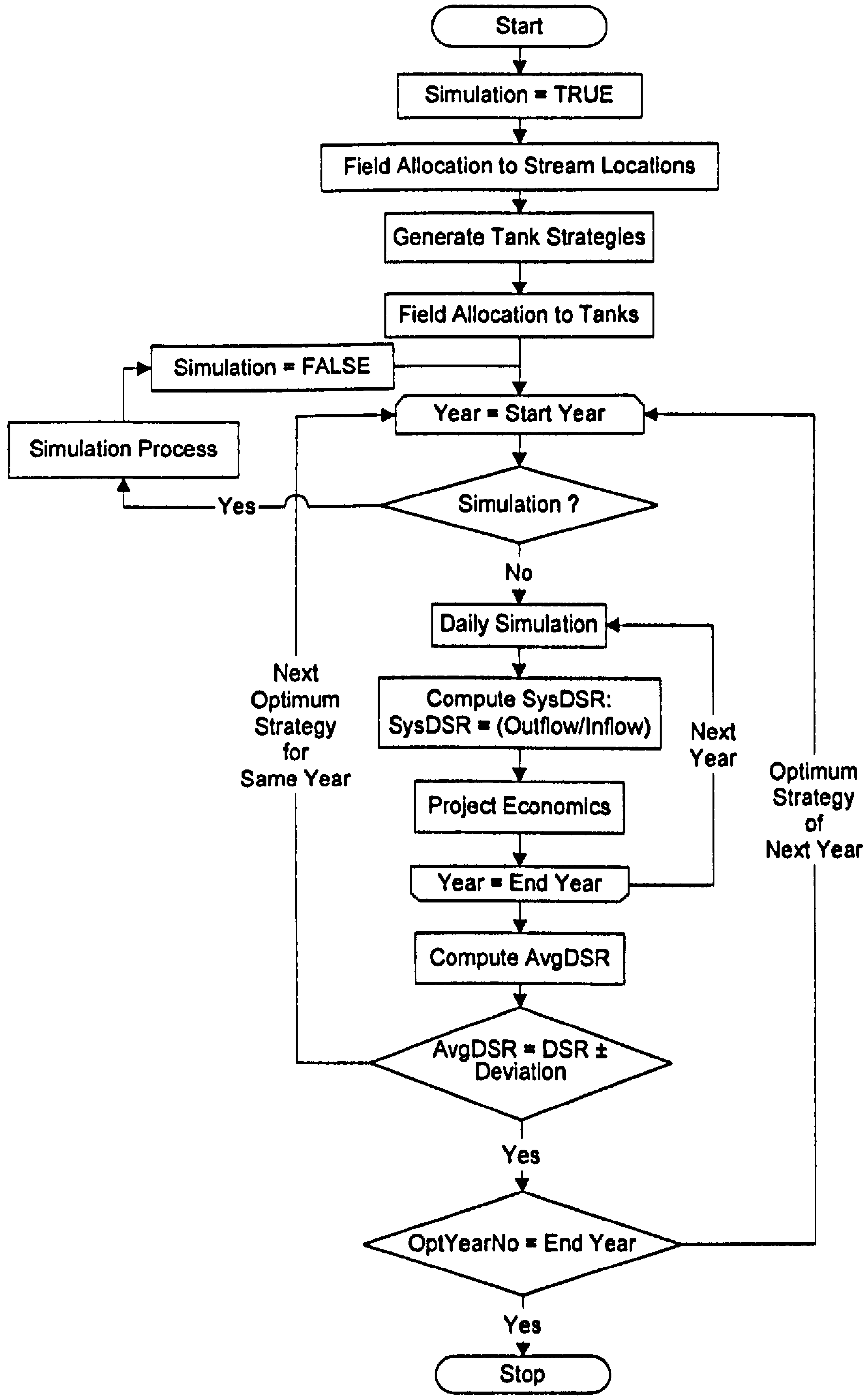


Figure 6.15 Flowchart of SOFTANK in optimization mode

6.4.3 Input data requirement of the model

The data required by SOFTANK model to derive the optimum tank system for the watershed is given below.

6.4.3.1 Climatic data

Climatic data includes daily values of climatic parameters i.e. I) rainfall, ii) maximum and minimum temperature iii) maximum and minimum relative humidity, iv) wind speed, v) sunshine hours and vi) pan evaporation.

6.4.3.2Crop data

Crop data includes the data on the commonly grown crops in the region. These are pearl millet, sorghum, wheat, gram, pigeon pea, soybean, sunflower, safflower, green gram, black gram, groundnut, maize, cotton, onion, tomato, fodder. The data includes land use code (this is used in CN value computation), sowing and harvesting date, initial and maximum root zone depth, days to maximum. root zone depth, number of critical growth stages, duration of growth stages and crop coefficient values for the stages, yield reduction factors, maximum yield, cost of cultivation and price of produce.

6.4.3.3 Field Data

Field data input consists of field number, field Cartesian coordinates, area and CN parameters.

6.4.3.4 Stream Data

Stream data includes Cartesian coordinates of the stream points, tank shape parameter at the stream point which defines the shape of the tank and seepage rate at the site of the stream point and index indicating the possible tank types at the stream point.

6.4.3.5 Soil data

Soil data includes field capacity, wilting point, bulk density, soil depth, capillary potential, saturated moisture content, porosity, saturated conductivity and hydrologic soil group.

6.4.3.6 Tank data

Tank dimensions. This data is required in calibration and evaluation mode.

6.4.3.7 Horticultural crop data

Horticultural crop data includes plant spacing, root zone depth, plant Kc, area factor (for drip irrigation), and average yearly net benefits.

6.4.3.8 Trench Data

Trench data include the width and depth of trench and spacing between the trenches.

6.4.3.9 Groundwater data

Groundwater data includes bed rock level, initial groundwater height, drainable porosity, non irrigation use (termed as other use).

6.4.3.10 Economic data

Economic data includes life of project, life of tank, wells, pumps, pipeline, trenches etc, interest and inflation rate, rate of earthwork, energy charges.

6.4.3.11 Other data

Irrigation scheduling option, source of water option, method irrigation for horticultural crops, irrigation efficiencies, number of years and number of tank strategies for which simulation to be carried out, design runoff depth (This depth is decreased to 25% for trench field), downstream release as a percent of inflow. Deviation allowed in the DSR,

6.5 Conclusion

This chapter presented the methodology for the optimum design of tank system for the watershed for obtaining the maximum net benefits. The novel features of the methodology are as follows

1. It optimizes the tank system for the watershed.
2. Tank type based on the orientation of command area around the tank has been introduced in generating tank strategy.
3. Field allocation for the catchment and command area of a tank is a dynamic process and changes with the tank strategy.
4. Methodology accounts for the *in situ* soil and water conservation practices like trenches in the catchments of tanks while optimising the tank system.

5. Groundwater storage is considered for recharge and withdrawal purpose in designing the tank strategy.
6. Down stream release (DSR) criteria is considered in optimising the tank strategy in the watershed.

The methodology for designing watershed based tank system thus considers many novel aspects which were not considered by earlier researchers. The methodology has been converted into a simulation-optimization model 'SOFTANK' by writing the computer programme in C language. The structure of the model is kept simple and data requirements matching with the field conditions. The model can be applied to real life situations for planning and evaluating tank systems in the watershed in semi-arid and sub-humid tropics.

Chapter-7

CASE STUDY DESCRIPTION AND MODEL CALIBRATION

7.1 Summary

This chapter presents the details of two case study watersheds in the semiarid region of Maharashtra state of India and discusses the methodology that should be followed for the calibration of SOFTANK model with these case studies. Results of calibration are also presented and discussed.

7.2 Introduction

The methodology was proposed in Chapter 6, to decide optimum tank system in the agricultural watershed. The methodology starts with generation of tank strategies based on the number of stream points in the watershed. The tank strategy includes number of tanks, their locations and types. The simulation results in the tank system for the watershed with storage capacity and optimum dimensions of tanks in addition to the parameters of the tank strategy. The methodology considers the influence of *in-situ* water harvesting techniques like trenches in the catchment of the tank while optimising the tank system. The three storages i.e. soil, tank and aquifer are integrated while arriving at the optimum tank system. This methodology formed the model – SOFTANK.

Two case study watersheds were selected from the semi-arid region of Maharashtra, India for demonstrating the applicability of the proposed methodology to obtain the optimum tank system design. The simulation of water balances of different storages considered in SOFTANK model needs to be calibrated for certain parameters before using SOFTANK. The details of the case study watersheds along with the calibration procedure for SOFTANK are presented in this Chapter. This Chapter further discusses as to how the calibration results be analysed to decide the calibration parameters.

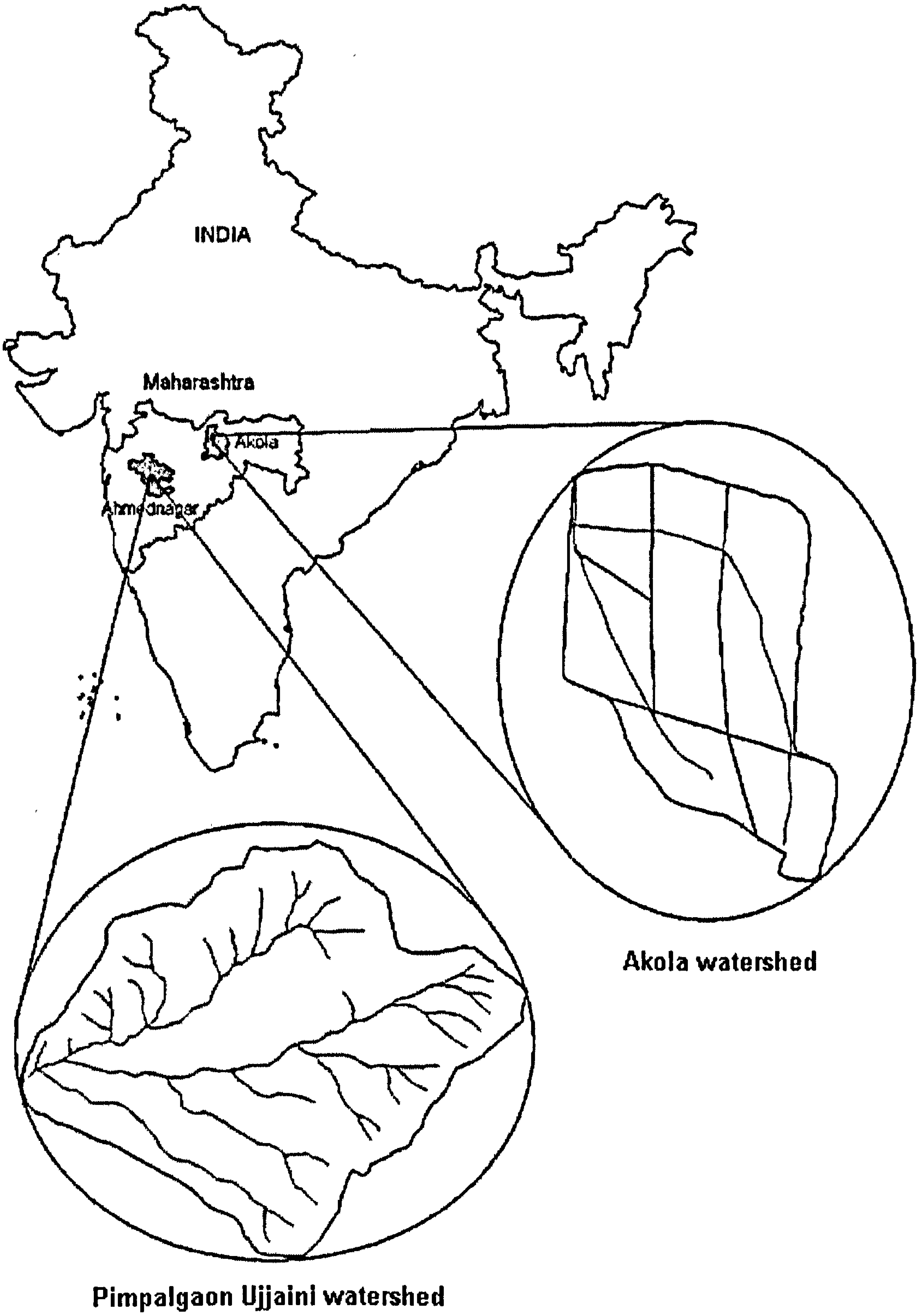


Figure 7.1 Locations of the case study watersheds

7.3 Description of case study watersheds

Two watersheds namely Akola and Pimpalgaon Ujjaini (PU) were selected for testing the validity of the proposed methodology of tank system design. These watersheds fall under two different agroclimatic zones of Maharashtra state of India i.e. assured rainfall zone and scarcity zone respectively. As discussed in Section 4.3.6.1, it is difficult to get data on the tank irrigation systems in developing countries and hence the basis for selection of these watersheds was the availability of required data for this study. These watersheds are being monitored by two agricultural universities in the state. The watersheds also differ in size and management strategy in addition to the agroclimatic zones. The Akola watershed is a small 28 ha research watershed whereas Pimpalgaon Ujjaini watershed is a large watershed with an area of 1326 ha. In Akola watershed the management decisions are under the control of the University while in Pimpalgaon Ujjaini watershed the fields belong to farmers and are managed by them. The areas fall in the semiarid tropical zone of Maharashtra state. The location map of these two case study watersheds is shown in Fig. 7.1. In both watersheds bedrock geology is comprised of volcanic rocks, which predominantly consists of basalt. Bedrock level ranges from 8 to 10 m below the ground surface. The water is mainly stored in the unconfined aquifer above the bedrock level.

7.3.1 Akola watershed

This is a small research watershed developed at Agro-Ecology and Environmental Centre, Central Research Station, Dr. Panjabrao Deshmukh Krishi Vidyapeeth (Agricultural University), Akola. This station comes in eastern Maharashtra, India with latitude of 20 42' north and longitude of 77.02' east. Akola is situated at an altitude of 307.41 m above mean sea level. Research on water harvesting and crop production is being carried out in this watershed for more than 10 years. The map of the watershed is shown in Fig. 7.2. The boundary of the watershed is not a natural boundary since the natural boundary has been modified by roads and fields in the watershed. There are two small streams in the watershed joining at the outlet. The watershed is divided into six micro-catchments, which drains runoff into the tank at the outlet of each micro-catchment. Since it is a research watershed of the University, all management decisions are controlled by the University. Land use in the watershed comprises agricultural, horticultural and silvipasture crops. Irrigation is given to the agricultural and horticultural crops through tank and wells.

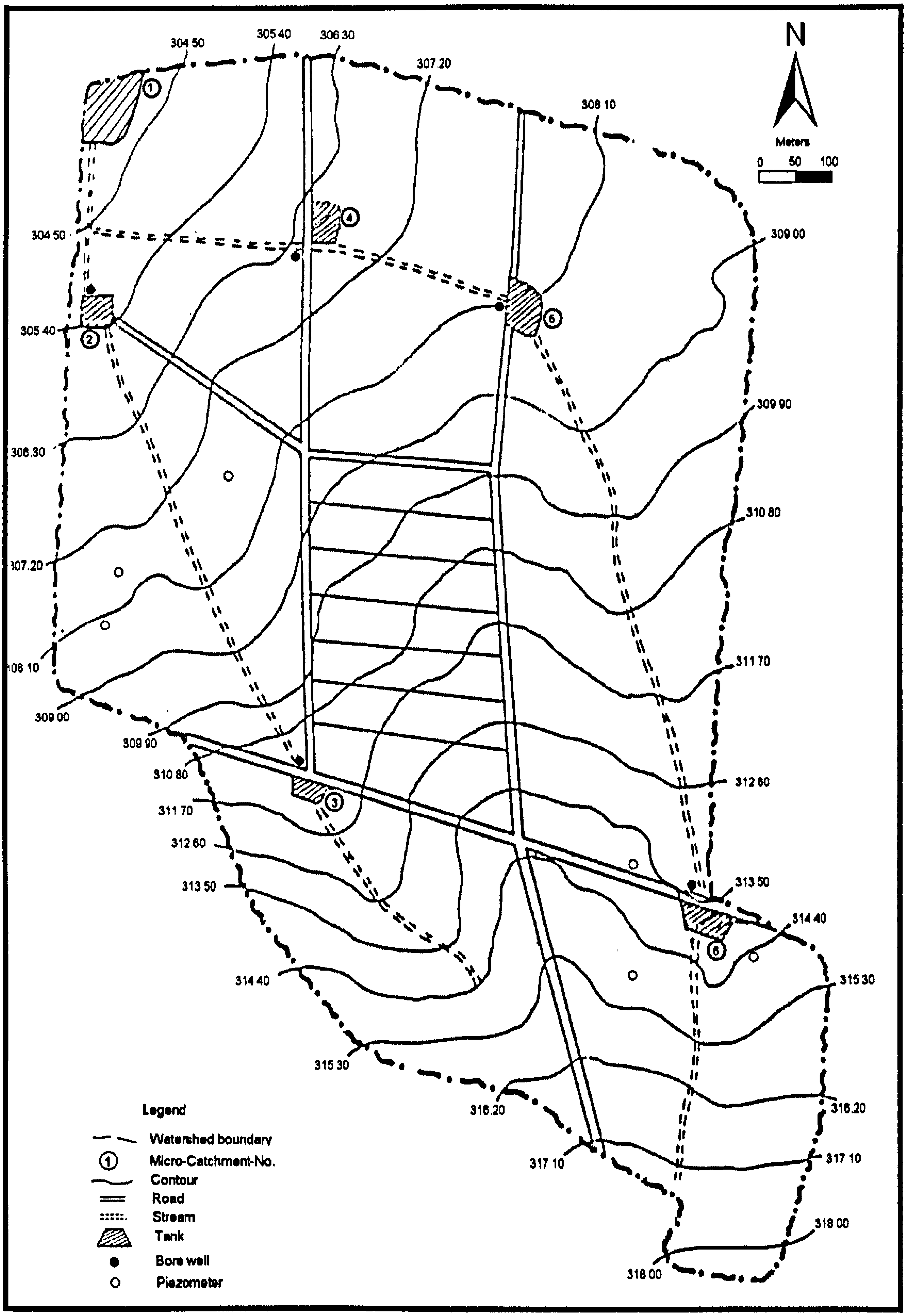


Figure 7.2 Map of Akola watershed

7.3.1.1 Climate at Akola

The climate of the region is semi-arid monsoonal type and characterised by three distinct seasons viz. summer with hot and dry weather from March to May; monsoon, warm and rainy from June to October; and winter, dry and mild cold from November to February. Average annual rainfall (based on 30 years) is about 880 mm distributed over 48 rainy days. In a year about 86 per cent of the mean total rainfall is received during the monsoon period in 40 rainy days (June-September). About 3 per cent is received during pre monsoon clouds burst and about 11 per cent during the post monsoon period. The mean annual maximum and minimum temperatures are 340C and 20.40C respectively. Summer months are fairly hot with maximum air temperature ranging from 37 to 420C with relative humidity ranging from 26 to 29 per cent. April and May are the hottest months of the year (40.50C to 42.50C) with the lowest relative humidity in April. The winter months experience mild cold with average temperature ranging from 21 to 240C. (Dr. PDKV, Akola 2000). Rainfall analysis has been carried out extensively at the station. Bharad *et al* (1993) analysed the frequency of rainfall for a period of 20 years (1967 to 1986) based on daily rainfall data and observed that

1. Two peaks of rainfall occur during 26^{th} and 31^{st} meteorological weeks
2. Sufficient rains for sowing of crops are received in 24^{th} or 25^{th} meteorological week (3^{rd} or 4^{th} week of June).
3. Occurrence of two dry spells one during 27^{th} to 29^{th} meteorological week during initial crop growth and second in 34^{th} meteorological week during development period of long duration crops (cotton, pigeon pea) is a common feature.
4. One wet spell during 31^{st} to 33^{rd} meteorological week (July or August) creates excess water problems leading to adverse effect on crop growth and intercultural operations and
5. Winter rains from southeast monsoon are uncertain.

7.3.1.2 Data for Akola watershed

Data in respect of climate, watershed characteristics, soils, crops, tanks and irrigation are documented for Akola watershed in Dr. PDKV, Akola (2002) and was used in the calibration and application of the SOFTANK model for this watershed.

7.3.1.2.1 Climatic data

Daily values of following climatic parameters from 1976 to 2004 were used.

1. Maximum temperature
2. Minimum temperature
3. Maximum relative humidity

4. Minimum relative humidity
5. Actual sunshine hours
6. Wind velocity
7. Rainfall and
8. Pan evaporation

7.3.1.2.2 Watershed data

Watershed data included data on stream points, fields, crops, soils, tanks, groundwater, and irrigation practices and discussed in this section.

7.3.1.2.3 Stream points

As discussed earlier stream points are the possible locations of tanks on the stream. But in calibration and evaluation mode of SOFTANK they are the actual locations of tanks on the stream. The Akola watershed has two streams. The coordinates of these stream points are given in Table 7.1.

Table 7.1: Stream point coordinates for Akola watershed

Stream point No.	X-coordinate	Y-coordinate	Z-coordinate
1	16.2	2.5	304.00
2	15.8	5.5	305.40
3	12.0	13.5	311.30
4	12.5	4.0	306.50
5	8.4	5.5	308.30
6	5.2	15.5	313.90

7.3.1.2.4 Fields

The watershed is divided into different fields. The details of the fields' coordinates for Akola watershed are given in Table 7.2. Model compares the coordinates of stream points and fields and allocates the fields to different stream points. Fields are uniformly sloping with slopes ranging from 0.5 to 2.5%.

7.3.1.2.5 Hydrologic characteristics

Hydrologic characteristics are required for runoff computations by SCS CN method. These characteristics include land use, treatment, hydrologic condition and hydrologic soil groups. These characteristics for different fields for the watershed are given in Table 7.3. Treatment refers to any soil conservation treatment for crop production and includes straight rows, contoured and contoured plus terraced. Treatment in the Akola watershed was considered under contoured plus terraced. Hydrologic condition refers to how sparse or dense the ground cover is, and thus how easily water runs off the surface. The hydrologic condition is called "poor" if the ground cover is relatively sparse, "good" if it is relatively dense, and "fair" in between. Hydrologic condition "poor" results in more runoff followed by hydrologic condition "fair" and "good". Hydrologic condition ranged from "fair" to "good" in the watershed.

Hydrologic soil groups are the properties of the soils and were identified based on the following information.

- A—Well-drained sand and gravel; high permeability.
- B—Moderate to well-drained; moderately fine to moderately coarse texture; moderate permeability.
- C—Poor to moderately well-drained; moderately fine to fine texture; slow permeability.
- D—Poorly drained, clay soils with high swelling potential, permanent high water table, claypan, or shallow soils over nearly impervious layer(s).

Land use in the watershed included agriculture, horticulture and silvipasture system. The details of the land use are given in Table 7.4.

Table 7.2: Field coordinates for Akola watershed

Field No	Catchment No	X-coordinate	Y-coordinate	Z-coordinate	Area, ha	Soil type
1	1	9.0	16.5	314.40	1.20	SCL
2	1	12.0	13.5	311.30	1.80	SCL
3	1	12.0	13.5	311.30	0.85	SCL
4	2	15.8	5.5	305.40	3.30	SCL
5	3	14.1	4.0	305.30	1.00	SCL
6	3	16.2	4.0	304.50	1.00	SCL
7	3	16.2	2.5	304.00	1.85	SCL
8	4	12.5	4.0	306.50	2.75	SL
9	4	12.5	4.0	306.50	0.05	SL
10	4	12.2	7.8	308.50	0.34	SCL
11	4	12.2	8.5	308.90	0.35	LS
12	4	12.2	9.2	309.10	0.36	SL
13	4	12.1	10.0	309.50	0.36	SCL
14	4	12.0	10.8	309.90	0.34	LS
15	4	12.0	11.5	309.90	0.35	LS
16	4	12.0	12.4	310.90	0.40	LS
17	5	8.4	5.5	308.30	6.80	SL
18	6	5.2	15.5	313.90	0.5	SL
19	6	5.2	15.5	313.90	3.4	SL

Table 7.3: Hydrological characteristics of fields for Akola watershed

Field No	Catchment No	Land use	Treatment	Hydrologic condition	Hydrologic soil group
1	1	Horticulture	CCT	Good	C
2	1	Horticulture	CCT	Good	C
3	1	Horticulture	CCT	Good	C
4	2	Silvipasture	CCT	Good	C
5	3	Horticulture	--	Good	C
6	3	Horticulture	--	Good	C
7	3	Horticulture	--	Good	C
8	4	Agriculture	--	Good	B
9	4	Agriculture	--	Good	B
10	4	Agriculture	--	Good	C
11	4	Agriculture	--	Good	B
12	4	Agriculture	--	Good	B
13	4	Agriculture	--	Good	C
14	4	Agriculture	--	Good	B
15	4	Agriculture	--	Good	B
16	4	Agriculture	--	Good	B
17	5	Silvipasture	--	Good	B
18	6	Horticulture	--	Good	B
19	6	Bare	--	Poor	B

(CCT= Continuous contour trenches)

Table 7.4: Land use details for Akola watershed

Field No	Land use	Crop	Plant spacing m	Area ha
1	Horticulture	Gooseberry	5 x 5	1.20
2	Horticulture	Custard apple	5 x 5	1.80
3	Horticulture	Ber	5 x 5	0.85
4	Silvipasture	Anjan + Stylo hemata	5 X 5	3.30
5	Horticulture	Guava	5 x 5	1.00
6	Horticulture	Pomegranate	5 x 5	1.00
7	Horticulture	Custard apple	5 x 5	1.85
8	Horticulture	Oranges	5 x 5	2.75
9	Agriculture	Sorghum		0.05
10	Agriculture	Sorghum		0.34
11	Agriculture	Sorghum		0.35
12	Agriculture	Sorghum		0.36
13	Agriculture	Sorghum		0.36
14	Agriculture	Cotton		0.34
15	Agriculture	Cotton		0.35
16	Agriculture	Cotton		0.40
17	Silvipasture	Anjan + Stylo hemata	5X5	6.80
18	Horticulture	Mango	10x 10	0.5
19	Bare	--		3.4

7.3.1.2.6 Soils

Soils in the watershed vary in depth, colour and other morphological characteristics. The soil properties are given in Table 7.5. These soil properties were used in the estimation of irrigation requirements, runoff, infiltration and evaporation.

Table 7.5: Soil data for Akola watershed

Soil Id	Soil type	FC,%	WP,%	BD, gm/cm^3	Depth cm	Ks mm/h	CP mm	n	HSG	θ_s
1	SCL	32.20	15.10	1.42	118	1.5	218.5	0.40	C	0.43
2	SCL	32.50	19.19	1.40	117	1.5	218.5	0.40	C	0.43
3	SCL	32.50	15.08	1.38	74	1.5	218.5	0.40	C	0.43
4	LS	21.58	10.15	1.38	20	29.9	61.3	0.44	B	0.40
5	LS	24.34	12.2	1.34	20	29.9	61.3	0.44	B	0.40
6	LS	25.79	13.50	1.31	20	29.9	61.3	0.44	B	0.40
7	SCL	31.30	16.10	1.27	76	1.5	218.5	0.40	C	0.33
8	SL	29.20	15.30	1.22	81	10.9	110.1	0.45	B	0.41
9	LS	20.90	15.10	1.25	83	29.9	61.3	0.44	B	0.40
10	SCL	31.10	16.70	1.25	80	1.5	218.5	0.40	C	0.33
11	SL	29.10	15.20	1.32	79	10.9	110.1	0.45	B	0.41
12	SL	28.98	15.20	1.39	60	10.9	110.1	0.45	B	0.41

(SCL:= Sandy clay loam, LS= Loamy sand, SL= Sandy loam, FC= Field capacity, WP = Wilting point, BD= Bulk density, Ks = Saturated hydraulic conductivity, CP= Capillary potential, n = Porosity, HSG= Hydrological soil group, θ_s = Saturated moisture content)

7.3.1.2.7 Crops

Different crops cultivated in the watershed are presented in Table 7.4. The common crops of the region are sorghum, wheat, pigeon pea, soybean, sunflower maize and cotton. The details of crops are given in Appendix A7-2. These details were used while demonstrating the utility of SOFTANK model for optimization of tank system.

7.3.1.2.8 Tanks

There are six tanks in the watershed. Runoff is collected in the tanks during wet spells of monsoon and the water in the tanks is used for groundwater recharge, and irrigation. There are two streams with tank No. 1 being common to both streams at the outlet of the watershed. The dimensions of the tanks are given in Table 7.6. Seepage rate for the tanks is considered as 24 mm/day (Dr. PDKV, Akola 2002). Seepage rate is considered same for all tank sites and constant throughout the study period. Shape of the tanks was inverted truncated pyramid.

Table: 7.6 Dimensions of existing tanks in Akola watershed

Tank No.	Catchment No	Top length (m)	Top width (m)	Bottom length (m)	Bottom width (m)	Depth (m)	Capacity (m^3)
1	3	24.3	24.3	20.3	20.3	2	1000
2	2	23.4	23. 4	19. 4	19. 4	2	918
3	1	17.6	17. 6	13. 6	13. 6	2	488
4	4	20.1	16. 1	20. 1	16. 1	2	656
5	5	26.3	26.3	22.3	22.3	2	1186
6	6	19.0	19.0	15.0	15.0	2	578

7.3.1.2.9 Trenches

The continuous contour trenches data in the form of the cross section of the trench and spacing between the trenches are presented in Table 7.7. Fields 1, 2, 3 (Catchment-1) and 4 (Catchment-2) are treated with continuous contour trenches.

Table 7.7: Trench specifications in the Akola watershed

Field Id	Area ha	Trench width, m	Trench depth m	Spacing, m
1	1.20	0.6	0.3	5
2	1.80	0.6	0.3	5
3	0.85	0.6	0.3	5
4	3.30	0.6	0.3	5

7.3.1.2.10 Piezometers

Eight piezometers (P_1, P_2, P_3, P_4, P_5, P_6, P_7, and P_8) were installed in the watershed. Out of these, two piezometers P_1 and P_5 became non functional and hence their observations were not available. Piezometers P_2, P_3, P_4 were present in micro-catchment 2, piezometers P_6, in micro-catchment 5 and piezometers P_7, P_8 in micro-catchment 6. The locations of these piezometers are shown in the watershed map (Fig 7.2). The data on groundwater levels were available for the Akola watershed and this data for 7 years i.e. from 1996-97 to 2002-03 were used for calibration of the model parameters. The data are given in Appendix A7-2.

7.3.2 Pimpalgaon Ujjaini watershed

This watershed is located at Pimpalgaon Ujjaini village in Ahmednagar district of Maharashtra state, India. The watershed is located at 15 km northeast from Ahmednagar. The latitude and longitude of study area are 74.05^0 east and 18.15^0 north respectively. The crop production activities in the watershed are controlled by farmers. The Groundwater Project of Mahatma Phule Krishi Vidyapeeth (MPKV) conducts the water balance study in the watershed. There are two percolation tanks on two streams in the watershed. Irrigation to the crops is mainly through well irrigation and these percolation tanks serve the purpose of groundwater recharge only. The map of Pimpalgaon Ujjaini watershed is shown in Fig: 7.3.

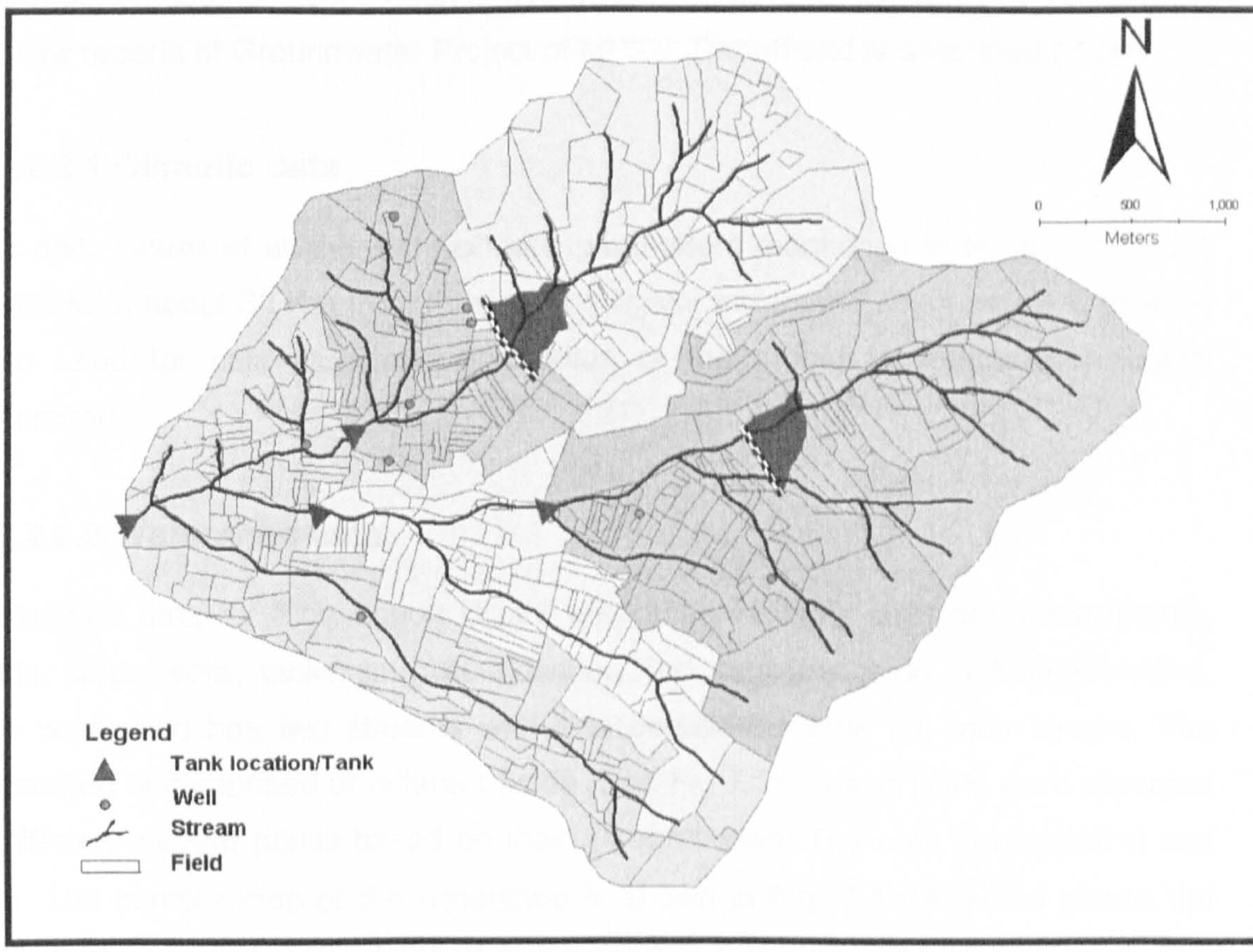


Figure 7.3 Map of Pimpalgaon Ujjaini watershed *(Source: Groundwater Project, MPKV, 2000)*

7.3.2.1 Climate at Pimpalgaon Ujjaini watershed

The region experiences dry climate except during southwest monsoon season. The climate is usually hot and potential evaporation is about 1800 mm. The mean annual rainfall for the region is 642 mm, most of which falls in four months of monsoon i.e. from July to October. Weekly distribution of rainfall shows that the rainfall starts in late June to early July. There is however, recession during late July and early August. Again, there is good rainfall in late August and September. The rainfall totally recedes by mid-October. This is the usual pattern found in the drought prone area of Maharashtra state. Another climatic feature is dry spells. Breaks in monsoon are normally experienced during late July and August. These dry spells occur during *kharif* season and hence *kharif* season is considered as risky for rainfed crop production (Patil 1981). The winter starts from November to February, followed by summer from March to May. The mean maximum and minimum temperatures are 35^0 C and 10^0 C recorded in summer and winter seasons respectively.

7.3.2.2 Data for Pimpalgaon Ujjaini Ujjaini watershed

The required data for Pimpalgaon Ujjaini watershed were documented in Research Review reports of Groundwater Project of MPKV, Rahuri and is described below.

7.3.2.2.1 Climatic data

The daily values of all the eight climatic parameters mentioned in Section 7.3.1.2.1 available at about 30 Km from Pimpalgaon Ujjaini watershed site from 1975 to 2004 were used for calibration and application of the model for Pimpalgaon Ujjaini watershed.

7.3.2.2.2 Watershed data

Watershed data for Pimpalgaon Ujjaini watershed included data on stream points, fields, crops, soils, tanks, and groundwater. The data are given in Appendix-A7-3. The watershed has two streams with one percolation tank on each stream. The watershed is comprised of different fields (See Fig 7.3). These fields were allocated to different stream points based on their z-coordinates. The area is undulating and hilly. The contour map of the watershed is shown in Fig. 7.4. (At some places the natural boundary of the watershed is modified due to administrative reasons). The soils in the watershed ranged from very shallow to very deep and from sandy loam to clay in texture.

7.3.2.2.3 Stream points

There are two streams in the watershed and data on stream points are given in appendix A7-3.

7.3.2.2.4 Fields

There are 447 fields in the watershed and the field data are given in appendix A7-3.

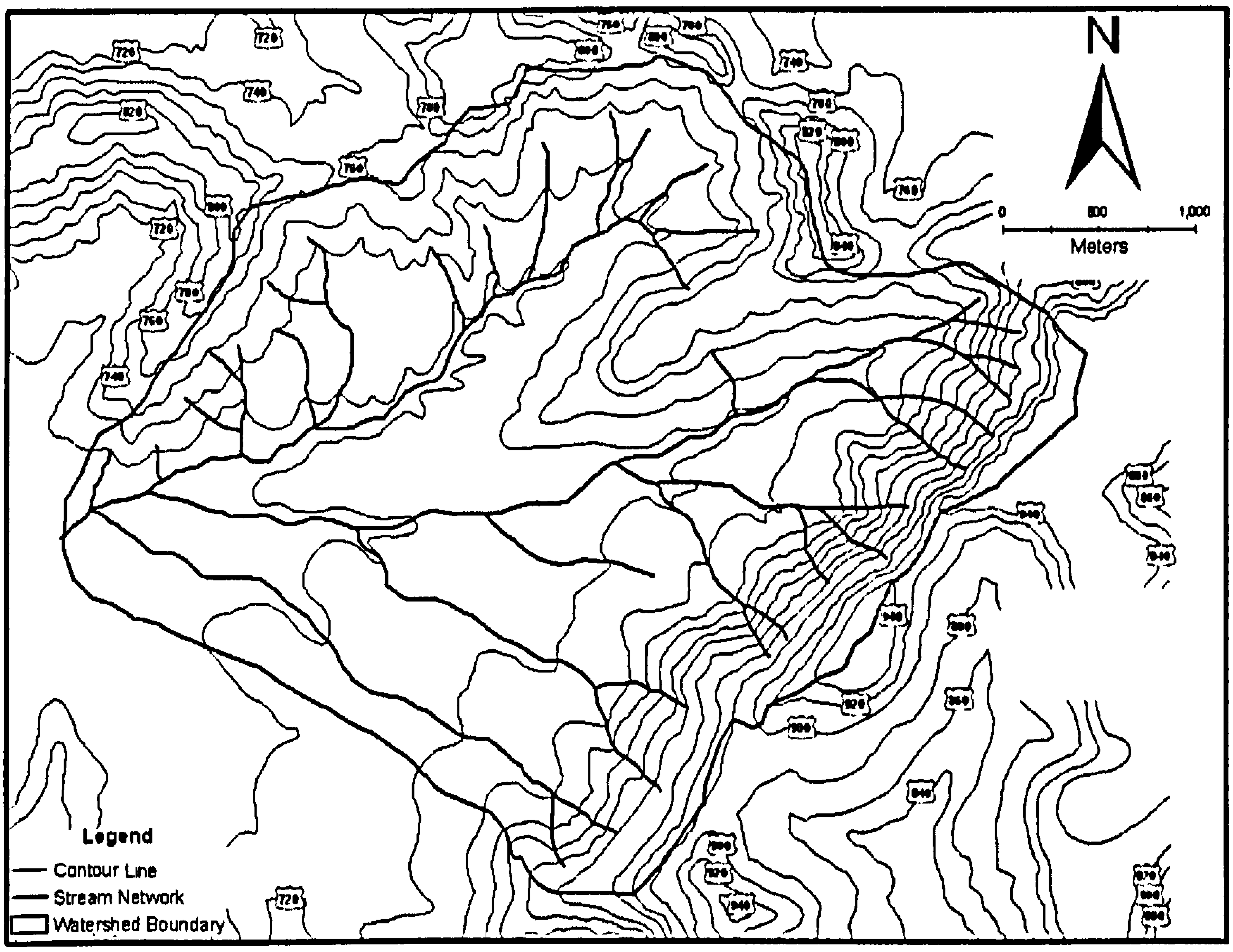


Figure 7.4 Contour map of Pimpalgaon Ujjaini watershed
(*Source: Groundwater Project, MPKV, 2000*)

7.3.2.2.5 Hydrologic characteristics

Hydrologic soil groups in the watershed belonged to hydrologic soil group B, C and D and are shown in Fig. 7.5.

7.3.2.2.6 Soils

Soils in the watershed vary in depth, colour and other morphological characteristics. The soil properties are given in appendix A7-3.

7.3.2.2.7 Crops

Common crops in the watershed are sorghum, pearl millet, wheat, gram and fodder. Land use in the watershed is shown in Fig. 7.6. Fields are used for single *kharif* cropping or single *rabi* cropping or double cropping. Most of the area downstream of the percolation tanks comes under double cropping system. The area in the catchment of the tanks is mostly with shrubs.

Figure 7.5 Hydrologic soil groups in Pimpalgaon Ujjaini watershed
(*Source: Groundwater Project, MPKV, 2000*)

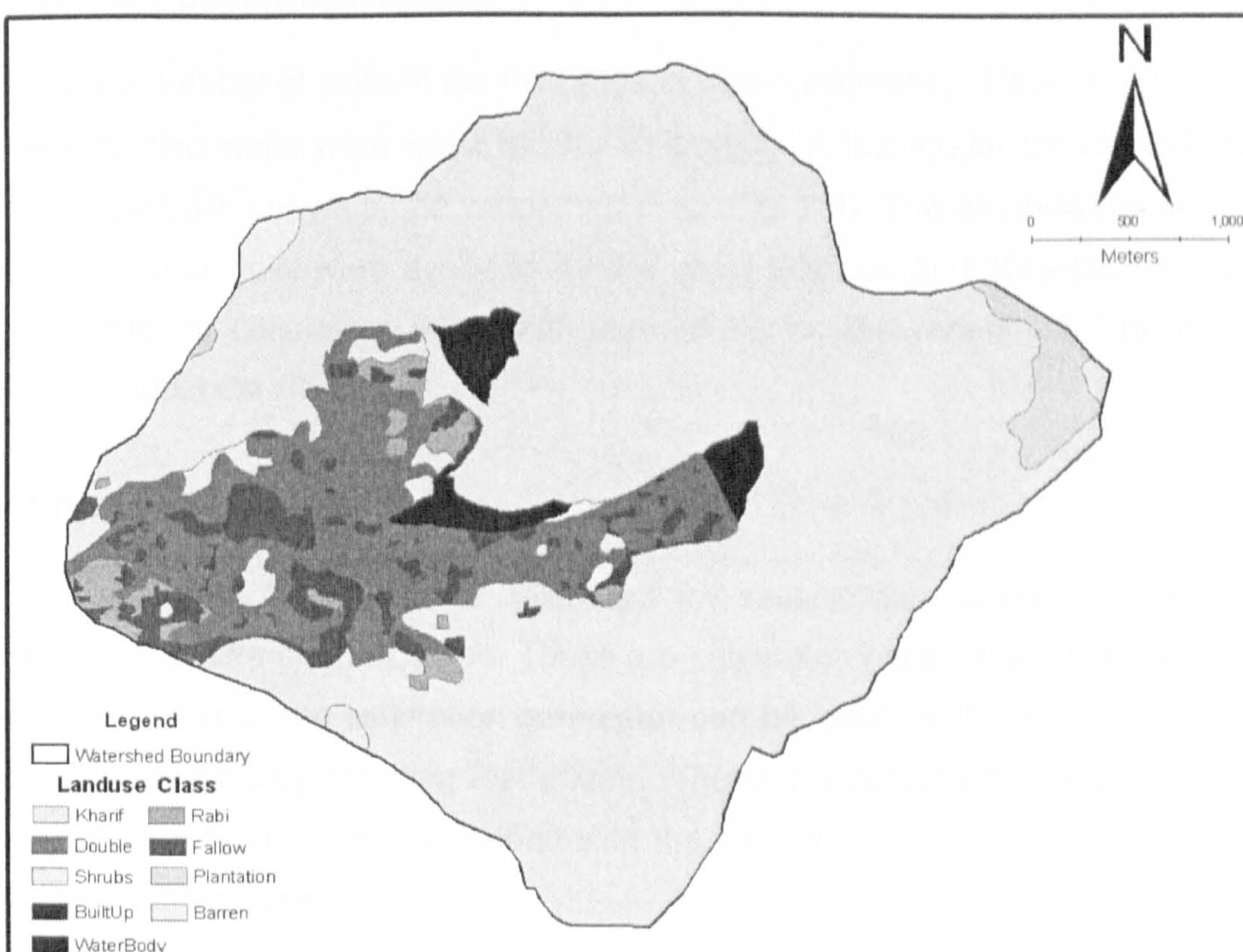


Figure 7.6 Land use in Pimpalgaon Ujjaini watershed
(*Source: Groundwater Project, MPKV, 2000*)

7.3.2.2.8 Tanks

There are two percolation tanks one each on the two streams in the watershed. These tanks are used for recharging the groundwater only. Water is not used from storage of the tanks for irrigation or domestic purpose. The details of the percolation tank are given in Table 7.8. These tanks are of embankment type with irregular shape of the reservoir. This shape was approximated to the square prism shape in the analysis. Seepage rate for both the tanks was considered as 24 mm/day (Groundwater Project, MPKV 2000).

Table: 7.8 Details of percolation tanks in Pimpalgaon Ujjaini watershed

Percolation tank No.	Water spread area (ha)	Storage capacity (ha-m)	Catchment area (ha)
Tank I	20.5	69.6	297.41
Tank II	11.5	21.6	279.40

7.3.2.2.3 Trenches

Trenches did not exist in the Pimpalgaon Ujjaini watershed.

7.3.2.2.3 Observation wells

There are number of wells in the Pimpalgaon Ujjaini watershed. Data on groundwater levels of nine wells were used for the calibration of the model for the watershed. These wells are shown in the watershed map (Fig. 7.3). The groundwater level data from the open wells were available for the years 2001-02 and 2002-03. These data were used for calibrating the model parameters for the watershed. The data are given in Appendix A7-3.

7.4 Calibration study

The model SOFTANK can be calibrated for several parameters involved in the simulation of different processes. These are calibration parameters. The validity of a particular value of the calibration parameter can be tested with different parameters (test parameters) by adopting test criteria. These are described in this section. The procedure of calibration is described with the help of two case studies discussed in the previous sections.

7.4.1 Calibration Parameter

The calibration parameters used for calibrating the model for a specified watershed (or for watershed with similar characteristics) are of the following two types.

1. Micro level calibration parameters
2. Macro level calibration parameters

7.4.1.1 Micro level calibration parameter

Micro level calibration parameters are incorporated through runoff. Runoff from the fields is estimated with the help of SCS-CN method. The calibration parameters in the SCS-CN model are the curve numbers and initial abstraction values. Observed runoff data are required for calibration of these parameters.

7.4.1.2 Macro level calibration parameters

Macro-level calibration parameters are incorporated through recharge to groundwater which is estimated with the help of water balance of the watershed. Daily values of recharge and withdrawal determine the groundwater level in the aquifers in the watershed. The calibration parameters for the recharge to groundwater are drainable porosity and groundwater flow exponent. Observed groundwater levels are required for calibration of these parameters.

7.4.2 Test Parameters

The following parameters are selected as the test parameters in the model for testing the performance of calibration parameters.

1. Runoff volume
2. Groundwater level

7.4.3 Test Criteria

The observed and simulated values (by the model) are compared with RMSE (root mean square error) criteria (equation 7.1) for the runoff volume and groundwater level calibration.

The following test criterion is incorporated in the model.

(1) Root mean square error (RMSE)

$$rmse = \left(\sum_{i=1}^{n} (Sm_i - Ob_i)^2 / n \right)^{1/2} \quad (7.1)$$

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 test parameter for i th observation

7.4.4 Calibration test

Calibration test for Akola watershed was carried out with SOFTANK model and described below.

7.4.4.1 Groundwater level calibration for Akola watershed

The ground level calibration for Akola watershed was carried out with the help of observed well water levels data (weekly values) for six observation wells for eight years. The drainable porosity of the aquifer was 0.1. The value of the calibration parameter for drainable porosity was adjusted to arrive at the minimum RMSE between observed and computed groundwater levels.

The calibration was repeated for number of combinations of drainable porosity calibration parameter and groundwater flow exponent. The following combination gave the minimum RMSE value of 1.819.

Drainable porosity calibration parameter:	0.2
Groundwater flow exponent	1.14

The observed and model estimated groundwater levels for different wells in the watershed are shown in figures from 7.9 to 7.14. These are reduced levels above the mean sea level. The model estimated groundwater levels with 95% and 99% confidence limits are shown in Fig 7.7 and Fig. 7.8

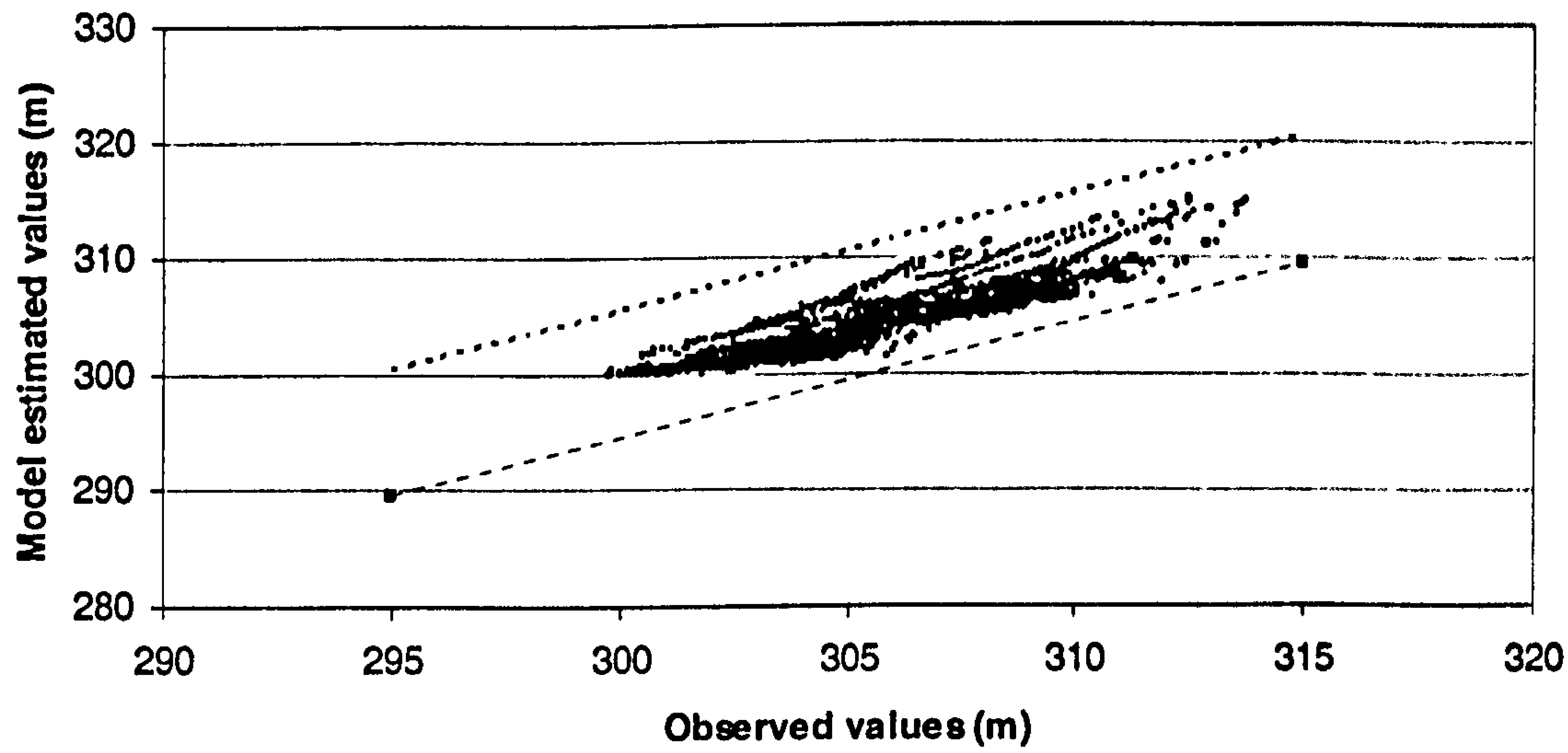


Figure 7.7 Observed and model estimated groundwater levels and 95% confidence limits for Akola watershed

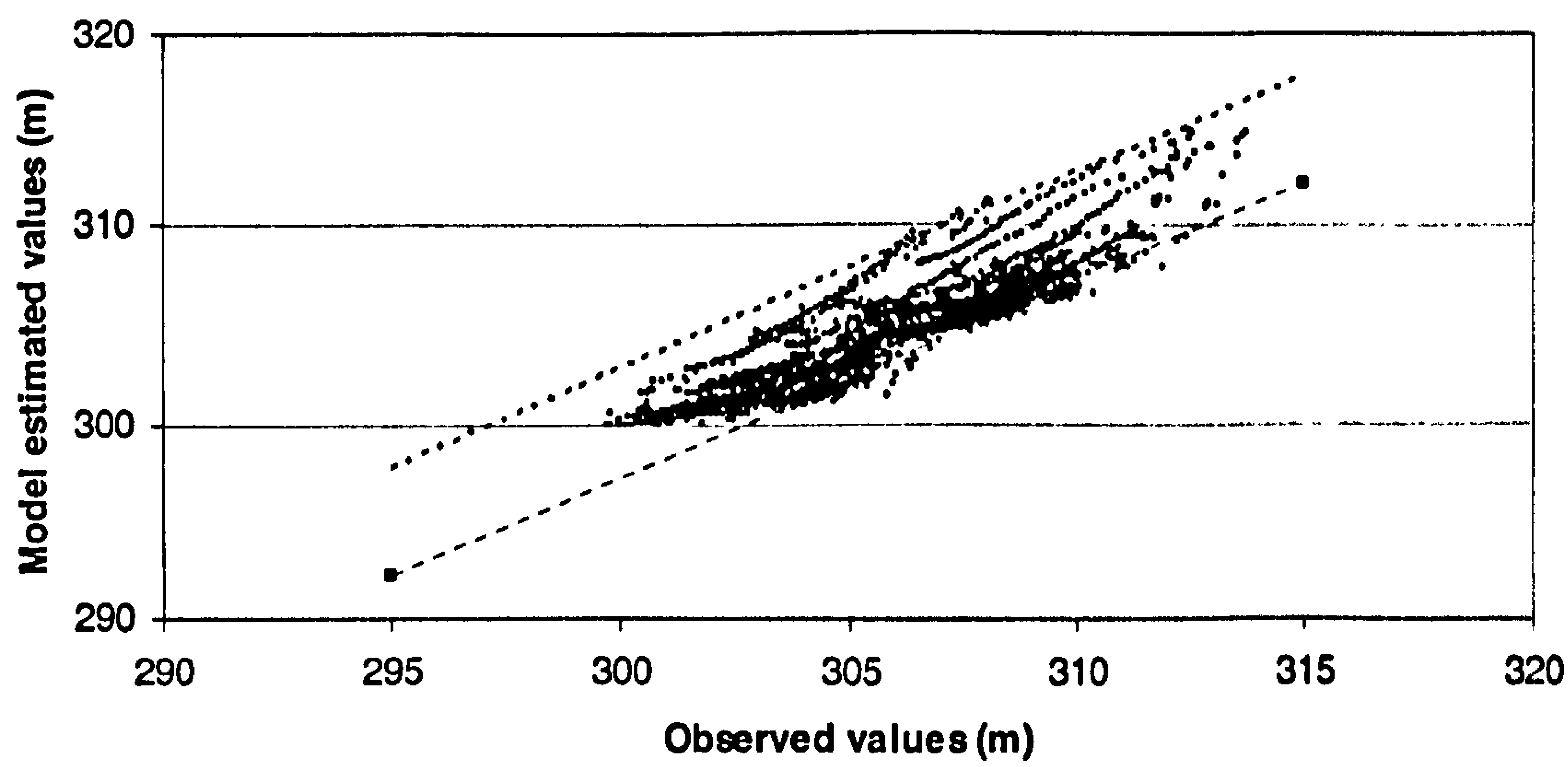


Figure 7.8 Observed and model estimated groundwater levels and 99% confidence limits for Akola watershed

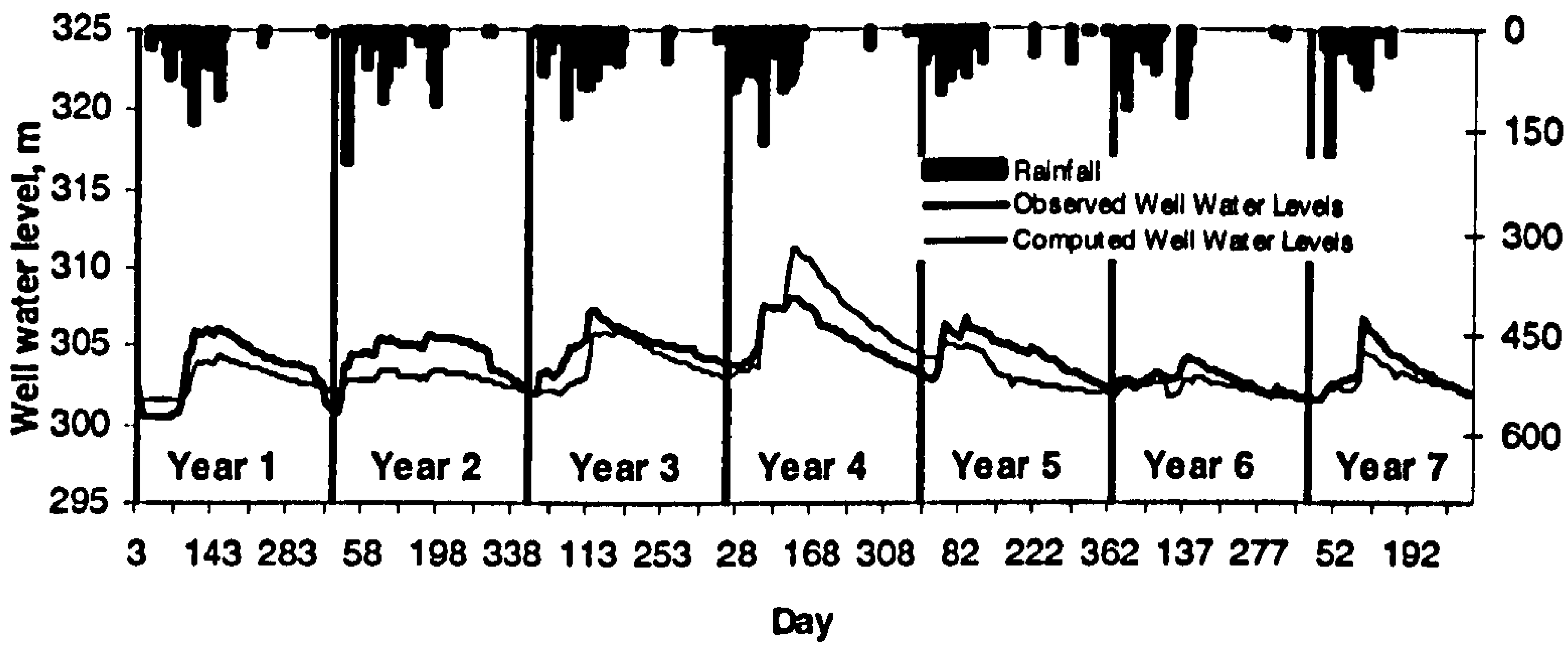


Figure 7.9 Observed and computed well water levels for Well No 1, Akola watershed

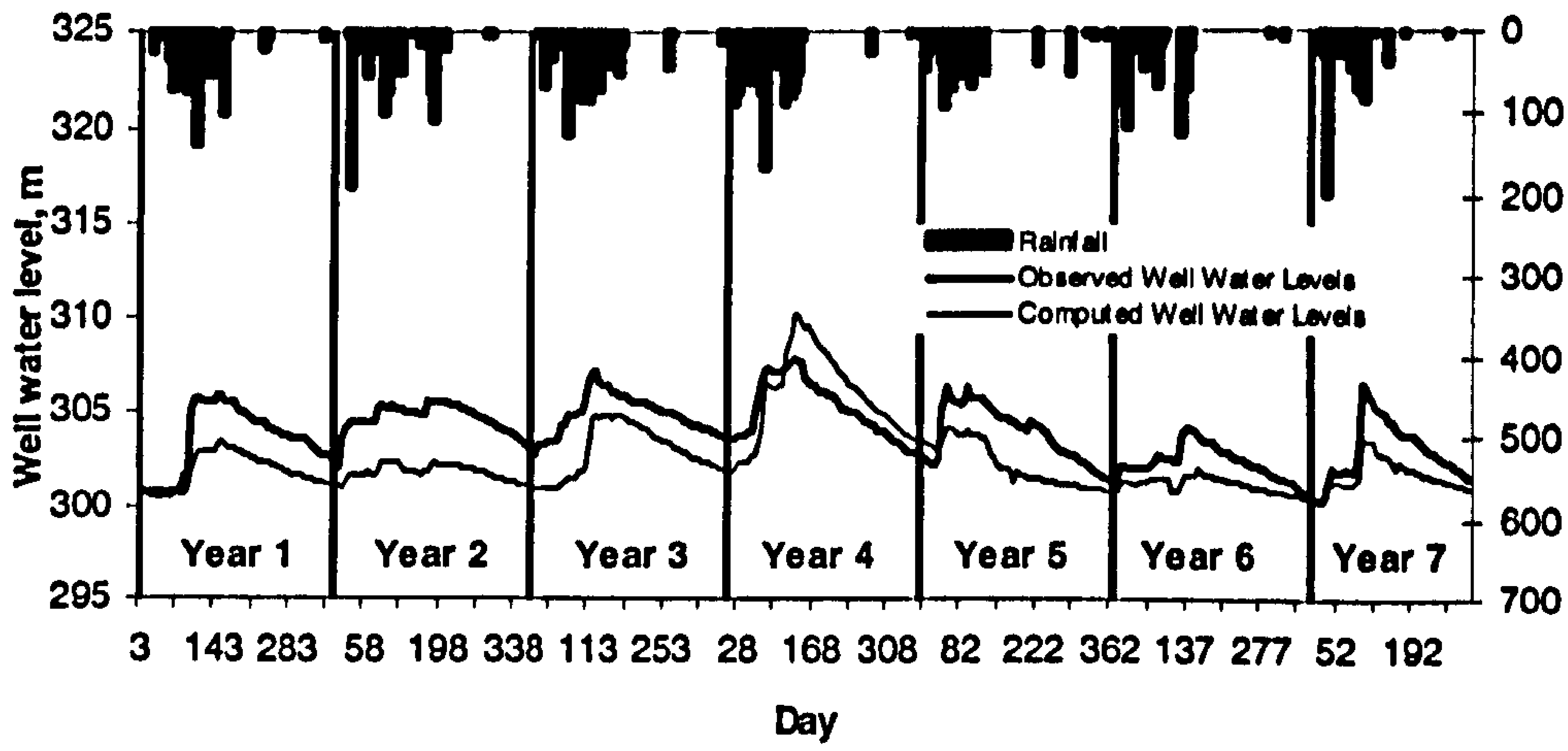


Figure 7.10 Observed and computed well water levels for Well No 2, Akola watershed

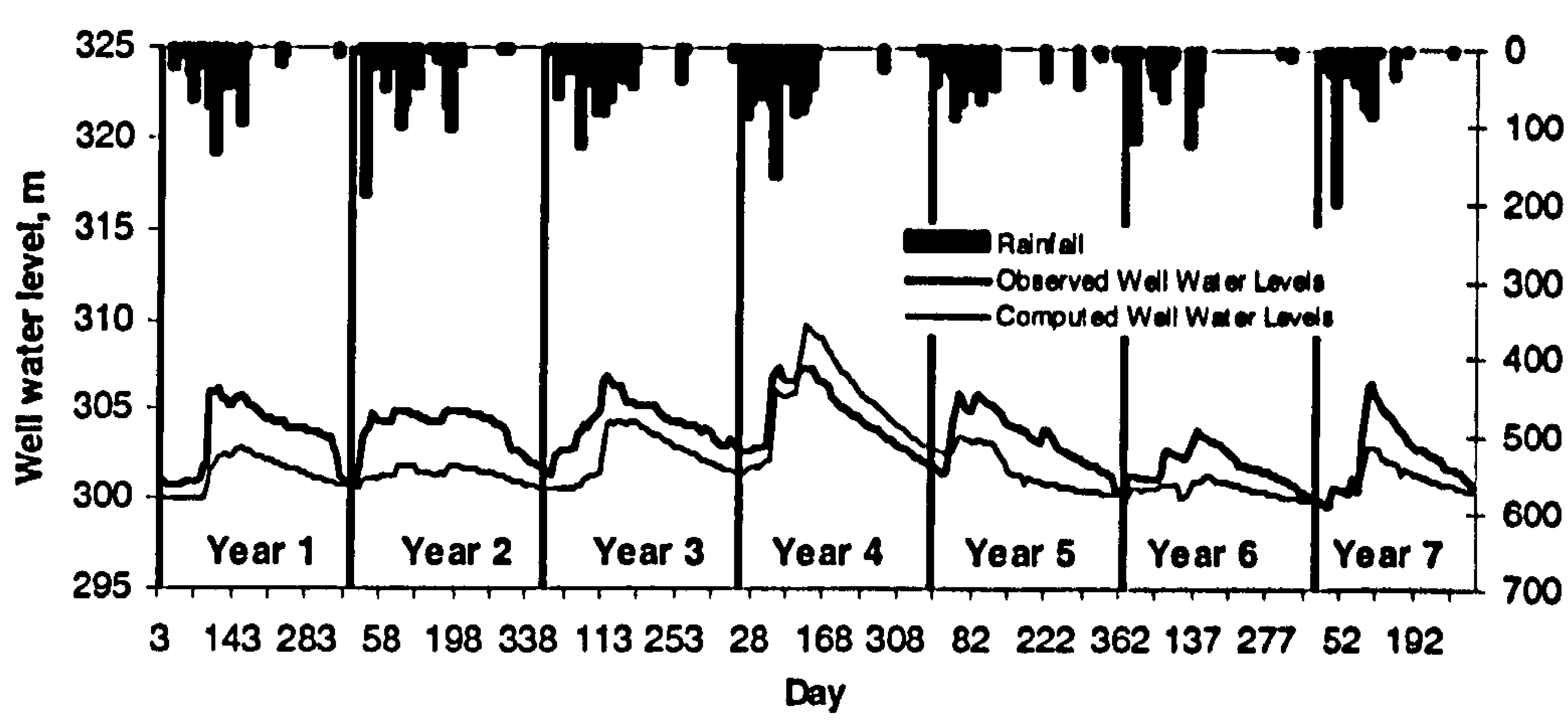


Figure 7.11 Observed and computed well water levels for Well No 3, Akola watershed

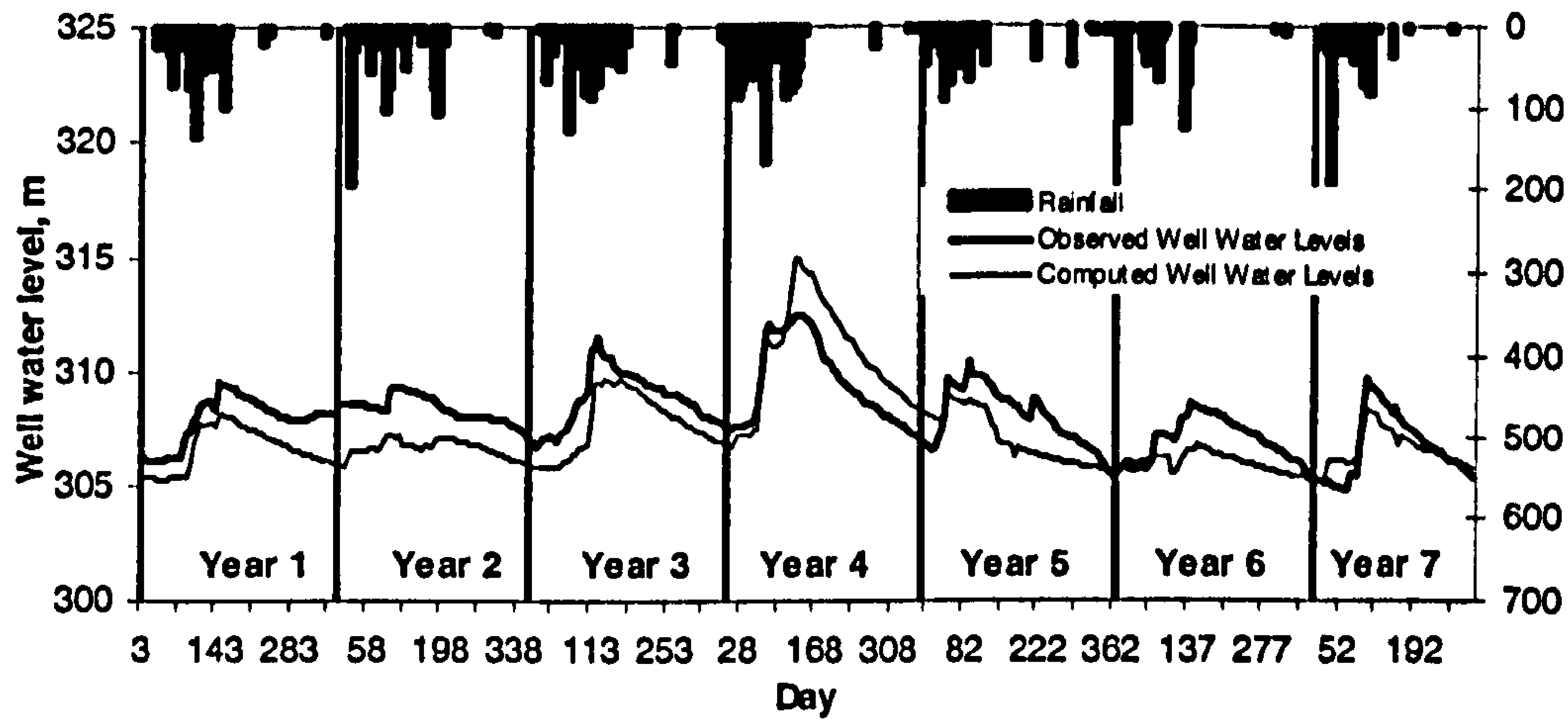


Figure 7.12 Observed and computed well water levels for Well No 4, Akola watershed

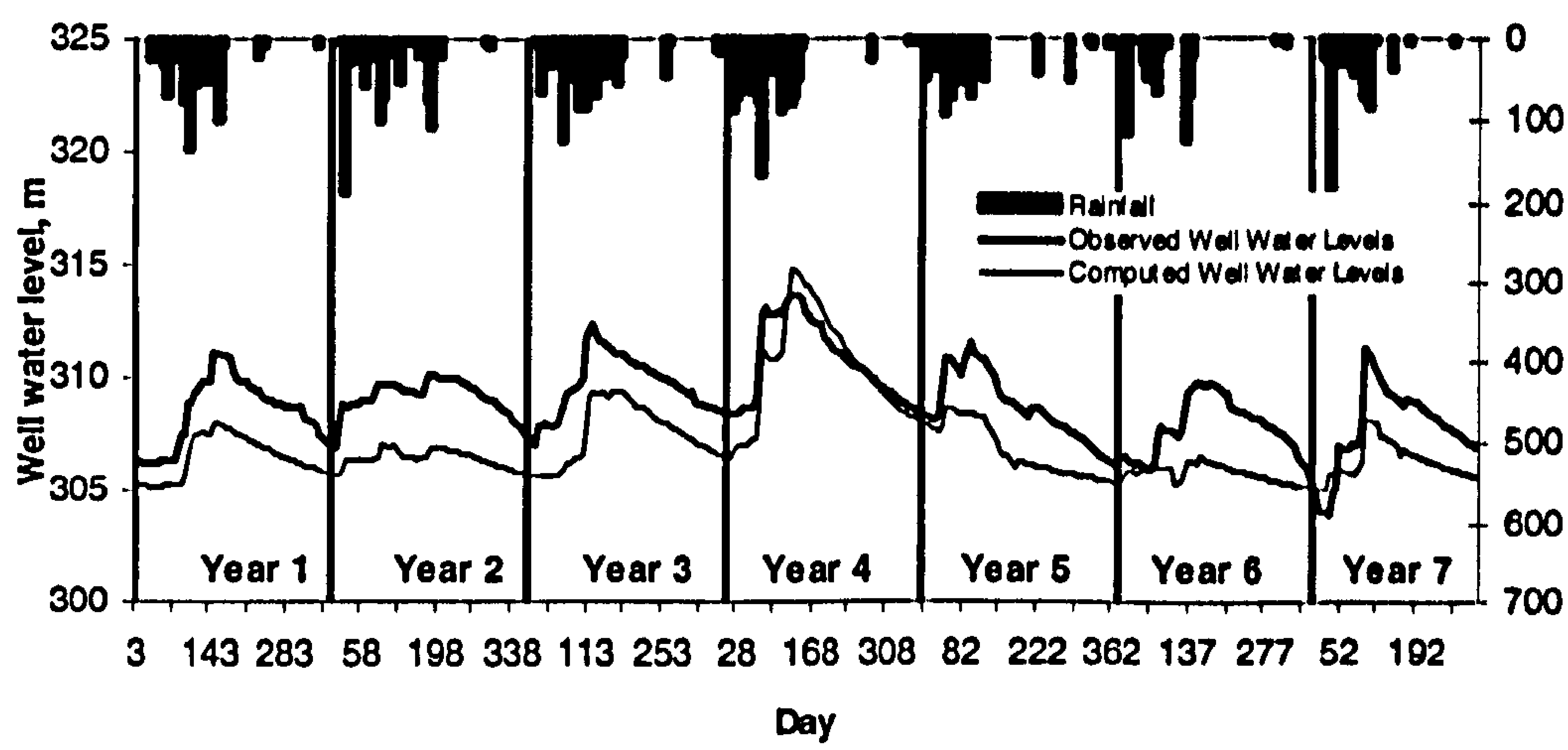


Figure 7.13 Observed and computed well water levels for Well No 5, Akola watershed

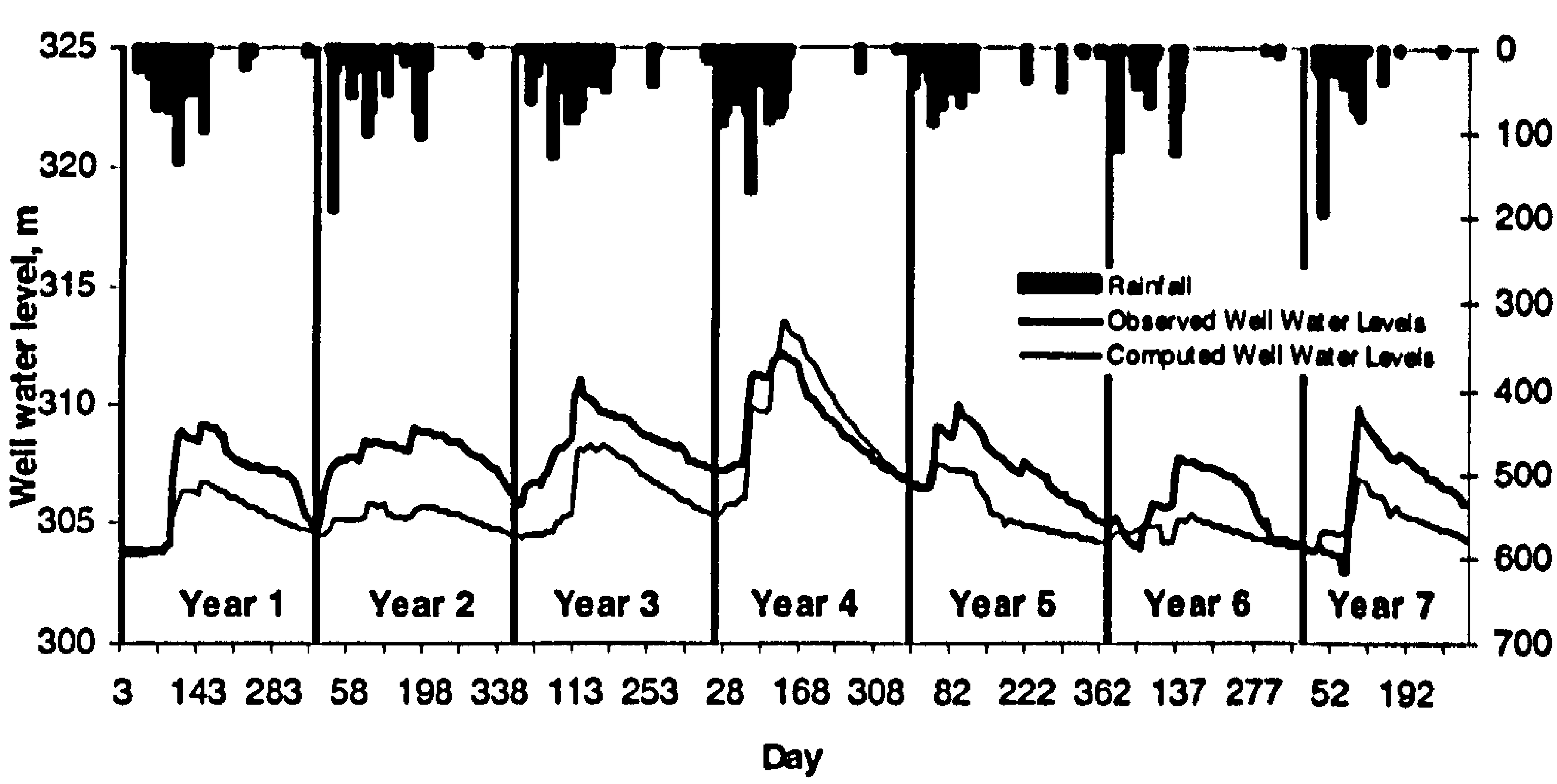


Figure 7.14 Observed and computed well water levels for Well No 6, Akola watershed

Figs 7.9 to 7.14 show that the trend of variation of observed groundwater levels and model estimated groundwater levels is same for all the wells. However model tends to underestimate the groundwater levels. Fig 7.7 indicates that all the model estimated groundwater level values lie in 95% confidence limits of observed values. Fig 7.8 indicates that about 10% of model estimated values lie outside 99% confidence limits of observed values. The source of variation in simulated values may be due to empirical nature of groundwater flow exponent introduced in the model.

7.4.4.2 Groundwater level calibration for Pimpalgaon Ujjaini watershed

Groundwater level calibration was carried out for Pimpalgaon Ujjaini watershed. Observed well water level data (monthly values) of nine wells for two years were used for calibration. The drainable porosity value of the aquifer was taken as 0.1. The values of drainable porosity calibration parameter and the groundwater flow exponent for minimum RMSE value of 4.43 for Pimpalgaon Ujjaini watershed were found as below.

Drainable porosity calibration parameter:	0.02
Groundwater flow exponent	1.10

The observed and model estimated groundwater levels for nine wells are shown in figures from 7.17 to 7.25. The model estimated groundwater levels at 95 and 99% confidence limits are shown in Fig. 7.15 and 7.16 respectively.

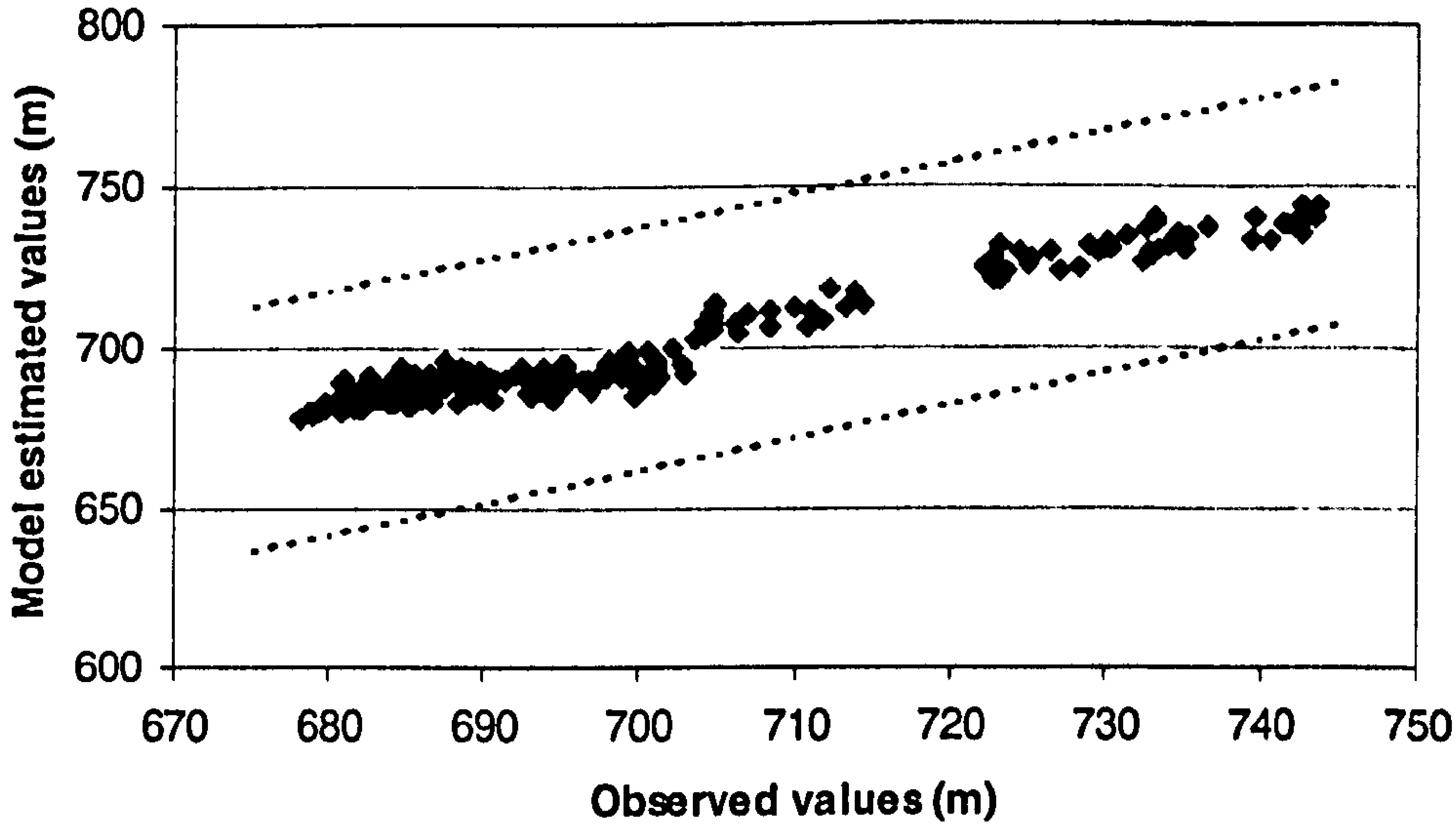


Figure 7.15 Observed and model estimated groundwater levels and 95% confidence limits for Pimpalgaon Ujjaini watershed

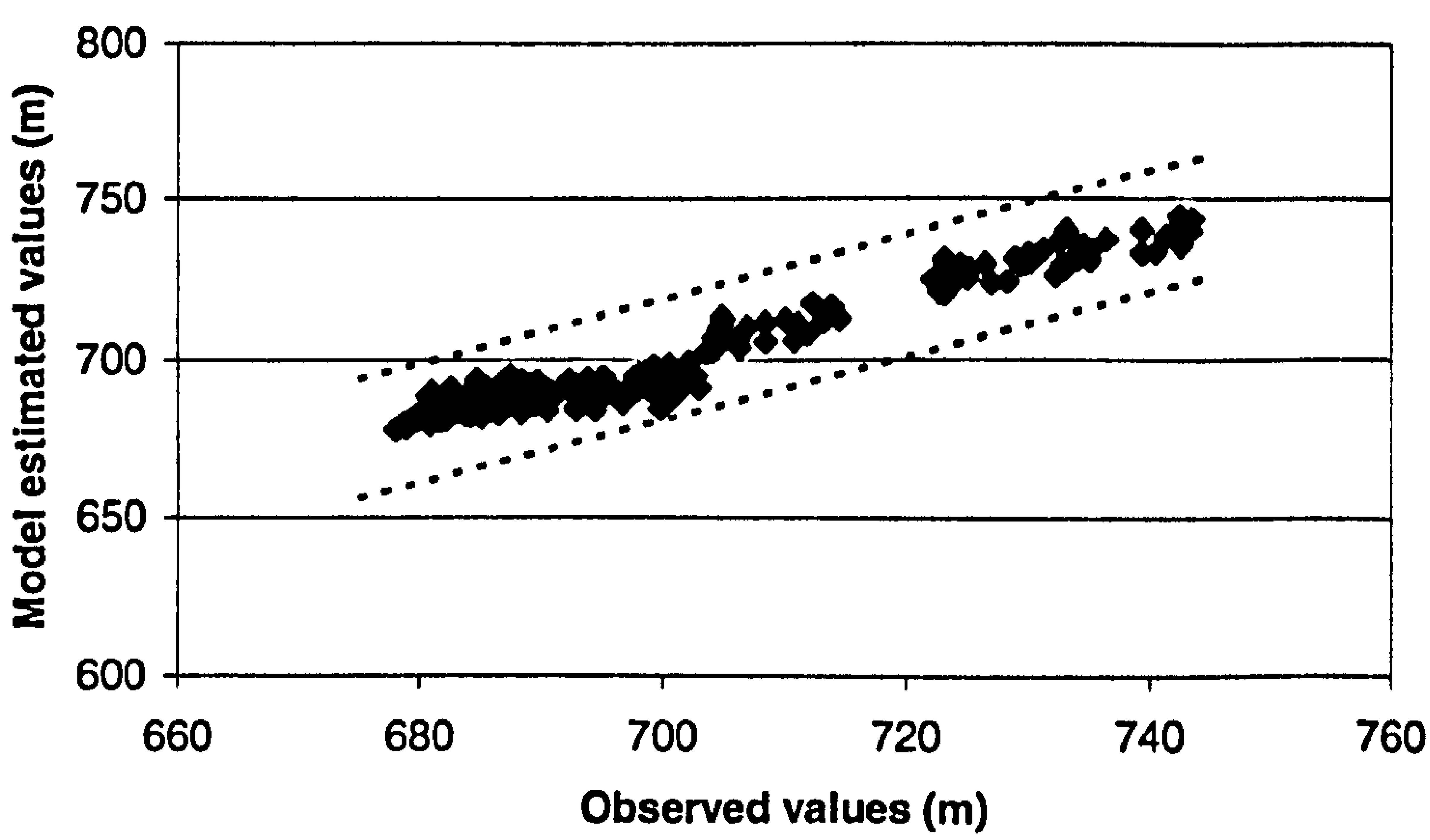


Figure 7.16 Observed and model estimated groundwater levels and 99% confidence limits for Pimpalgaon Ujjaini watershed

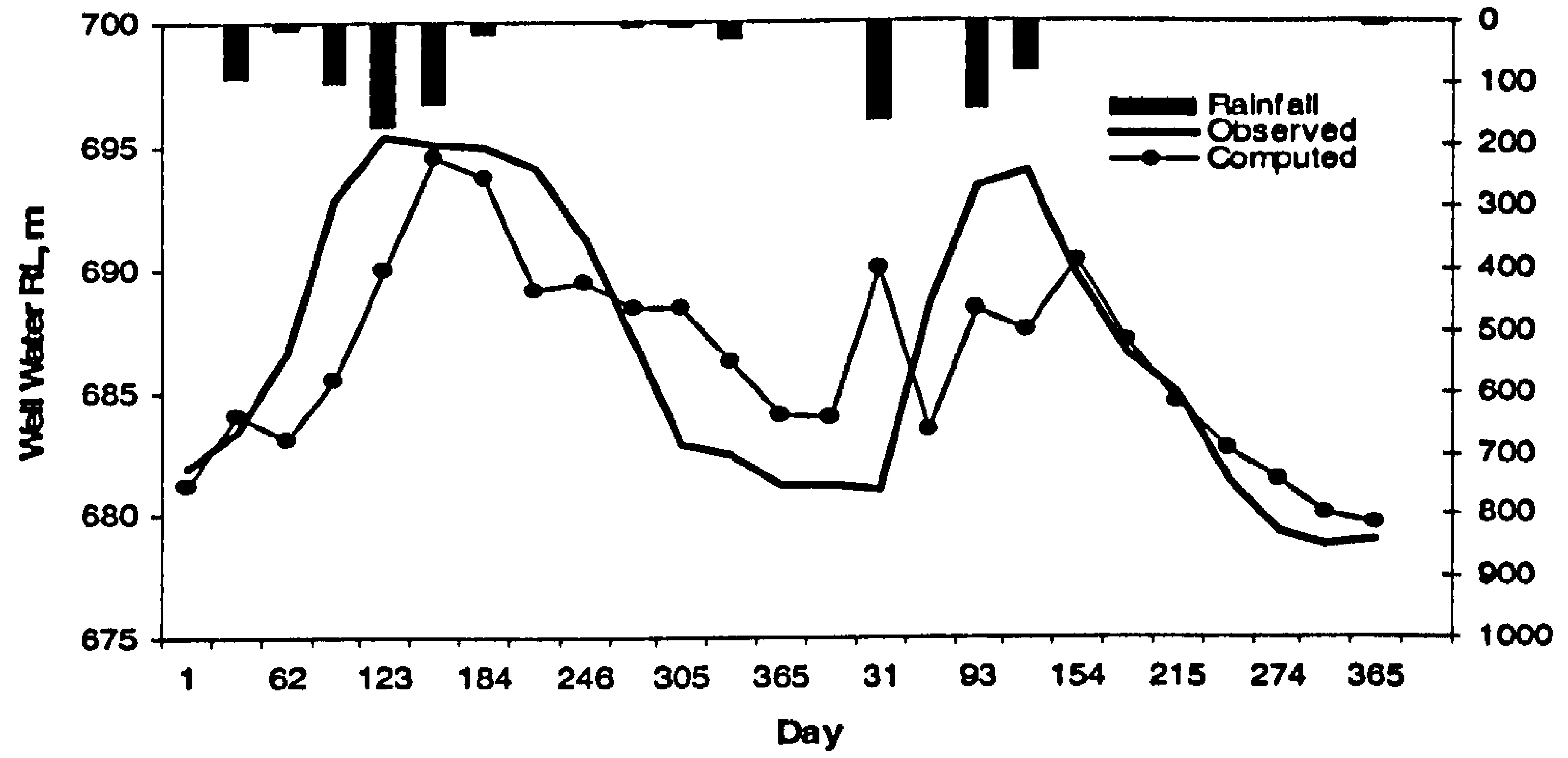


Figure 7.17 Observed and computed well water levels for Well No 1, Pimpalgaon Ujjaini watershed

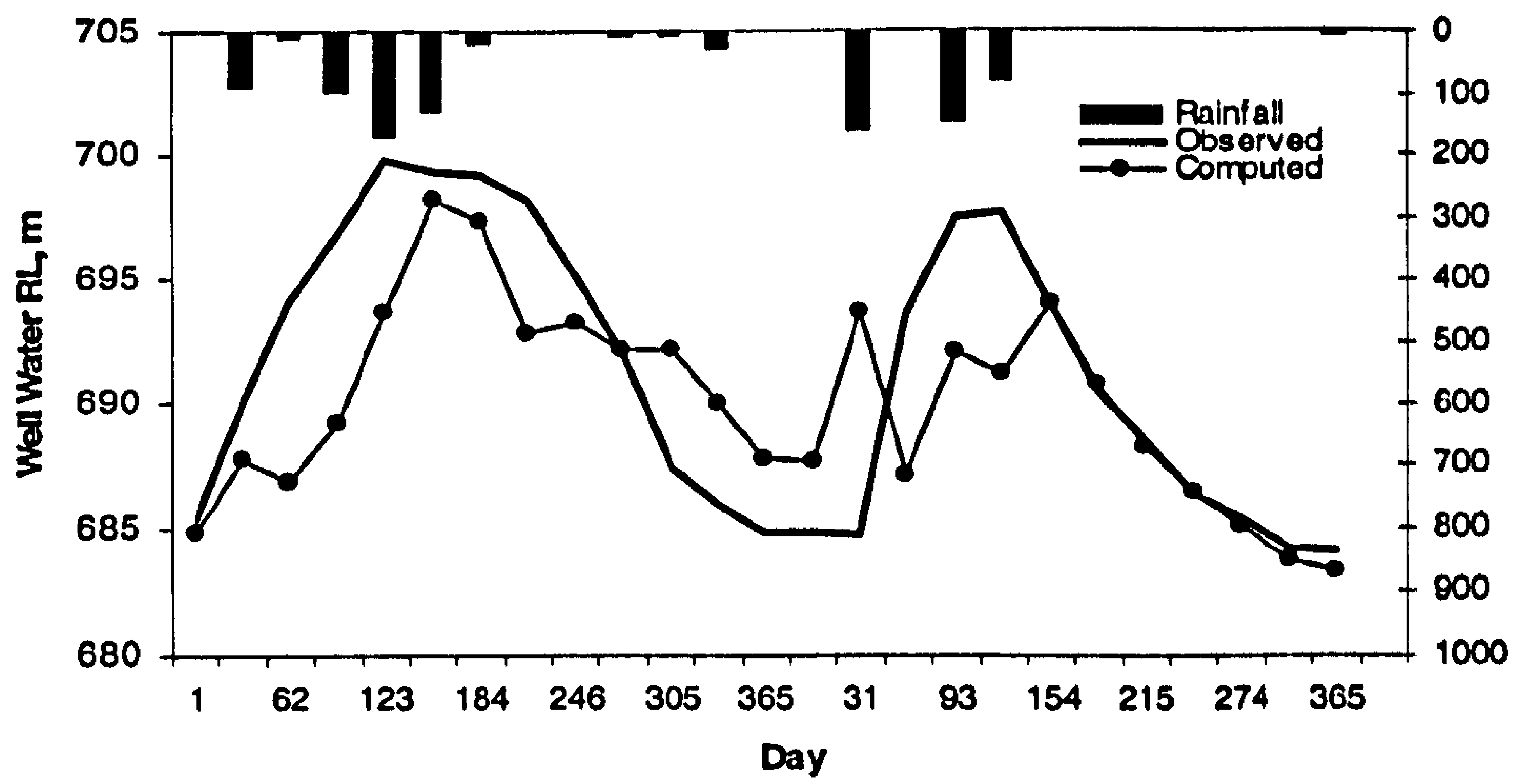


Figure 7.18 Observed and computed well water levels for Well No 2, Pimpalgaon Ujjaini watershed

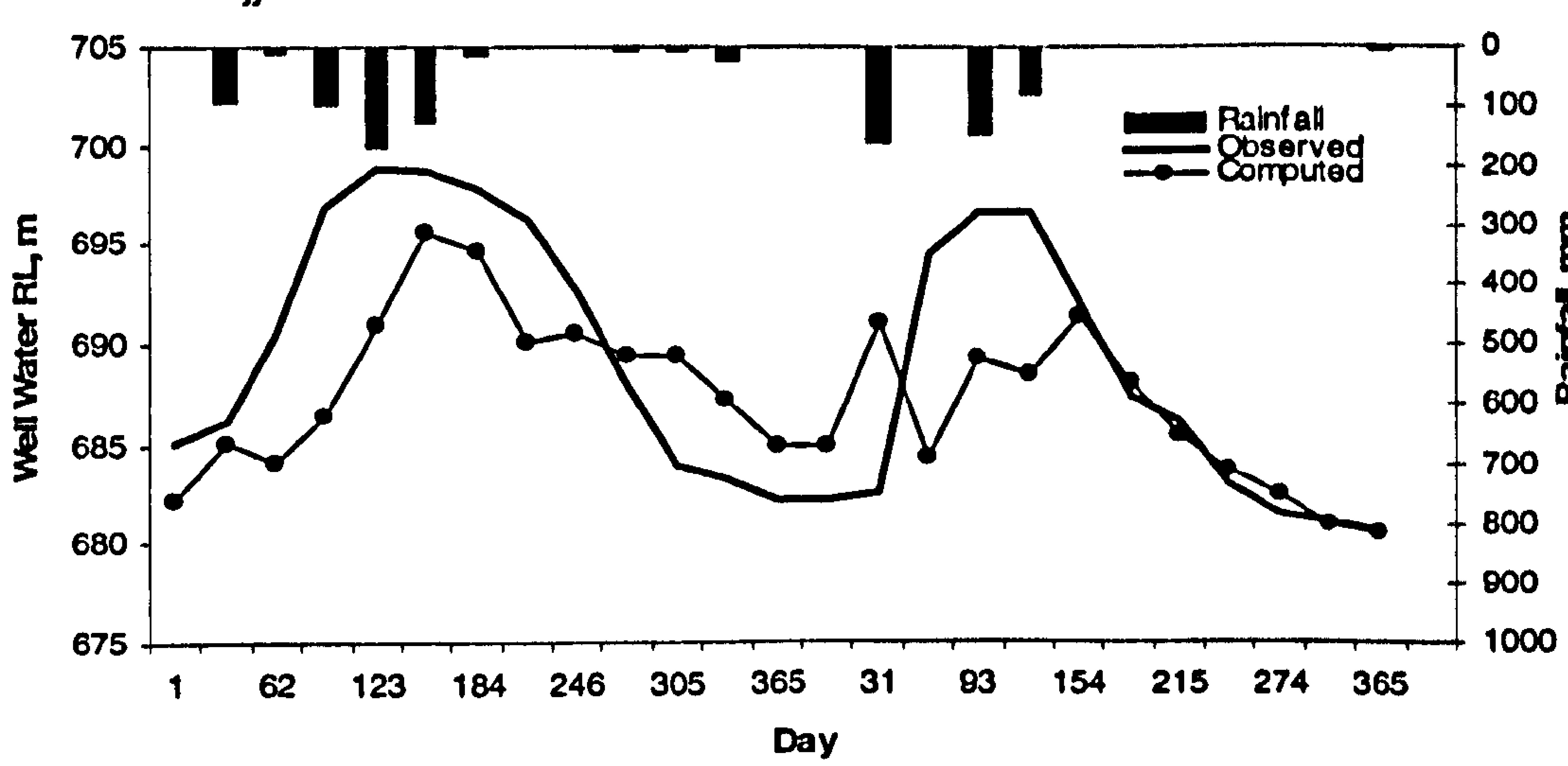


Figure 7.19 Observed and computed well water levels for Well No 3, Pimpalgaon Ujjaini watershed

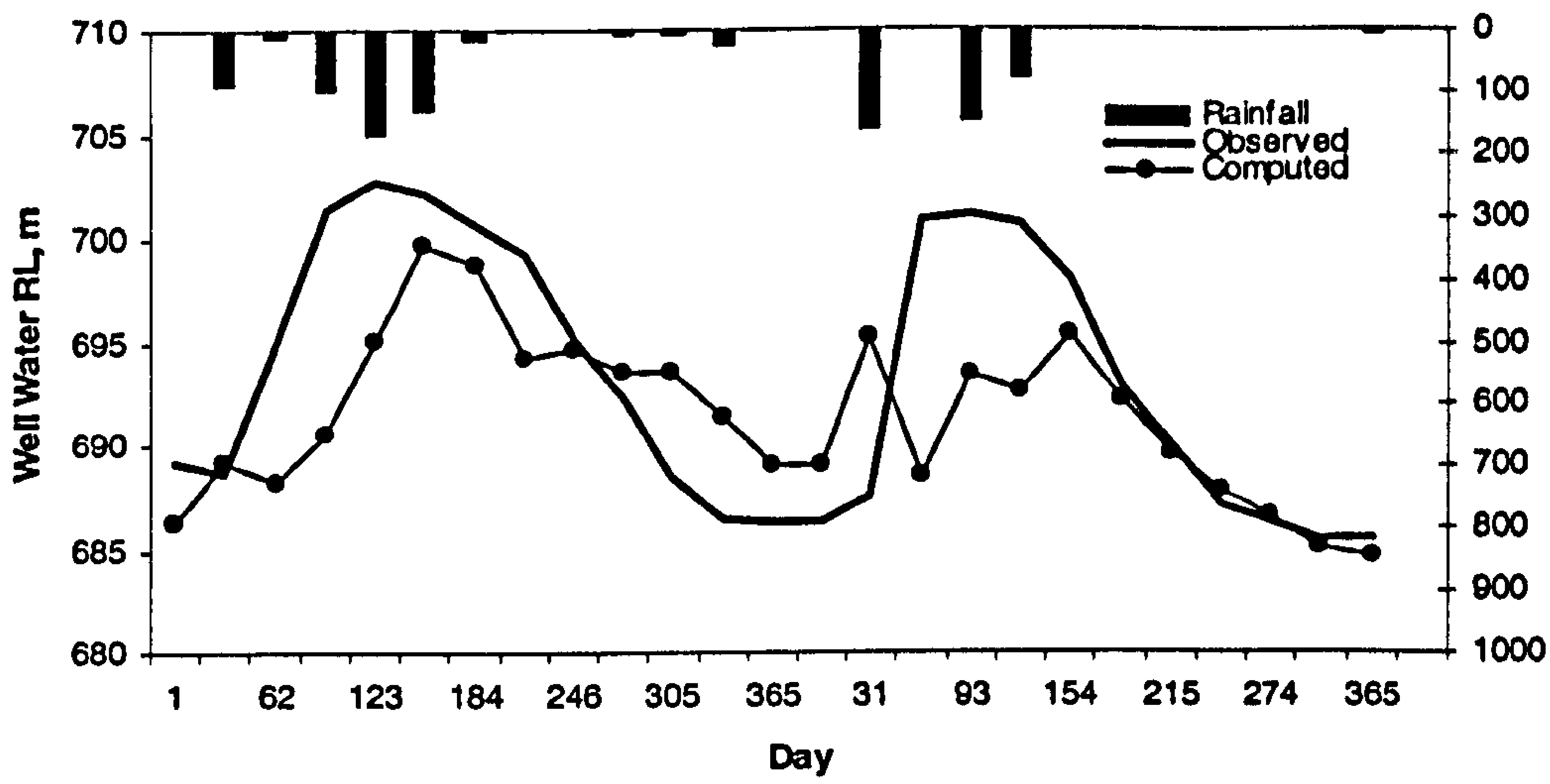


Figure 7.20 Observed and computed well water levels for Well No 4, Pimpalgaon Ujjaini watershed

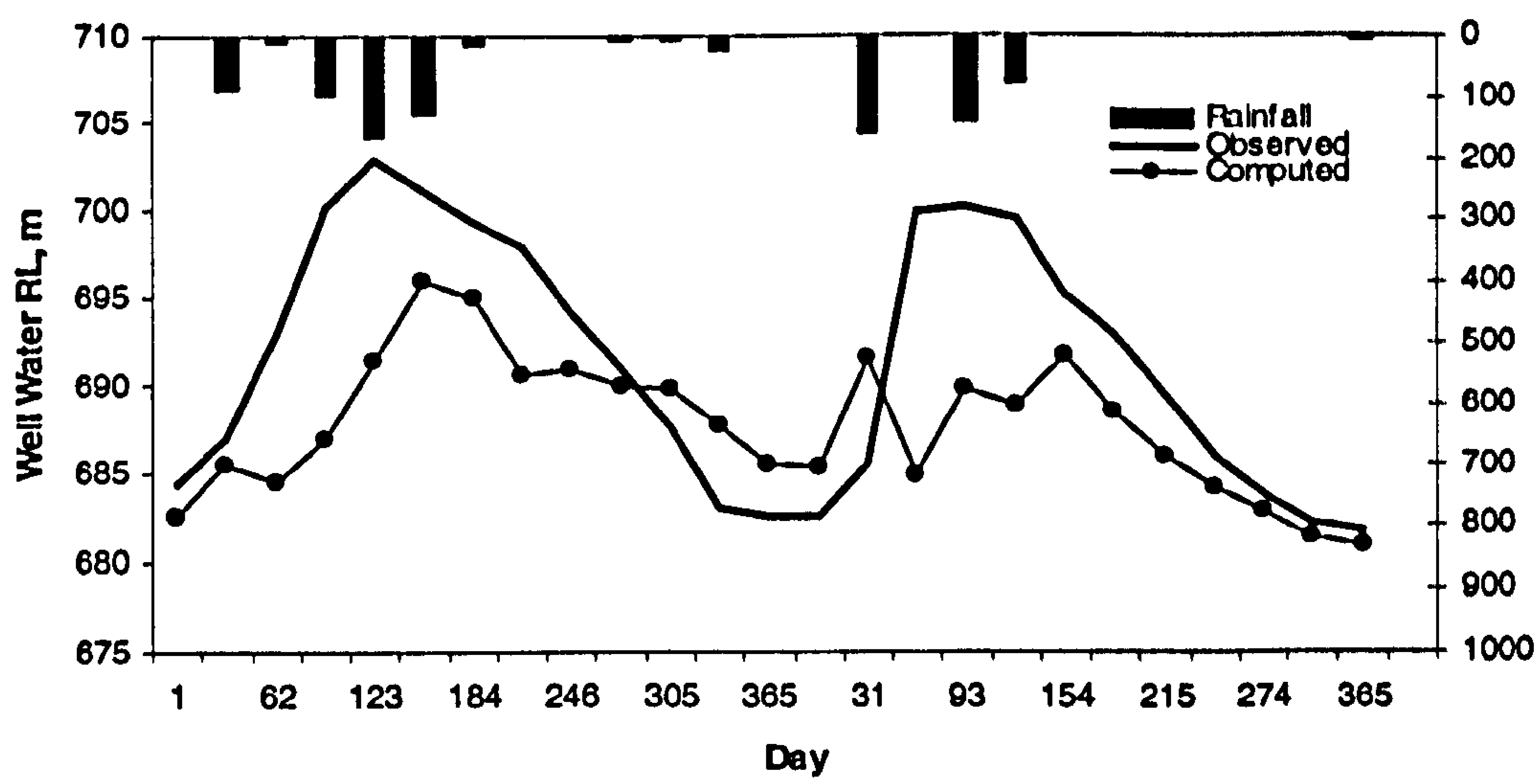


Figure 7.21 Observed and computed well water levels for Well No 5, Pimpalgaon Ujjaini watershed

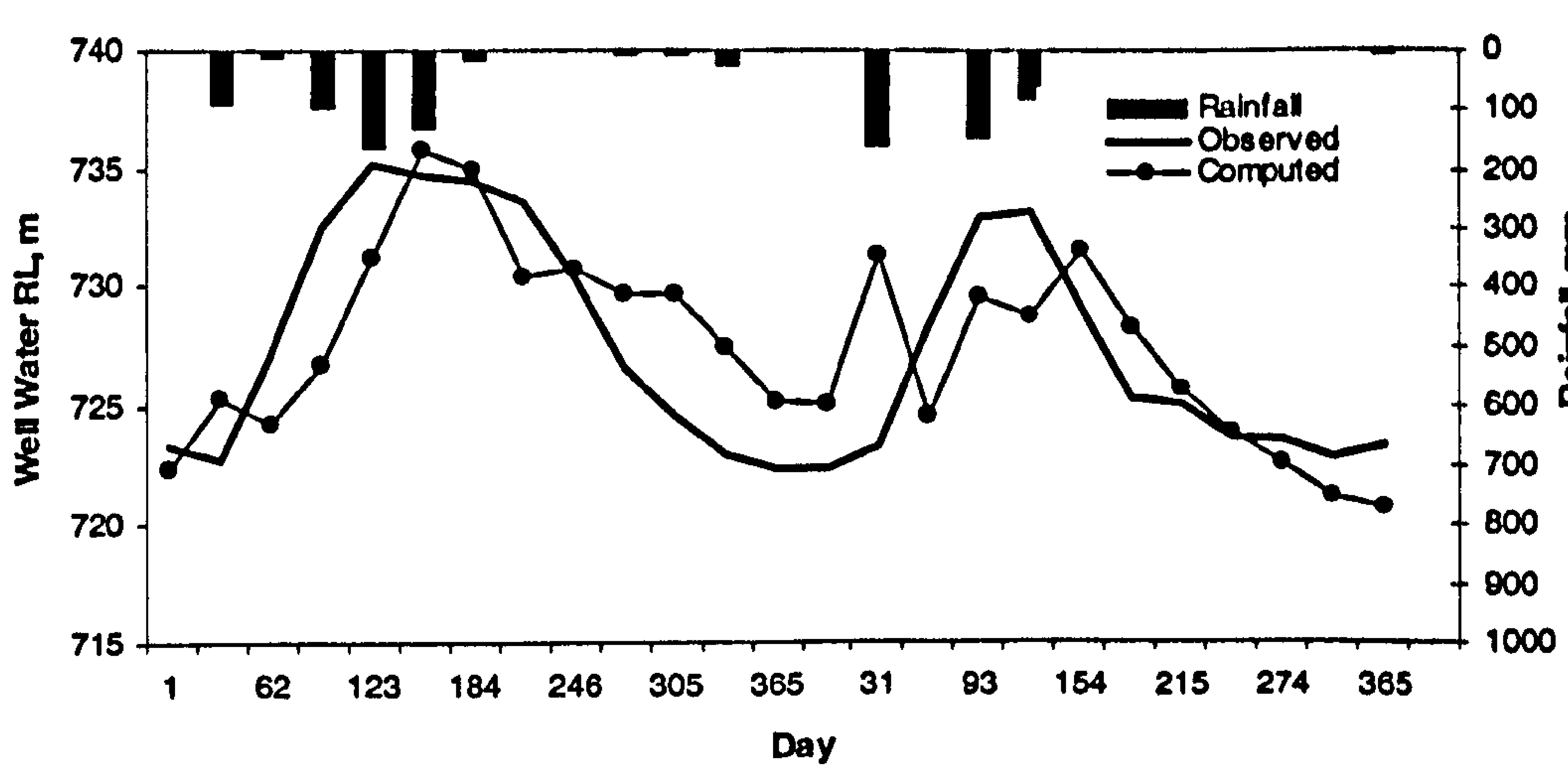


Figure 7.22 Observed and computed well water levels for Well No 6, Pimpalgaon Ujjaini watershed

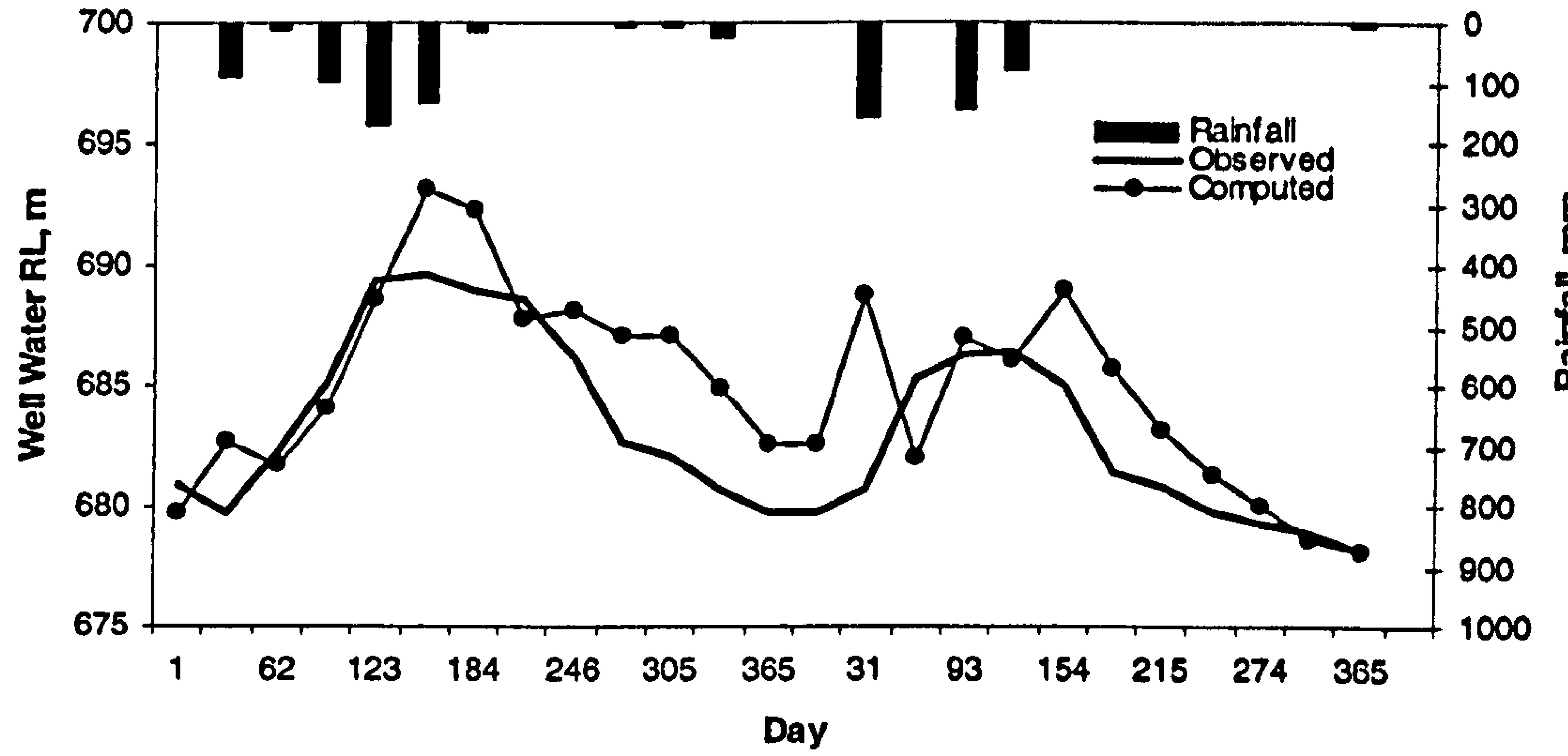


Figure 7.23 Observed and computed well water levels for Well No 7, Pimpalgaon Ujjaini watershed

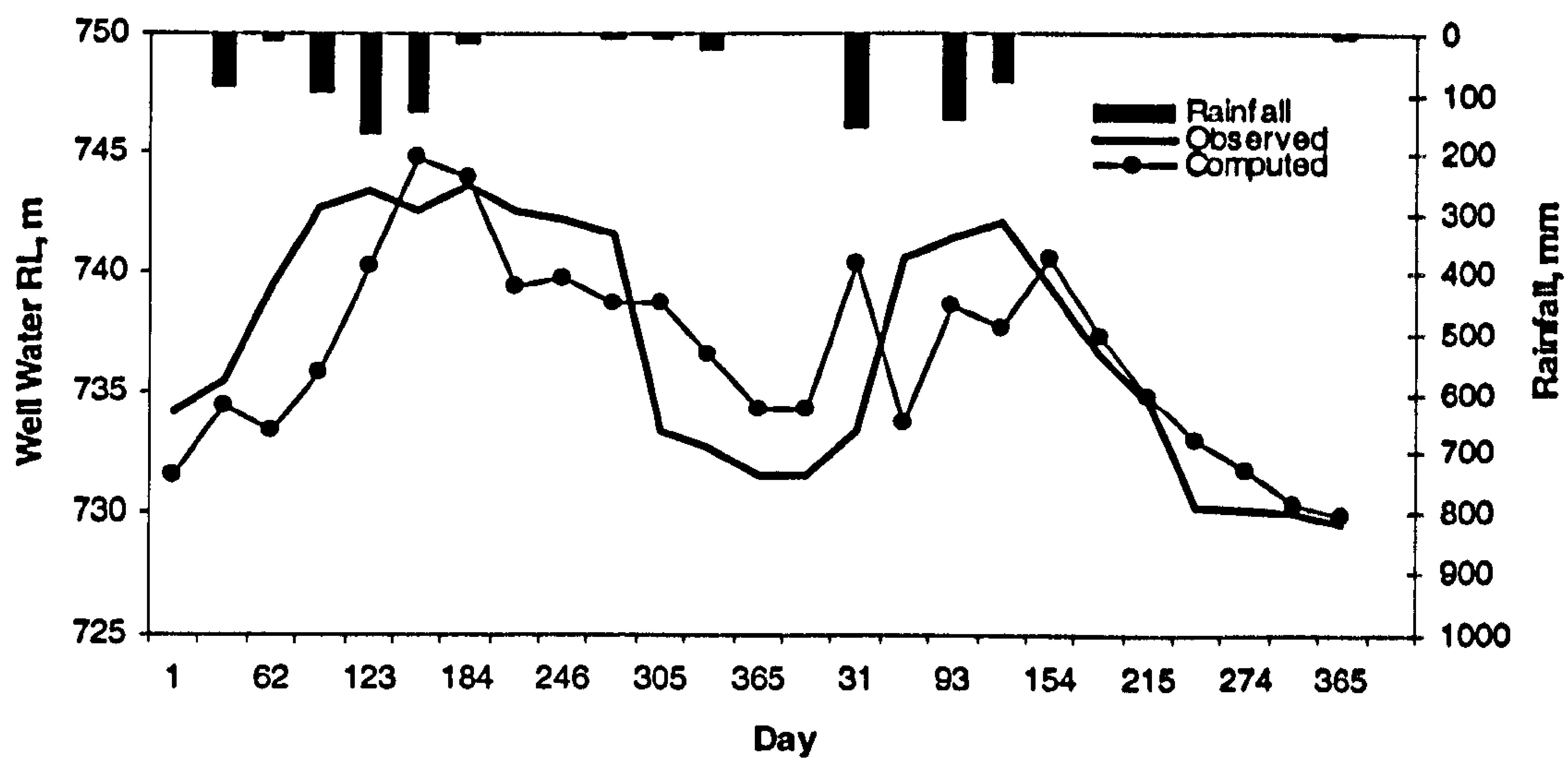


Figure 7.24 Observed and computed well water levels for Well No 8, Pimpalgaon Ujjaini watershed

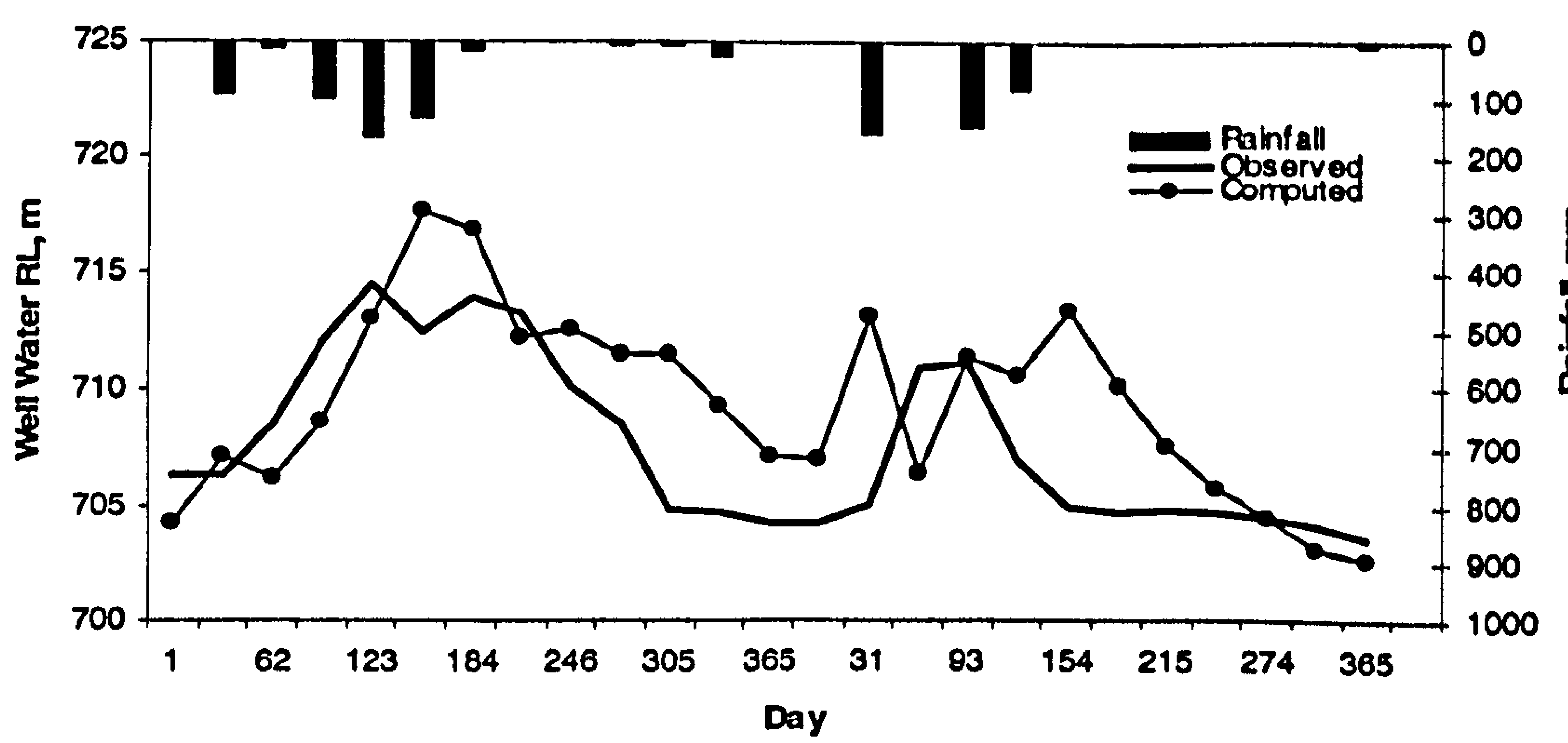


Figure 7.25 Observed and computed well water levels for Well No 9, Pimpalgaon Ujjaini watershed

Figs 7.17 to 7.25 show that the trend of variation of observed groundwater levels and model estimated groundwater levels is same for all the wells. Figs 7.15 and 7.16 indicate that all the model estimated groundwater level values lie within 95 and 99% confidence limits of observed values. However there are sharp fluctuations in the model estimated groundwater levels. Since in this watershed the source of irrigation is groundwater and irrigation was scheduled as fixed depth with fix interval there is sharp variation in the estimated values. And the simple bucket type approach used for groundwater balance may also contribute to this variation.

7.5 Closure

The chapter described the details of two case study watersheds in the semiarid region of Maharashtra, India. Akola watershed is representative of small watersheds in the state, which can be managed by a group of farmers. Pimpalgaon Ujjaini watershed is representative of large watersheds, which are developed by the State governments and NGOs. They are managed by the entire village community. This Chapter described the calibration procedure of SOFTANK. The model SOFTANK was calibrated for these two watersheds. The model predicted the groundwater levels within reasonable accuracy for both the watersheds. The calibrated parameters obtained here will be used for evaluating the existing tank systems in these watersheds and also for simulating different tank strategies and finally arriving at the optimum tank system for these watersheds. These are discussed in the subsequent chapters.

Chapter–8

EVALUATION OF TANK IRRIGATION SYSTEMS

8.1 Summary

This chapter discusses the results of evaluation of the existing tank systems in the Akola and Pimpalgaon Ujjaini watersheds. The results are discussed with the help of water balance of the watershed and the project economics. The Akola watershed contains CCTs in catchment 2 and 3; hence the investigation of the first hypothesis is also discussed.

8.2 Introduction

Evaluation of the existing tank systems in the watershed helps in the identification of individual water balance components and system indicators like CCR, CSR as discussed in Chapter 4. The performance of the tank system can be improved by knowing the causes of low system performance. It helps to address specific constraints in the performance of the system. It is also possible to suggest changes in the management of the tank systems to improve their performance. It further helps in generating information, which is useful in developing guidelines for upgrading the existing or designing new tank systems. Moreover different tank systems can be compared by evaluating their performance parameters. Previously some tank systems were evaluated by different researchers and are discussed in Section 4.3.6. Tank systems in the Akola and Pimpalgaon Ujjaini watersheds considered for this study are evaluated and discussed in this Chapter.

It is emphasized here that this evaluation study evaluates the current tank systems in the watershed. It does not consider the year to year variation in crops and other practices in these watersheds. The rates used in the economic analysis are the current rates. The tank systems are evaluated for climatic data series of 28 years for Akola and 29 years for Pimpalgaon Ujjaini watersheds. Tanks in the Akola watershed are smaller and used for storage of water for irrigation and also groundwater recharge, whereas tanks in the Pimpalgaon Ujjaini watershed are large and used for groundwater recharge only. This chapter presents the results of evaluation of the tank systems in these watersheds as obtained with SOFTANK model.

Before discussing the results it will be appropriate here to mention the pre-simulation features of SOFTANK model. SOFTANK generates tank strategies depending on the maximum possible number of stream points in the watershed and allocates fields to the respective stream points. Later this field allocation changes with the tank strategy (see Section 6.3.5). Accordingly tank strategy No 1926 (generated by SOFTANK) was identified as the existing tank strategy for the Akola watershed and tank strategy No 94 was identified as the existing tank strategy for Pimpalgaon Ujjaini watershed. Field allocation to different tanks for Akola watershed is given in Table 8.1.

Table 8.1 Field allocation for tank strategy No. 1926 for Akola watershed

Tank No.	Stream point No.	Tank type	No. of catchment fields	Catchment field No.	No. of command fields	Command field No.
1	1	2	3	5,6,7	3	5,6,7
2	2	2	1	4	1	4
3	3	2	3	1,2,3	3	1,2,3
4	4	2	9	8,9,10,11,12,13 ,1415,16	9	8,9,10,11,12,13 ,14,15,16
5	5	2	1	17	1	16
6	6	2	2	18,19	1	17

8.3 Evaluation of tank irrigation system in Akola watershed

Evaluation of tank irrigation system in Akola watershed was carried out for the existing practices in the watershed. The data used for evaluation were the same as that used for calibration and are given in Chapter-7 and Appendix.A7-1. The watershed is mostly used for horticultural and silvipasture crop production with small area kept for common agricultural crops. The watershed consists of six catchments with one tank at the outlet of each catchment. There are two streams in the watershed and they join near the outlet of the watershed. Water is used for irrigation from tanks as well as groundwater. Some portion of groundwater is used for domestic use (termed as other use). There are 19 fields in the watershed. Horticultural crops are cultivated on eight fields, silvipasture on two fields, common agricultural crops on smaller eight fields and one field is kept barren. The horticultural crops were irrigated by drip system. The climatological approach was used for scheduling irrigations. The agricultural crops were irrigated by surface irrigation. Irrigations were scheduled at 50% depletion with full depth of irrigation application. The application efficiency was considered as 70%. If limited water was available in the tank, the fields nearest to the tanks were given preference for irrigation. If water was not available in the tank, irrigations were applied through wells. The existing tank system in the Akola watershed was evaluated by running the SOFTANK model in the evaluation mode. Model was run for climatic data from 1976-77 to 2003-04 (28 years).

8.3.1 Water balance for Akola watershed

The water balance analysis gives information about the pattern of losses and productive water use and hence forms an important part in the evaluation of the tank system in the watershed. The water balance analysis for the Akola watershed was carried out and discussed under three balances i.e. field water balance, tank water balance and the groundwater balance. Since trenches exist in the catchments of tank No. 2 and 3, components of the trench water balance are also discussed.

8.3.1.1 Field water balance

In Akola watershed there are 19 fields with horticulture, silvipasture and some common field crops. Some part of the watershed is barren. The details of land use have been discussed in Chapter-7. Components of field water balance are shown in Fig. 8.1. Inflow to the fields was through rainfall and irrigation and outflows were runoff, evapotranspiration and deep percolation. Runoff going to the tanks was found about 18.96% (28 years average) of rainfall. Evapotranspiration and deep percolation accounted for about 72.39% and 9.92% of total outflow. Deep percolation was 10.62% of rainfall. This component of field water balance contributes to the groundwater storage, which can later be used for irrigation through wells as per the concept of IWSS. Runoff was less due to the presence of trenches in some parts of the watershed. Evapotranspiration accounted for a major outflow component in the field water balance since most of the area in the watershed was covered with horticulture, silvipasture and agricultural crops.

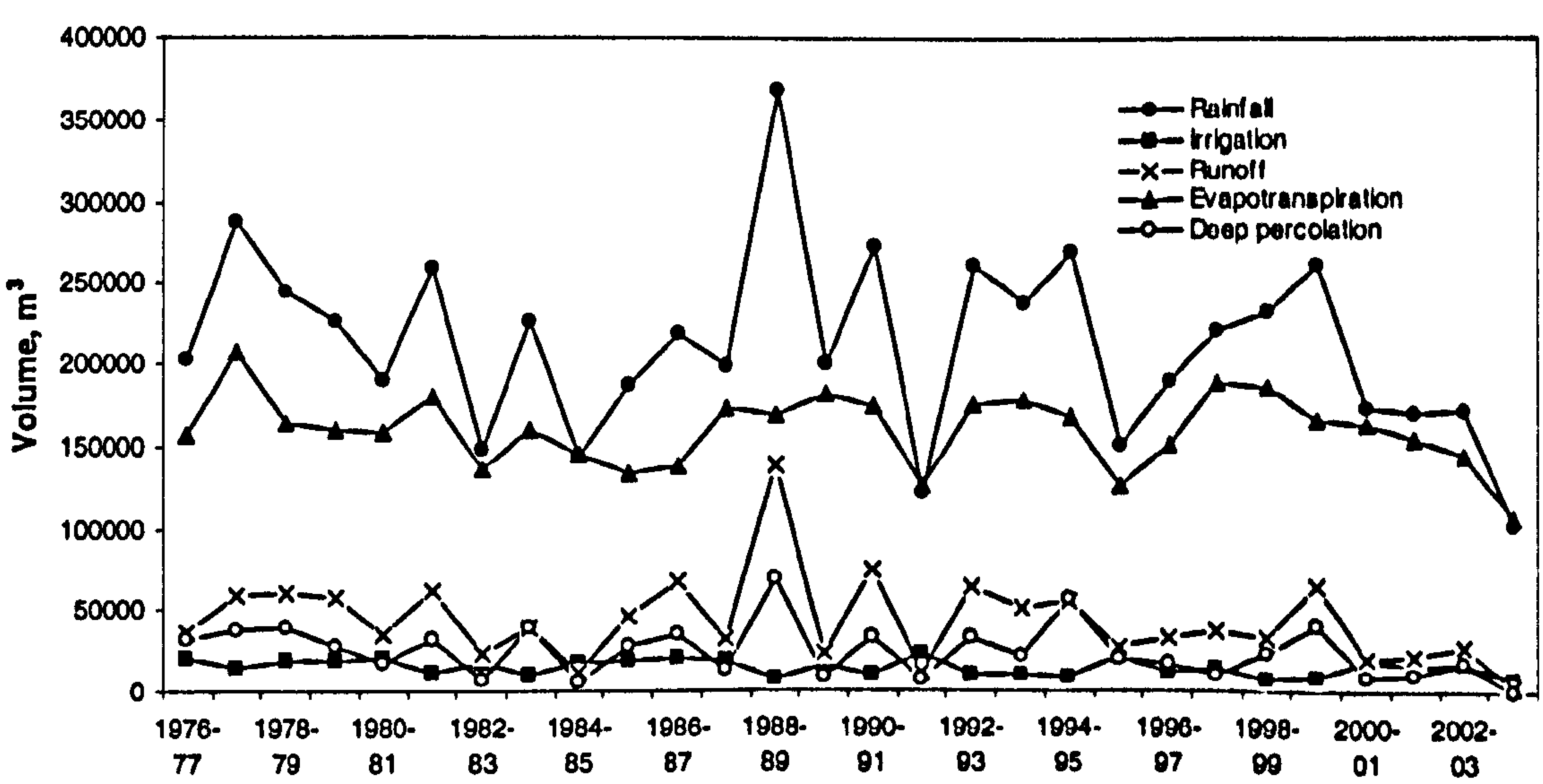


Figure 8.1 Components of field water balance for Akola watershed

8.3.1.2 Tank system water balance

Water balance for the tank system gives quantitative information about inflows, overflows, seepage, evaporation and irrigation from the tank system. Tank system here consists of all the six tanks in the watershed. The water balance components for the tank system are given in Table 8.2 and Fig. 8.2. Total tank system storage capacity was 4824.43 m^3. From the table it is seen that, inflow ranged from 0.8 to 29.44 times the total storage capacity of tank system with an average (28 years) of 9.41. Major portion of this inflow went as outflow from the watershed. An average downstream release (DSR) was 65.62%. Seepage, evaporation and irrigation contributed respectively 23.75, 4.04 and 6.55% of the inflow to the tank system.

Table 8.2 Yearly tank system water balance components for Akola watershed

Year	Rainfall, mm	Inflow $10^3 m^3$	Overflow $10^3 m^3$	DSR	Evaporation $10^3 m^3$	Seepage $10^3 m^3$	Irrigation $10^3 m^3$
1976-77	760.43	38.3	25.8	67.5	1.6	8.8	2.0
1977-78	1075.30	61.5	44.0	71.5	2.3	12.9	2.3
1978-79	914.50	62.7	51.6	82.4	1.4	8.2	1.5
1979-80	840.70	60.2	48.6	80.8	1.4	7.9	2.2
1980-81	707.90	37.0	25.7	69.4	1.3	8.4	1.6
1981-82	967.70	63.8	50.3	78.9	1.7	9.8	2.0
1982-83	551.90	24.0	14.2	59.4	1.1	6.4	2.2
1983-84	842.50	40.9	30.0	73.5	1.3	7.9	1.6
1984-85	538.00	12.4	4.2	34.2	0.9	5.0	2.3
1985-86	700.50	47.2	37.6	79.7	1.2	7.3	1.1
1986-87	817.40	69.5	60.3	86.8	1.1	6.6	1.4
1987-88	739.30	33.6	21.7	64.6	1.5	8.3	2.1
1988-89	1372.00	142.0	128.4	90.4	1.6	9.9	2.1
1989-90	747.30	24.9	13.0	52.2	1.4	7.9	2.2
1990-91	1019.30	78.0	62.9	80.6	1.7	10.5	3.0
1991-92	454.00	12.9	4.9	37.8	0.9	5.8	1.3
1992-93	977.40	66.6	54.6	82.0	1.6	9.0	1.4
1993-94	893.20	54.5	39.9	73.4	1.7	10.1	2.7
1994-95	1011.20	58.3	46.1	79.1	1.5	9.6	1.1
1995-96	562.40	28.9	19.9	68.9	1.1	6.4	1.5
1996-97	710.40	34.6	23.3	67.4	1.4	7.2	2.7
1997-98	827.80	38.8	23.4	60.2	1.9	11.5	2.1
1998-99	870.20	35.7	21.5	60.3	1.6	9.2	3.4
1999-00	976.50	67.5	53.5	79.3	1.6	10.1	2.3
2000-01	646.40	22.0	9.8	44.5	1.5	8.5	2.3
2001-02	634.10	22.9	10.9	47.6	1.3	8.3	2.4
2002-03	639.10	29.4	19.1	65.0	1.2	7.4	1.7
2003-04	380.80	3.9	0.0	0.0	0.4	2.4	1.1

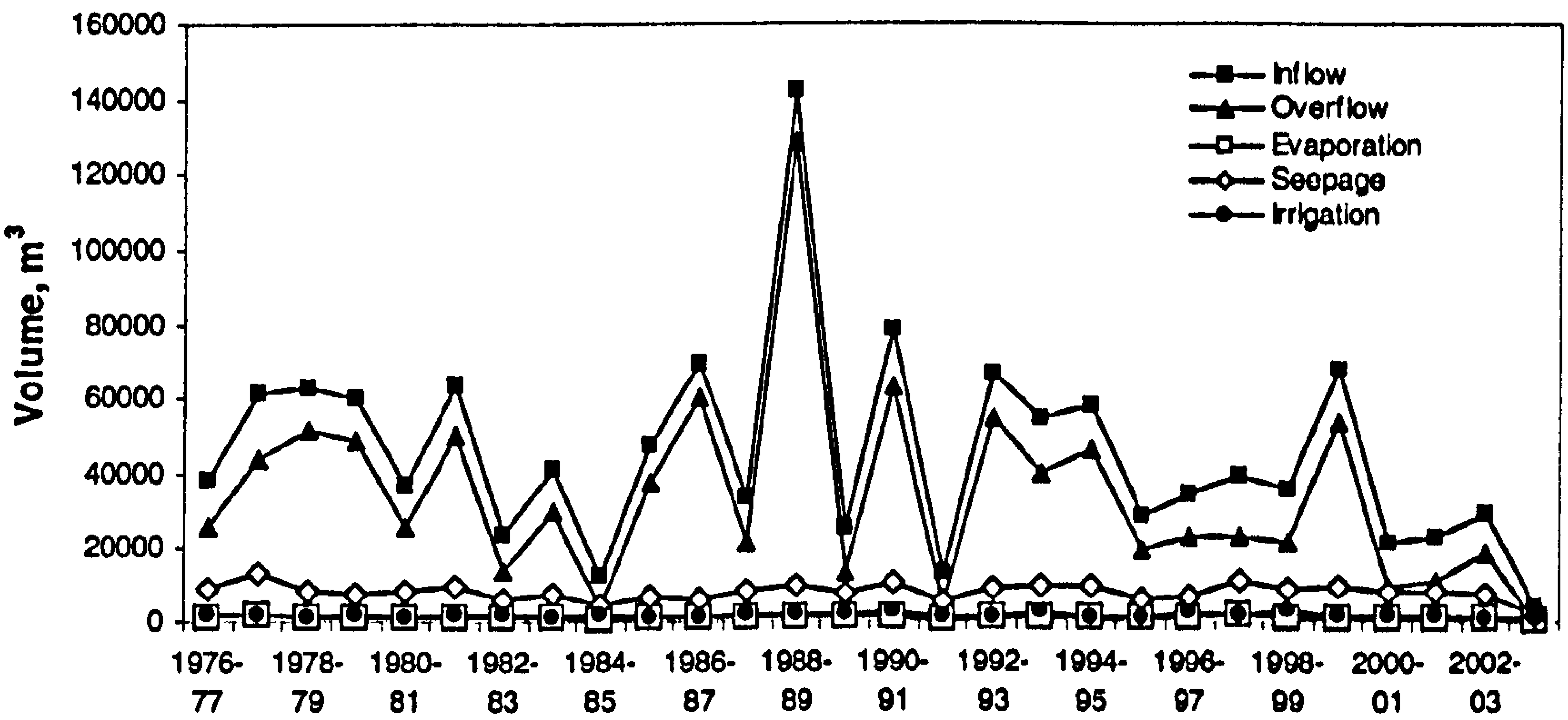


Figure 8.2 Tank system water balance components for different years for Akola watershed

8.3.1.3 Individual tank water balance

It is also important to know the water balance components of individual tank in the tank system since water supply and demand parameters are different for different tanks. These components for six tanks are given in Table 8.3. The catchments of tank No. 2 and 3 were treated with CCTs and hence these tanks received less inflow as compared to other tanks in the watershed. Inflows were 1213 and 896 m^3/ha of catchment area in the case of tank No 2 and 3 whereas they were 9430, 5275, 2762 and 3087 m^3/ha in the case of tank No. 1, 4, 5 and 6 (see table 8.3 for the catchment areas of respective tanks). It suggests that CCTs reduce the inflow to the tanks and hence tank capacity can be reduced considering these reduced inflows. This finding supports the first hypothesis of this research. There was no irrigation from tank No. 2 and 5 since land use in the catchments of these tanks was silvipasture and irrigation was not given to the silvipasture. To compare the water balance of two tanks with different water supply and demand parameters two tanks i.e. tank No 1 and tank No 4 are considered. The catchment of tank No. 1 and 4 was 3.86 and 5.37 ha with land use of horticulture and agriculture respectively. Tank capacities were 1000 and 656 m^3 respectively. Inflow to tank No. 1 was more than that of Tank No. 4. But since irrigation to agricultural crops was through surface application and for horticultural crops was through drip, total irrigation volume through tank No. 4 was more (991.81 m^3) than tank No. 1 (624.56 m^3). It thus suggests that the irrigation water use from the tank depends on the total catchment-tank-command water balance. Though the figures are averages for 28 years, data of individual years showed similar trend.

Table 8.3: Tank water balance components of six tanks for Akola watershed (average of 28 years)

Tank No.	Catch. Area, ha	Land use	Capacity m^3	Inflow m^3	Overflow m^3	Evapo-ration, m^3	Seepage m^3	Irrigation m^3
1	3.86	Hort.	999.92	36399.24	33762.91	284.94	1726.09	624.56
2	3.26	SP	917.73	3956.02	2704.42	184.19	1067.41	0.00
3	3.78	Hort	487.52	3388.52	2478.25	96.15	597.40	216.72
4	5.37	FC	655.72	28328.24	25899.18	201.71	1228.75	991.81
5	6.65	SP	1185.59	18367.61	15633.45	411.24	2322.92	0.00
6	3.88	Hort	577.95	11979.84	10285.55	227.88	1315.02	147.19

(Hort: Horticulture, SP: Silvipasture, FC: Field Crops)

8.3.1.4 Groundwater balance

Groundwater balance involved estimation of the total recharge to groundwater from the watershed and total water withdrawal in the form of irrigation, other use and groundwater flow out of the watershed. Other use consists of water for domestic and livestock purpose. These components for 28 years are shown in Figs. 8.3 and 8.4. Field recharge contributed 54.04% of the total recharge to groundwater whereas tank and trench recharge contributed 23.76 and 22.19% respectively (Fig. 8.5). Groundwater flow was the major (72.09%) outflow component while irrigation and other use formed 25.74 and 2.17% of the total outflow from the groundwater storage (Fig. 8.5).

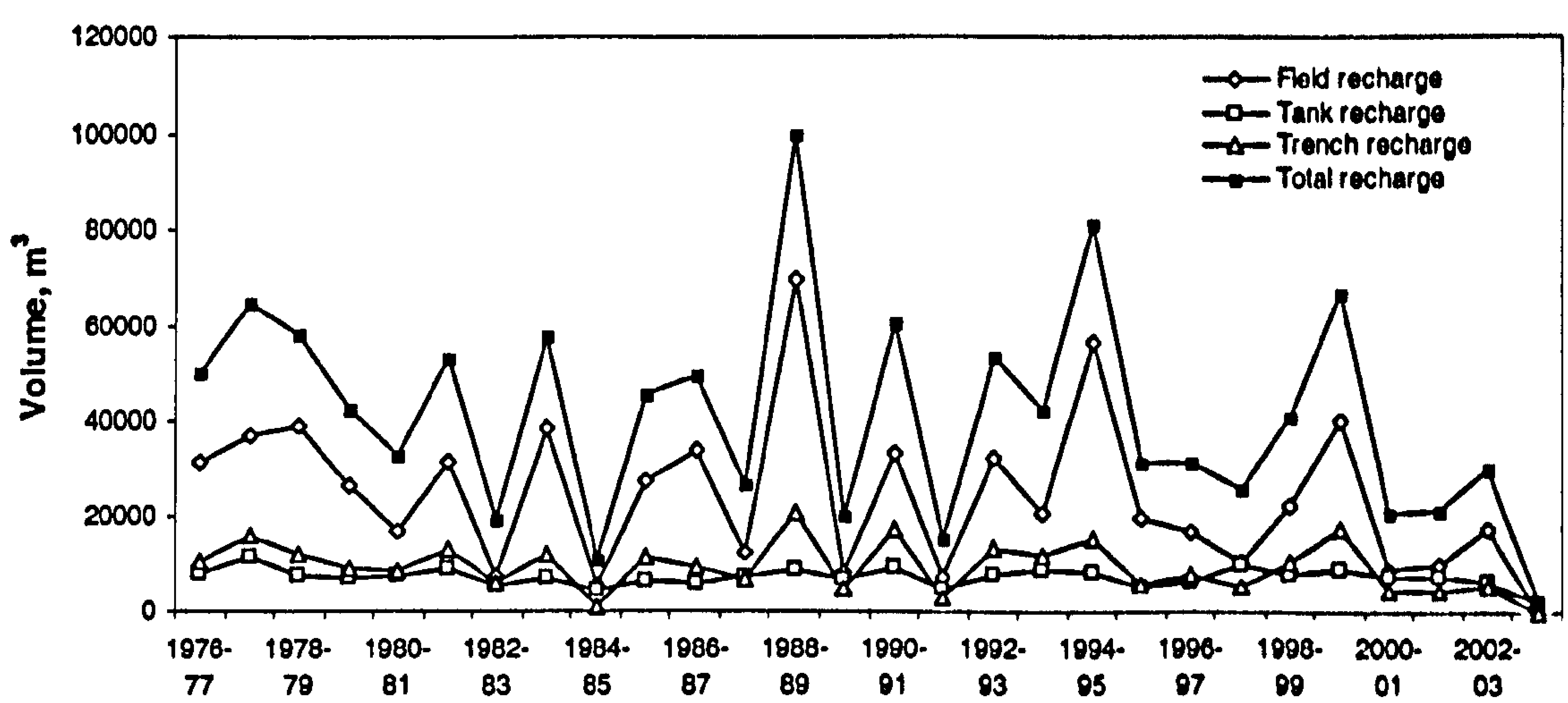


Figure 8.3: Groundwater recharge components for different years for Akola watershed

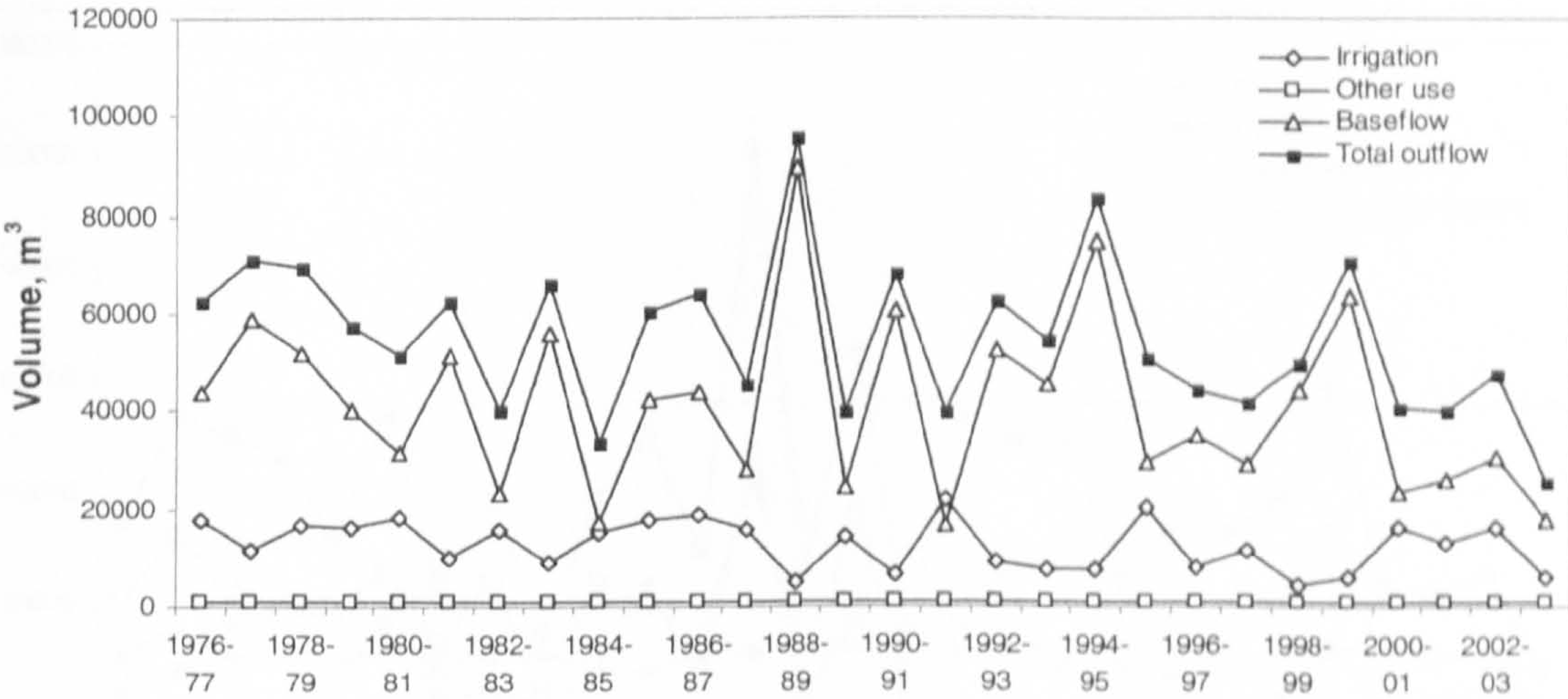


Figure 8.4: Groundwater withdrawal components for different years for Akola watershed

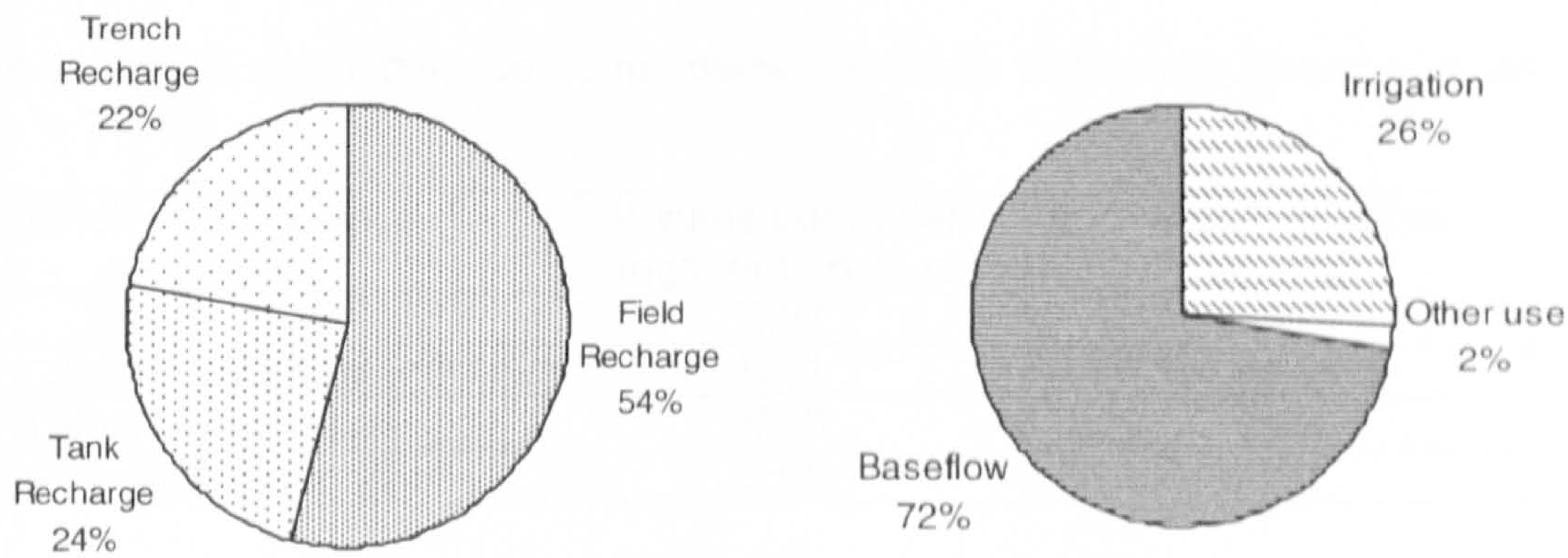


Figure 8.5 Contributions of groundwater recharge and withdrawal components for Akola watershed

8.3.1.5 Trench water balance

Trench water balance was performed as discussed in Chapter-3. Trench water balance has two-fold impact in the design of tank system in the watershed. It reduces the inflow to the tank and enhances groundwater recharge, which forms the part of the IWSS on which tank system is designed. The trench water balance gives the quantitative information about the water balance components across the trench. The trench water balance components are shown in Fig. 8.6 and the 28 years average values are given in Table 8.4. From the table it is observed that the major loss of water from the inflow to the trench was deep percolation (47.3%), followed by evaporation (34.6%) and overflow (18.1%).

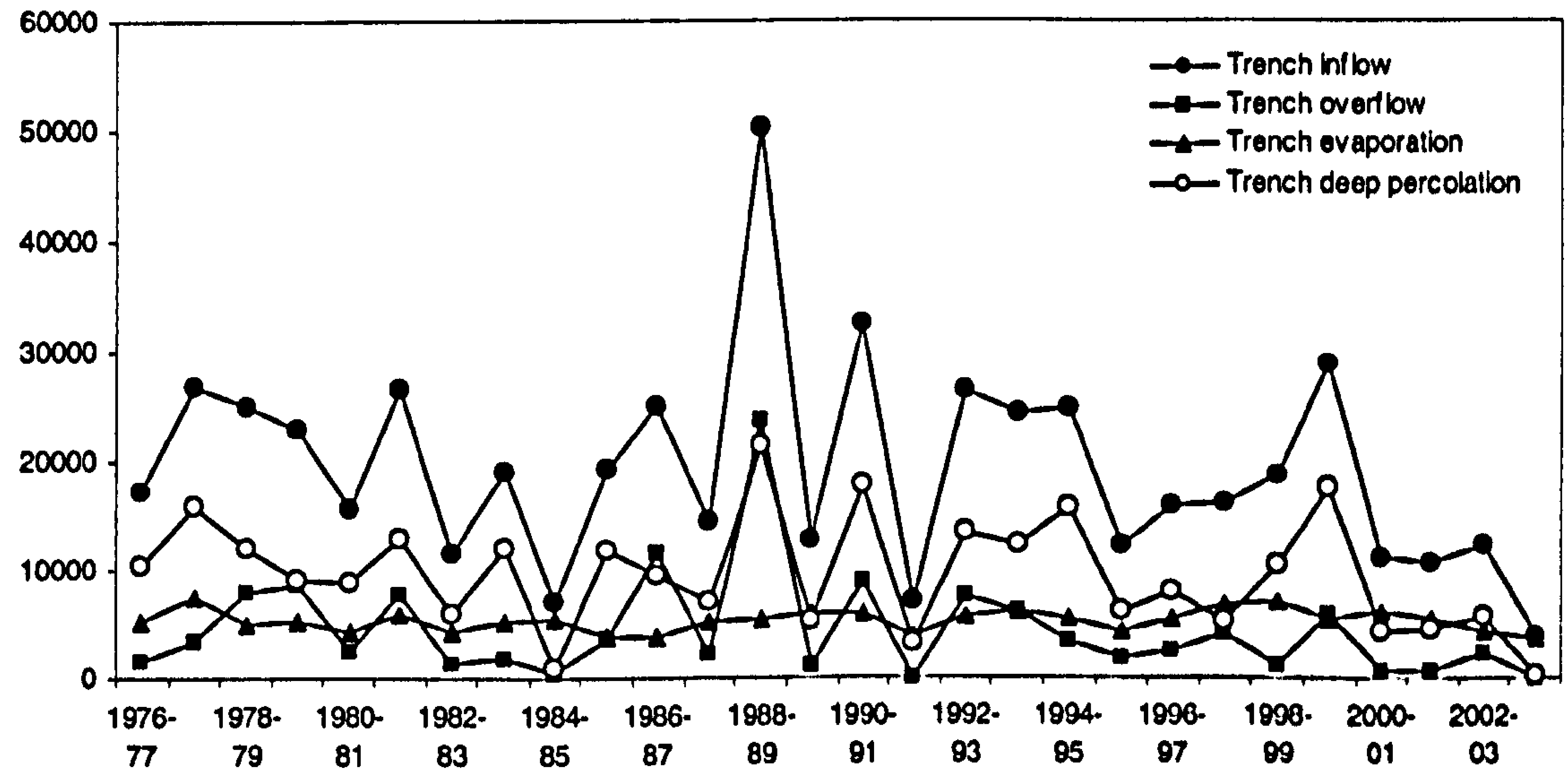


Figure 8.6 Trench water balance components for different years for Akola watershed

Table 8.4: Trench water balance components for Akola watershed (average of 28 years)

Trench water balance component	Volume per meter length of trench, m^3	Per cent of inflow volume
Trench inflow	1.37	--
Trench overflow	0.31	18.1
Trench evaporation	0.38	34.6
Trench deep percolation	0.68	47.3

8.3.1.5.1 Gross and net WHP

Gross and net WHP indicators for CCT were defined in Chapter 3 (see Section 3.5). They represent the total water intercepted by the trenches and total groundwater recharge through trenches respectively. Both these indicators are important in this study. Gross WHP indicates the influence of CCTs on the storages of downstream tanks whereas net WHP indicates the contribution of CCTs to groundwater storage (which is part of the IWSS). SOFTANK model was used to estimate these indicators for the existing trench system in the Akola watershed. The estimated yearly Gross and net WHP are presented in Table 8.5. From the table it is seen that CCTs store significant volumes of water and they are more effective when the yearly rainfall is less and/or number of rainy days are more. Though the average gross WHP was found 82%, it varied from as high as 100% (in less rainfall year of 2003-04) to as low as 53.25% (in the high rainfall year 1988-89). Net WHP varied from 4.08% (year 2003-04) to 63.67% (year 1994-95) with an average of 47.30%.

Table 8.5: Yearly gross and net WHP for the existing trench system in the Akola watershed

Year	Rainfall (mm)	No. of rainy days	Runoff (mm)	No. of runoff days	Gross WHP (per cent)	Net WHP (per cent)
1976-77	760.4	41	80.0	15	91.39	60.78
1977-78	1075.3	56	108.8	16	87.31	59.44
1978-79	914.5	49	129.2	16	68.50	48.38
1979-80	840.7	42	169.9	15	62.25	39.43
1980-81	707.9	44	87.2	13	83.51	56.03
1981-82	967.7	54	119.7	17	71.40	48.87
1982-83	551.9	30	29.9	5	89.08	51.46
1983-84	842.5	52	71.5	19	90.85	63.16
1984-85	538	32	26.5	5	92.25	14.41
1985-86	700.5	32	99.9	13	80.91	60.89
1986-87	817.4	36	192.5	14	54.05	38.28
1987-88	739.3	38	86.8	12	84.63	48.50
1988-89	1372	56	375.6	23	53.25	42.39
1989-90	747.3	43	30.6	10	90.43	43.95
1990-91	1019.3	38	199.6	12	72.93	54.59
1991-92	454	28	30.5	7	99.61	45.61
1992-93	977.4	44	183.0	18	71.80	50.61
1993-94	893.2	46	102.6	16	75.18	50.40
1994-95	1011.2	62	118.5	17	85.90	63.67
1995-96	562.4	33	87.9	9	85.01	50.63
1996-97	710.4	42	22.9	13	83.79	49.29
1997-98	827.8	46	88.6	14	75.02	33.07
1998-99	870.2	51	50.6	11	94.16	55.99
1999-00	976.5	49	120.7	15	79.40	60.83
2000-01	646.4	36	35.2	10	94.05	39.26
2001-02	634.1	33	72.9	13	94.04	43.46
2002-03	639.1	36	84.6	10	82.36	46.86
2003-04	380.8	34	4.9	3	100.00	4.08

SOFTANK model can also be used for designing the trench system for desired water harvesting potential by taking the repetitive runs of the model for different trench system specifications. In this case the water harvesting potential (WHP) can be related with monetary investment required in the construction of trenches to achieve that specific WHP. Such analysis was carried out for Akola watershed and the resulting graph is shown in Fig 8.7. This graph will be useful for planning the investment in the continuous contour trenches in the watershed.

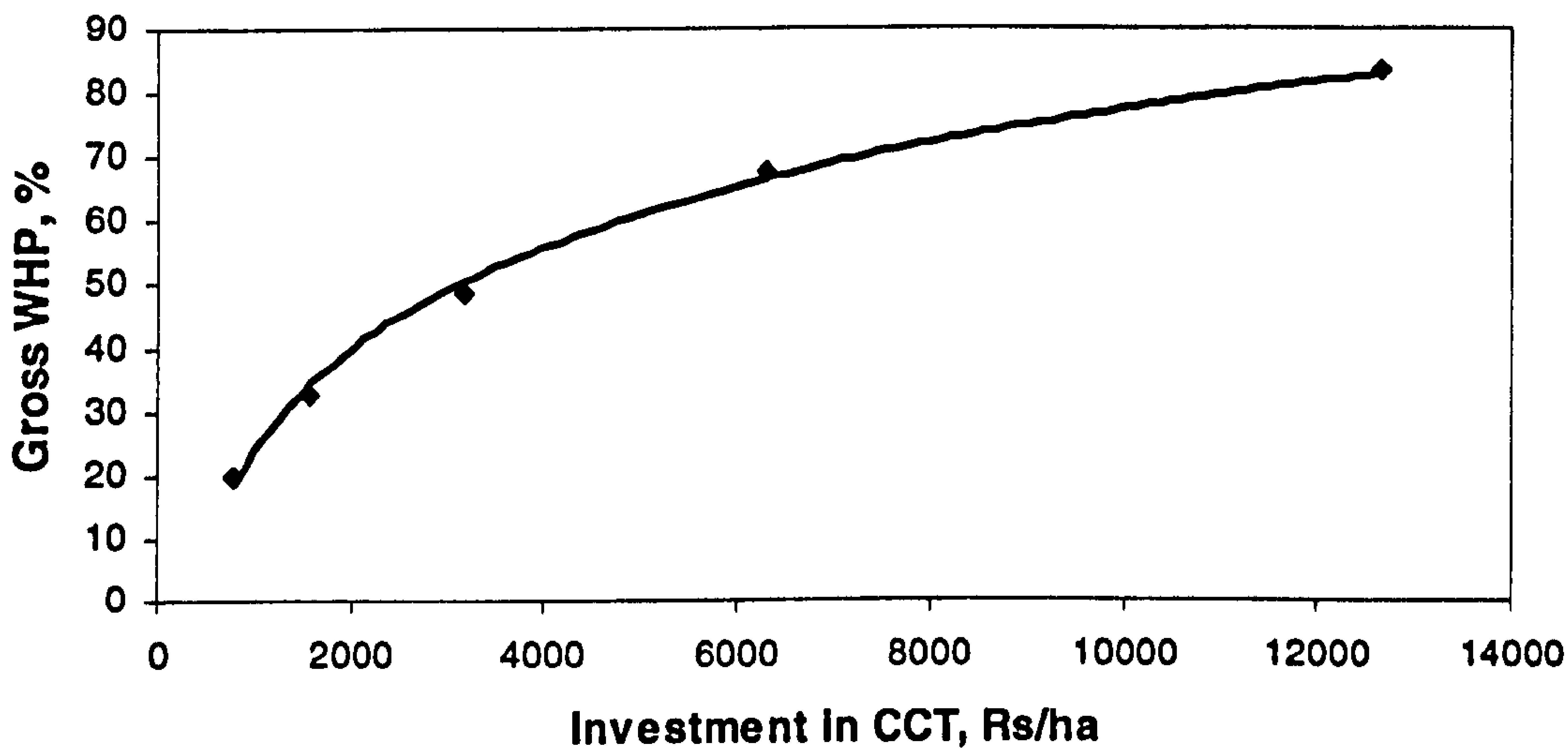


Figure 8.7: Gross water harvesting potential of CCTs as a function of investment

8.3.2 Catchment-storage-command relationship for Akola watershed

As discussed in Section 4.3.6.2 catchment-storage-command (CSC) forms an important relationship in the evaluation of the existing tank system. The CSC data for Akola watershed are given in Table 8.6. Less tank capacities have resulted into more CSR in the watershed. This is also indicated by the high downstream release of water (65.59%). Since all tanks were of type 2 (same catchment and command area), CCR for all tanks was one.

Table 8.6 Catchment area, storage, command area, CSR, CCR for Akola watershed

Tank No.	Catchment, ha	Storage, ha-m	Command, ha	CSR	CCR
1	3.8	0.10	3.8	38	1
2	3.3	0.09	3.3	37	1
3	3.8	0.05	3.8	78	1
4	5.4	0.07	5.4	76	1
5	6.7	0.12	6.7	56	1
6	3.9	0.06	3.9	65	1

8.3.3 Project economics of Akola tank system

Project economics of the tank irrigation system was carried out by considering all costs and benefits of the project. Costs included initial costs, maintenance costs, and crop cultivation costs. Initial costs included costs of tank excavation, pipeline, wells, pumps, and horticultural plantation. All the costs are for the year 2002-03. The cost of cultivation of rainfed and irrigated field crops, market rates of the produce, and net benefits of horticulture crops were taken from Cost of Cultivation Scheme, MPKV, Rahuri, India. These costs and rates are the average values for the state of Maharashtra. Excavation rates, cost of pump and pipeline are the prevailing market rates in the region. All the costs are given in Table 8.7. The wells in the watershed are bore wells and submersible pumps are installed on these wells. Pumping charges were computed for pumping from tanks and wells. Life of tanks and wells was considered as 30 years. Life of underground PVC pipeline was considered as 20 years and life of pumps and trenches was considered as 10 years. Life of horticultural crops varied from 10 to 30 years for different plants. Interest and inflation rates were taken as 11 and 5% respectively. Annualised values of initial costs were computed. Maintenance costs were taken as 4 % of the initial investment costs. Annual cost of drip irrigation set was worked out for 5 x 5 m spacing and 10 x 10 m spacing crops. Benefits were through the crop production in the watershed. Table 8.8 gives the annualised values of various costs and benefits for Akola watershed. The annual crop costs and benefits for different climate years are given in Table 8.9. In the year 2003-04 due to less rainfall crop sowing was not effected and hence crop cultivation costs are zero. However the benefits are the net benefits of horticultural crop production. The total incremental benefits in the watershed were 317682 at the incremental cost of 185657 giving benefit cost (BC) ratio of1.77. The average incremental cost and benefits per hectare of watershed (for 28 ha watershed) were Rs 6630 and Rs 11346 respectively. BC ratio is higher for the watershed due to the cultivation of horticultural crops.

Table 8.7: Different costs considered in the economics analysis for Akola watershed

Sr. No.	Item	Unit	Quantity	Rate, Rs	Value
1	Excavation for tanks	m^3	4232	30	126949
2	Excavation for wells	m^3		175	
3	Machinery drilling charges for borewells	m	30	125	3750
4	Pipeline, 110 mm, PVC, (including excavation), Model output	m	1667	73	121670
5	Submersible pump, 5 HP	1	3	22000	66000
6	Monoblock pump, 5 HP	1	3	12247	73482
7	Horticultural plantation				193625
8	Trench excavation	m^3	2525	30	75756

Table 8.8 Annualised values of costs and benefits.

Initial cost Rs	Maintenance cost, Rs	Drip cost Rs	Incremental crop cultivation cost, (details below) Rs	Total incremental cost Rs	Incremental benefits (details below) Rs	BC Ratio
65958	2638	110289	6772	185657	317682	1.71

Table 8.9 Annualised crop costs and benefits for Akola watershed

Climate data year	Incremental crop cultivation cost, Rs	Incremental crop benefits Rs
1976-77	7276	322585
1977-78	6704	311342
1978-79	7271	324858
1979-80	7128	318195
1980-81	7288	326549
1981-82	6661	311114
1982-83	7278	323761
1983-84	6669	309734
1984-85	7285	325732
1985-86	7319	323629
1986-87	7327	325903
1987-88	7318	324507
1988-89	6215	306193
1989-90	7223	325848
1990-91	6635	312829
1991-92	7398	325827
1992-93	6669	310895
1993-94	6637	312635
1994-95	6589	312326
1995-96	7395	324737
1996-97	7031	318938
1997-98	7223	325196
1998-99	6605	312598
1999-00	6627	311035
2000-01	7271	325944
2001-02	7263	326268
2002-03	7296	321104
2003-04	0	274807
Average	6772	317682

*(*Sowing of row crops was not initiated due to insufficient rainfall hence cultivation cost is nil, however the net benefits are from horticulture crops)*

8.3.4 Conclusion

From the study of different water balances for Akola watershed, it is observed that, about 34.4 % of runoff is harvested in the watershed and 65.6% goes out of the watershed. Recharge to groundwater takes place through field, tank and trenches. Trenches reduced the inflow to the tanks and contributed to groundwater recharge (supporting the part of the first hypothesis). Groundwater flow is the major groundwater outflow component. The BC ratio of 1.71 indicates that the tank system is economically feasible.

8.4 Investigation of the first hypothesis

When rainwater harvesting practices are adopted as part of watershed development projects, both *in situ* and *ex situ* practices are adopted during the development process. But due to the absence of suitable analytical tool, the effect of *in situ* practices on the storage capacities of *ex situ* practices (i.e. tanks) is not properly assessed or not assessed at all. Sometimes tanks are constructed as stand alone systems without consideration of *in situ* RWH practices. For example the percolation tanks in Maharashtra state are constructed under the Employment Guarantee Scheme by the State Government as isolated tanks. While designing these *ex situ* RWH structures for such cases, it is evident that the effect of *in situ* measures was not considered. Later *in situ* practices were adopted in the catchments of these tanks to control the soil erosion and siltation of the tanks. However as discussed in Chapter 2 *in situ* measures influence the storages of *ex situ* measures. The aim of this study is to optimally design the tank system and for this purpose all the factors that affect the storages need to be considered. Hence in this study it was hypothesised that

"*in situ* RWH systems influence the storages of downstream *ex situ* RWH systems (tanks) and hence both *in situ* and *ex situ* RWH systems should be considered together in the methodology for optimum design of *ex situ* RWH systems (tank system) in the watershed".

Literature reviewed and discussed in Chapter 2 strongly supported the fact that *in situ* RWH systems store significant volumes of runoff (which would have otherwise gone to tanks or rivers downstream). CCTs exist in the catchments 2 and 3 of the Akola watershed. The results on different water balances for Akola watershed as discussed in the preceding sections also supported the fact that CCTs store significant volumes of runoff. Therefore the literature review and the results of evaluation of the Akola watershed have supported the part of the hypothesis i.e. "*In situ* RWH systems influence the storages of downstream *ex situ* RWH systems (tanks)"

To further investigate the first hypothesis, simulation was carried out for the Akola watershed considering following two cases keeping all other factors same –

1. Catchments 2 and 3 treated with trenches (as currently existing case) and
2. Catchments 2 and 3 not treated with trenches (hypothetical case)

Simulation was carried out for climatic year 2003-03 with tank strategy No 1926. The DSR considered for simulation was 65% (This is the existing DSR in the watershed). Results in terms of water balances were obtained and discussed below.

8.4.1 Tank water balance

The tank water balance components are presented in Table 8.10. From the table it is seen that trenches in the catchments of tank-2 and tank-3 have reduced the inflow to the tanks by a factor of about 2. When trenches exist, inflow to the tanks is about half of the inflow when trenches do not exist. The required tank capacities of tank-2 and tank-3 are reduced nearly by 5 times due to the construction of trenches in their catchments (Fig 8.8). There are no trenches in the catchments of other tanks but their tank capacities are also reduced. This is due to the requirement of meeting DSR criterion of 65%. Due to the presence of trenches in the catchments of tank-2 and tank-3, runoff from the watershed gets reduced. Hence tank capacities of other tanks are required to be reduced so that more portion of inflow is allowed to go downstream to meet the downstream release criteria of 65%. Changes in other balance components of tanks are mainly due to changes in the tank capacities. Total runoff in the entire watershed going as inflow to the tanks was reduced from 31128 m^3 to 27705 m^3 due to the presence of trenches in the two catchments.

Table 8.10: Water balance components (m^3) for different tanks with trenches (T) and without trenches (NT) for Akola watershed

Tank	Capacity		Inflow		Overflow		Seep+Evap		Irrigation	
No	NT	T	NT	T	NT	T	NT	T	NT	T
1	977	866	21895	22688	19434	20324	2062	2054	399	311
2	208	35	5099	2140	4540	2039	559	102	0	0
3	239	43	4653	2051	3749	1926	817	125	88	0
4	1356	947	16415	18767	12621	15907	2258	1862	1537	997
5	1687	794	10845	11686	7179	9607	3665	2079	0	0
6	977	400	8574	8454	5998	7023	2472	1379	103	53

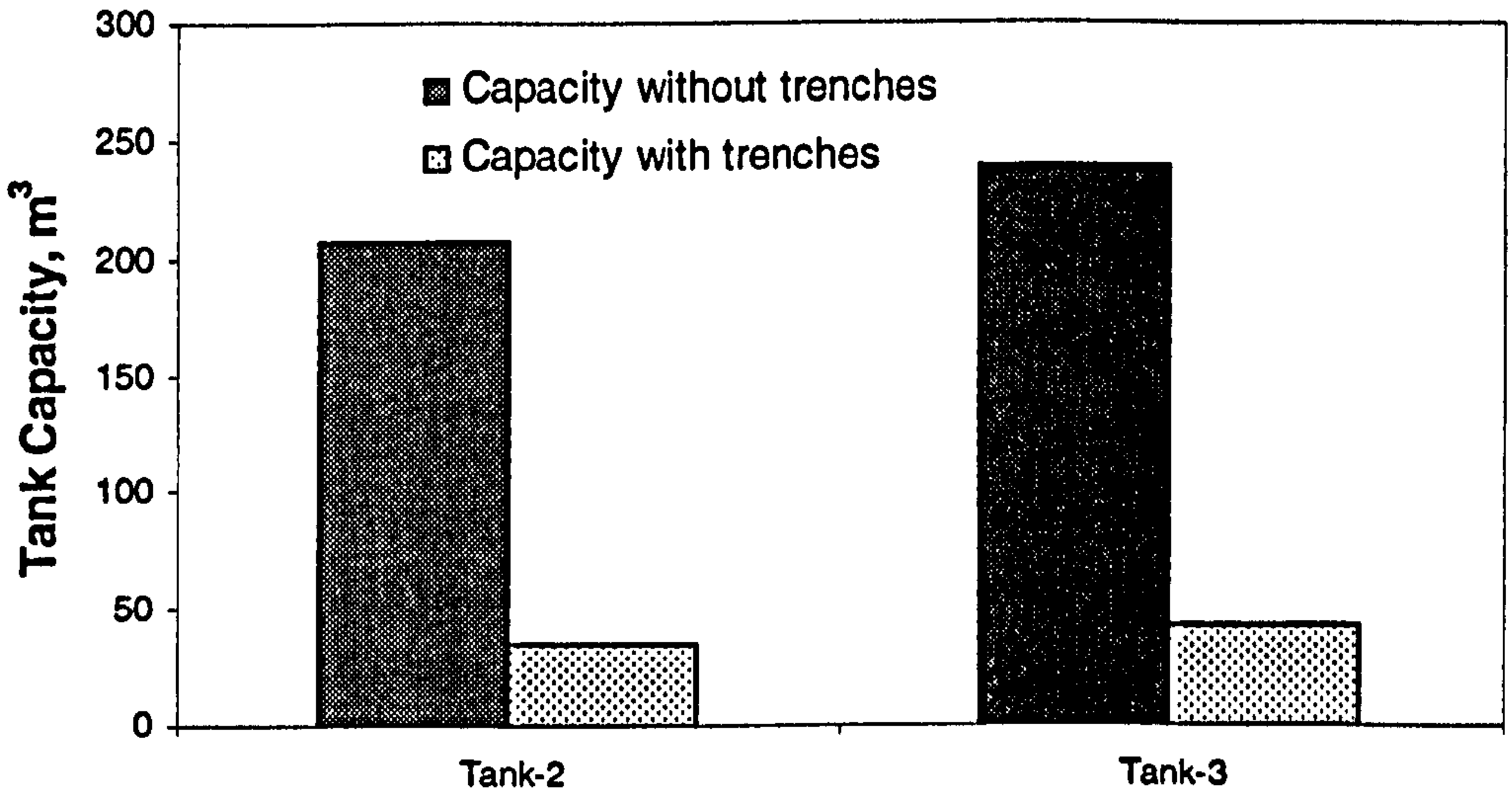


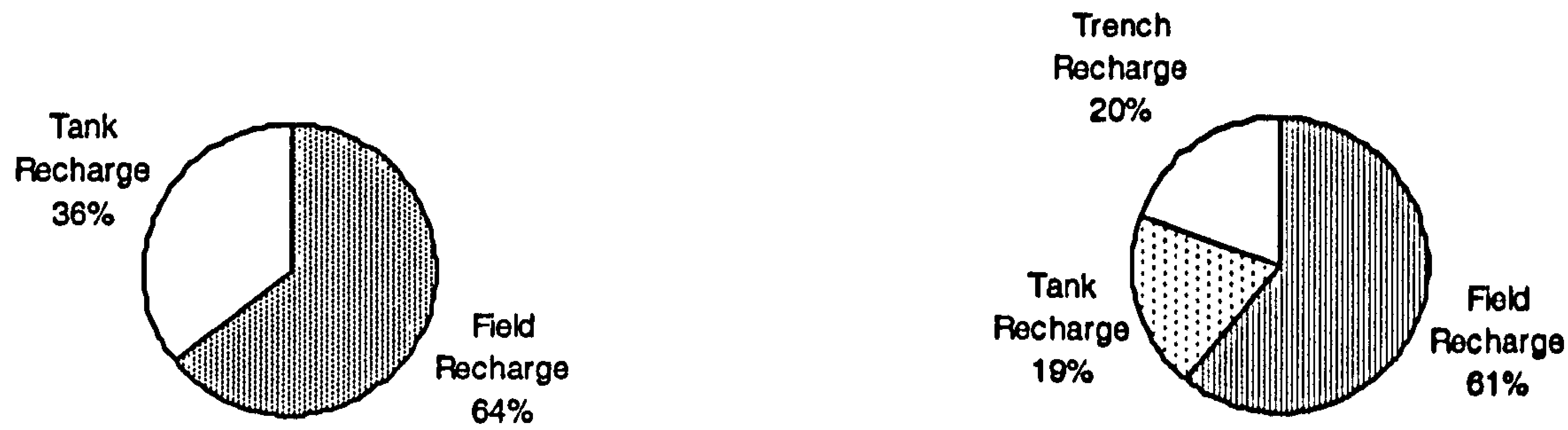
Figure 8.8: Tank capacities with and without trenches in the Akola watershed

8.4.2 Groundwater balance

The contributions of groundwater recharge components are shown in Fig 8.9. From the figure it is seen that when trenches do not exist, groundwater recharge takes place through field (64%) and tank (34%). But when trenches exist they also contribute to groundwater recharge (20%), in addition to field (61%) and tank (19%). When trenches do not exist, total groundwater recharge through field and tank is 26027 m^3, but when trenches exist the total groundwater recharge is 29172 m^3. Thus the presence of trenches has increased groundwater recharge by 3145 m^3 (increase of 12%).

From the results it is concluded that the presence of trenches changes the flow patterns in the watershed. The inflow to the tanks gets reduced due to the trenches in their catchments and the resulting tank capacities are much less than the tank capacities when trenches do not exist. Part of the inflow to the tanks which is intercepted by trenches is diverted to the groundwater as groundwater recharge.

Therefore findings of the study suggest that this aspect of influence of *in situ* RWH systems on the storages of downstream *ex situ* RWH systems (tanks) should be considered together in the methodology while designing storage capacities of tanks in the watershed. The first hypothesis is therefore accepted. While deriving the optimum tank strategy for Akola watershed this aspect has been considered in this study.



(a) No trench case (b) Trench case

Figure 8.9: Contributions of groundwater recharge components with and without trenches for Akola watershed

8.4.3 Conclusion:

The literature reviewed in Chapter-2, results of evaluation of Akola watershed and the simulation with and without trenches in the catchments 2 and 3, all supported the first hypothesis of this research and therefore the hypothesis "*in situ* RWH systems influence the storages of downstream *ex situ* RWH systems (tanks) and hence both *in situ* and *ex situ* RWH systems should be considered together in the methodology for optimum design of *ex situ* RWH systems (tank system) in the watershed" is accepted.

8.5 Evaluation of tank irrigation system in Pimpalgaon Ujjaini watershed

Pimpalgaon Ujjaini watershed is a large watershed with 1326 ha area. There are two tanks on two streams in the watershed. The tanks are mainly used for groundwater recharge and called as percolation tanks. Water is not used directly from the tanks for irrigation purpose. Common cereal, pulses and oilseed crops are grown in the command of the percolation tanks in the watershed with irrigation by groundwater. The land use and other aspects of the watershed are discussed in Chapter 7.

8.5.1 Water balance for Pimpalgaon Ujjaini watershed

The water balance analysis of the Pimpalgaon Ujjaini watershed was carried out and discussed under three balances i.e. field water balance, tank water balance and the groundwater balance. Trenches did not exist in the watershed and therefore trench water balance is not discussed.

8.5.1.1 Field water balance

There are 447 fields in Pimpalgaon Ujjaini watershed with an area of 1326 ha. Out of this 334.92 ha was under single cropping, 410.14 ha under double cropping, 490.84 ha was barren and 90 ha occupied under two tanks. Field water balance involved computation of various inflows to and outflows from the field. Inflows to the field were through rainfall and irrigation. Outflows from the field were surface runoff, evapotranspiration and deep percolation. The field water balance components are shown in Fig. 8.10. Annual rainfall was 541.25 mm. Runoff was 21.5% of rainfall. Evapotranspiration and deep percolation contributed 67.5% and 15.8% of the total outflow respectively. Deep percolation was 20.5% of the rainfall.

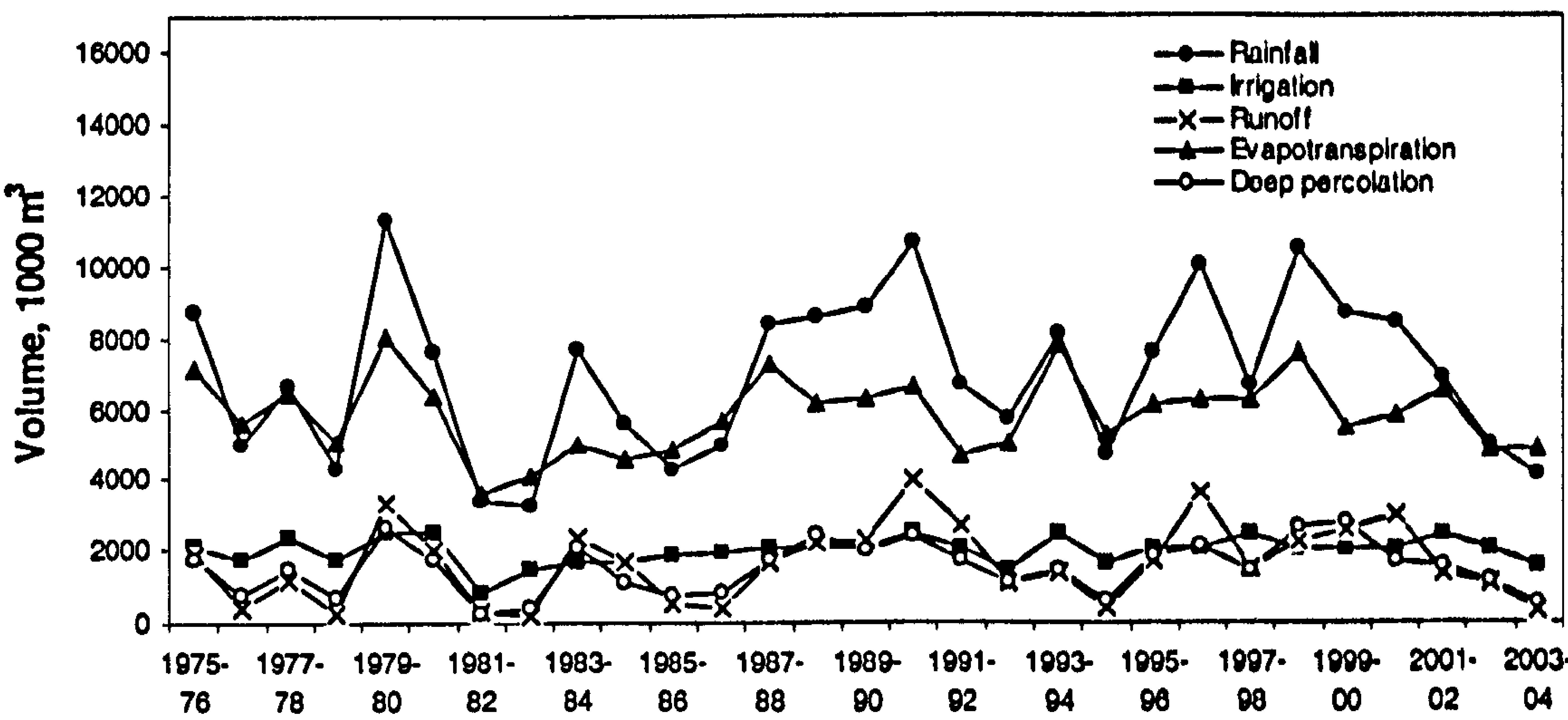


Figure 8.10 Components of field water balance for Pimpalgaon Ujjaini watershed

8.5.1.2 Tank system water balance

There are two percolation tanks on two streams in the watershed. Total storage capacity of two tanks is 91.2 ha-m. Tank system water balance components for 29 years are given in Table 8.11. From the table it is seen that, inflow ranged from 0.13 to 1.86 times the total storage capacity of tank system with an average (29 years) of 0.82. Major portion of this inflow was lost as seepage which accounted for 83.6% of the total outflow from the tank. Other loses were evaporation (13.6%) and overflow (2.6%). There was no carry over storage from the tanks. Though the overflow from the tanks was less, average DSR from the watershed was 58.5% since the tanks were at the middle of the watershed and area of watershed downstream of tanks contributed directly to the DSR. There was no irrigation from the tanks since tanks were used for groundwater recharge only. These components are also shown in Fig 8.11.

Table 8.11 Tank system water balance components for Pimpalgaon Ujjaini watershed

Year	Rainfall, mm	Inflow 1000 m^3	Overflow 1000 m^3	DSR	Evaporation 1000 m^3	Seepage 1000 m^3
1975-76	674.40	883.69	0.00	57.99	133.86	749.84
1976-77	383.30	242.33	0.00	52.76	29.82	212.51
1977-78	514.70	575.96	0.00	57.23	76.61	499.35
1978-79	332.80	195.30	0.00	52.48	23.66	171.64
1979-80	872.90	1412.98	56.25	62.32	203.90	1152.82
1980-81	589.60	936.75	12.92	58.42	128.39	795.44
1981-82	262.70	211.16	0.00	53.87	34.89	176.27
1982-83	249.60	119.07	0.00	54.75	16.20	102.87
1983-84	596.60	1064.44	103.51	62.78	142.63	818.30
1984-85	434.70	746.11	0.00	59.37	108.52	637.59
1985-86	331.50	275.02	0.00	57.13	34.34	240.68
1986-87	387.00	263.08	0.00	52.07	36.05	227.03
1987-88	649.40	806.99	0.00	57.36	110.55	696.45
1988-89	663.70	1008.69	74.03	61.97	149.44	785.22
1989-90	687.30	1041.94	0.00	58.18	146.99	834.11
1990-91	827.60	1693.96	140.46	63.83	223.31	1314.29
1991-92	522.20	1132.28	126.00	64.94	128.91	877.37
1992-93	443.90	511.27	0.00	58.18	62.63	448.64
1993-94	628.40	671.06	0.00	57.85	89.58	581.47
1994-95	369.20	248.23	0.00	53.99	29.57	218.67
1995-96	587.90	785.16	0.00	58.82	119.69	665.47
1996-97	776.50	1550.86	242.78	66.93	208.95	1099.12
1997-98	519.70	675.65	0.00	59.81	99.90	575.75
1998-99	812.60	999.59	0.00	60.83	131.37	868.22
1999-00	676.20	1157.25	118.23	63.68	159.42	879.61
2000-01	652.18	1325.12	71.92	61.25	177.96	1075.24
2001-02	536.07	662.96	0.00	57.80	102.03	560.93
2002-03	389.00	511.65	0.00	57.69	60.24	451.41
2003-04	324.47	205.85	0.00	52.94	28.46	177.39

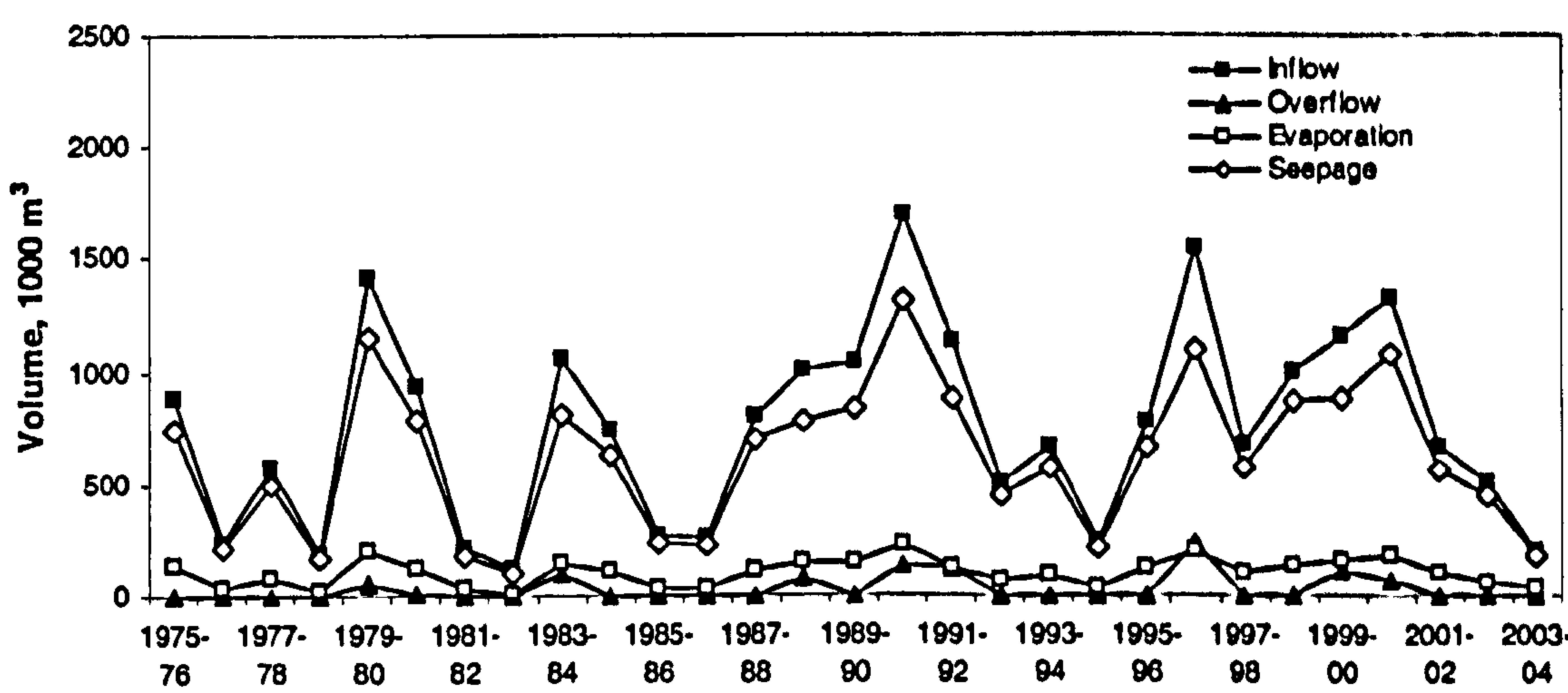


Figure 8.11 Tank system water balance components for Pimpalgaon Ujjaini watershed

8.5.1.3 Tank water balance

Tank water balance components of individual tanks are discussed in this section. The components are given in Table 8.12 and Fig. 8.12. Tank capacities were 69.60 and 21.70 ha-m. In tank No.1 annual inflow was less than the tank capacity whereas in tank No 2 annual inflow exceeded tank capacity. Of the total inflow, evaporation was about 15% in both the tanks whereas seepage was 85% in Tank No.1 and 74% in Tank No.2. There was no overflow from tank No.1.

Table 8.12: Individual tank water balance components for Pimpalgaon Ujjaini watershed (average of 29 years)

Tank No.	Capacity m^3	Inflow m^3	Overflow m^3	Evaporation m^3	Seepage m^3
1	695877	424172.2	0.00	60302.8	362280
2	216938	326924.9	33789.2	41983.9	250001

8.5.1.4 Groundwater balance

In estimating the groundwater balance for both the Akola and the Pimpalgaon Ujjaini (PU) watershed, it was assumed that underground storage volume is available below the watershed confined by bed rock at the lower boundary and ground surface as the upper boundary. Deep percolation from fields, trenches, seepage from tanks recharge this storage volume and water is withdrawn for irrigation and other use from the storage. In addition water from adjoining area may join this storage volume and water may flow outside the storage volume as groundwater flow. In the PU watershed, irrigation was scheduled at 28 days in rainy season and 21 days in post rainy season with an irrigation application depth of 55 mm.

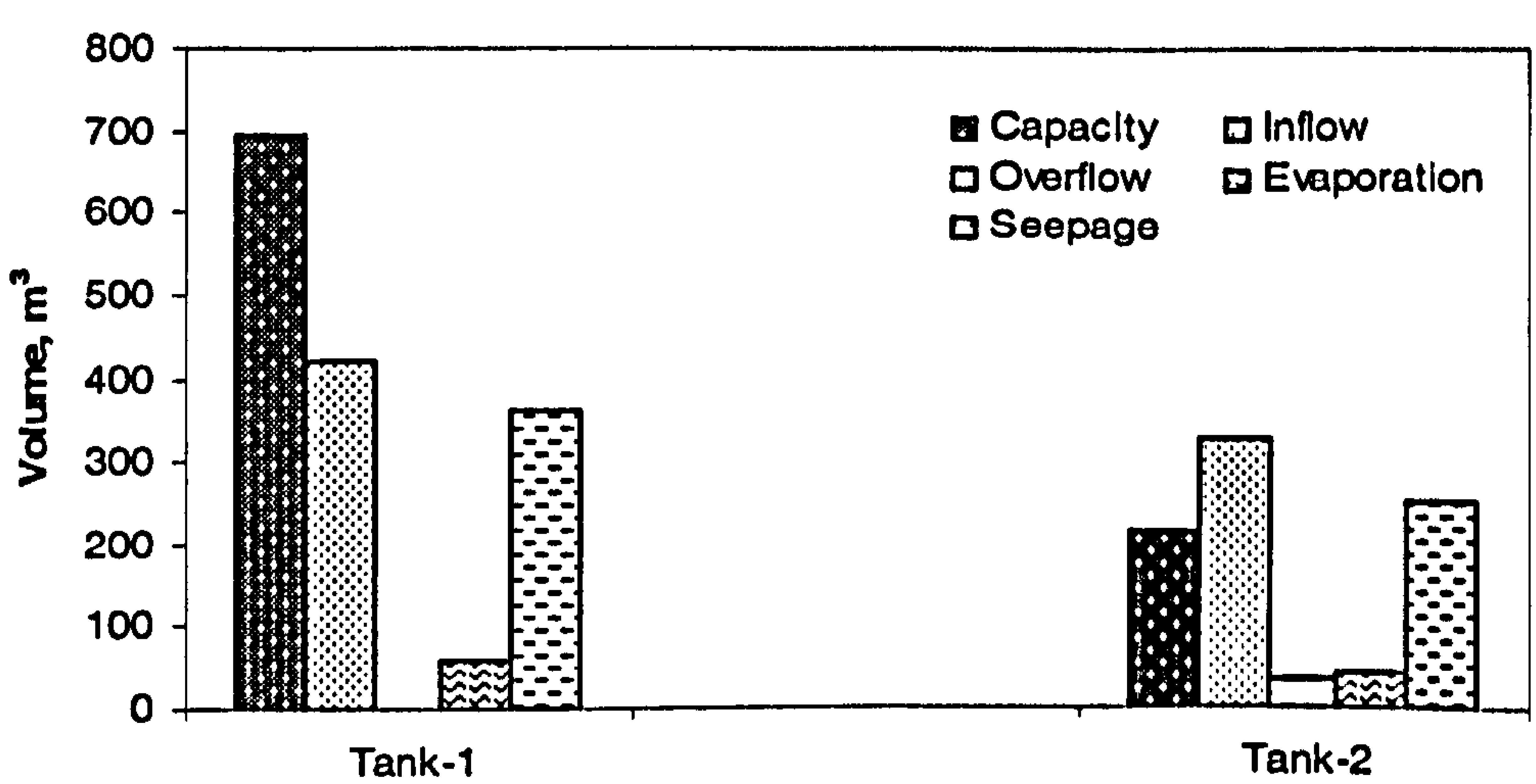


Figure 8.12: Tank water balance components for two tanks for Pimpalgaon Ujjaini watershed (average of 29 years).

Irrigation application efficiency was taken as 70%. Source of irrigation was open dug wells. There were 85 open dug wells in the watershed. Other use was estimated from the number of household units in the watershed. Field recharge and tank recharge were found to be 71 and 29% respectively. Groundwater flow was 33.26% of the total groundwater outflow whereas irrigation and other use contributed 65.53 and 1.21% respectively. The groundwater recharge and withdrawal components are shown in Fig 8.13 and Fig 8.14 respectively whereas contributions of recharge and withdrawal components are shown in Fig 8.15.

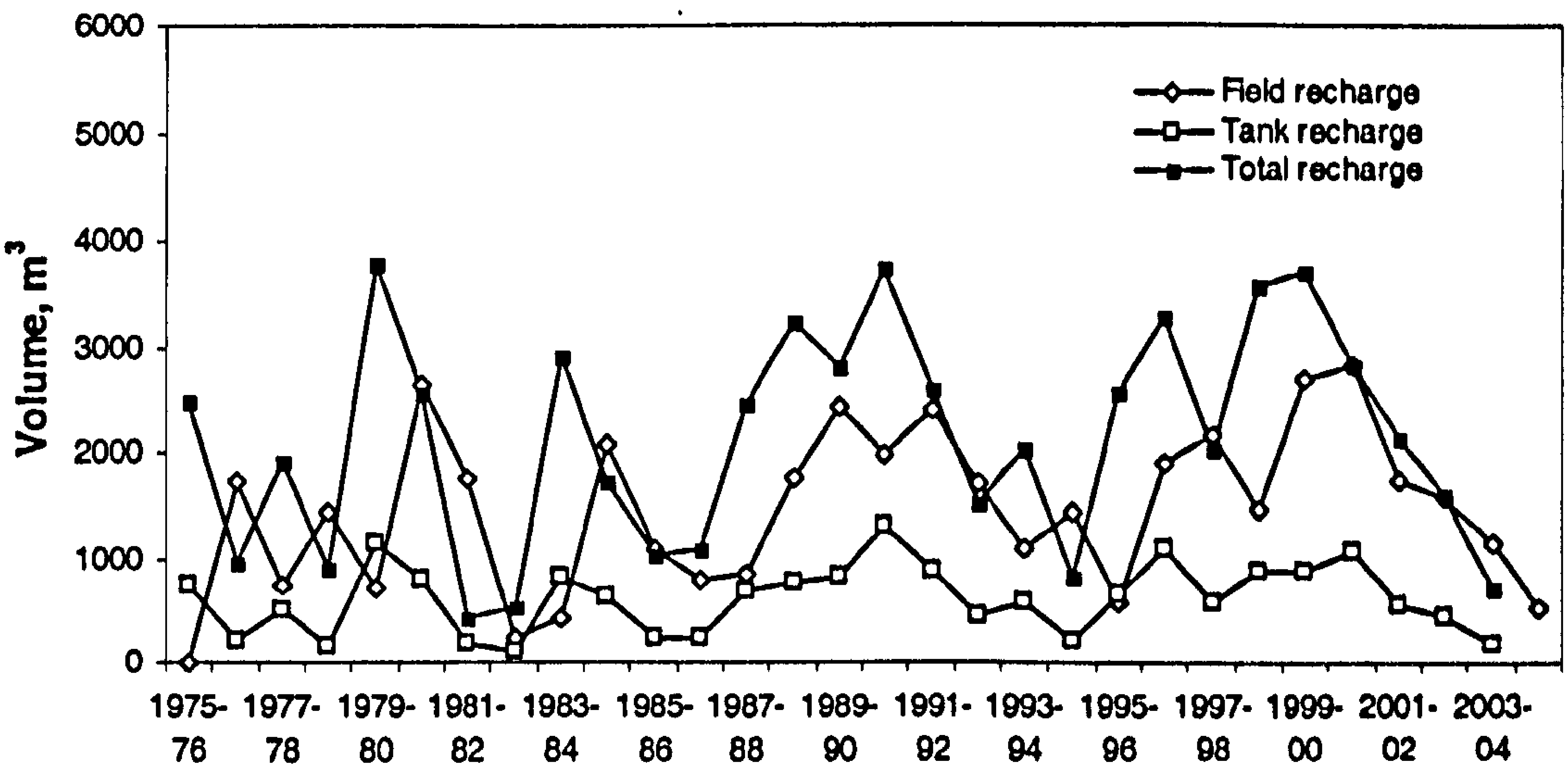


Figure 8.13: Groundwater recharge components for Pimpalgaon Ujjaini watershed

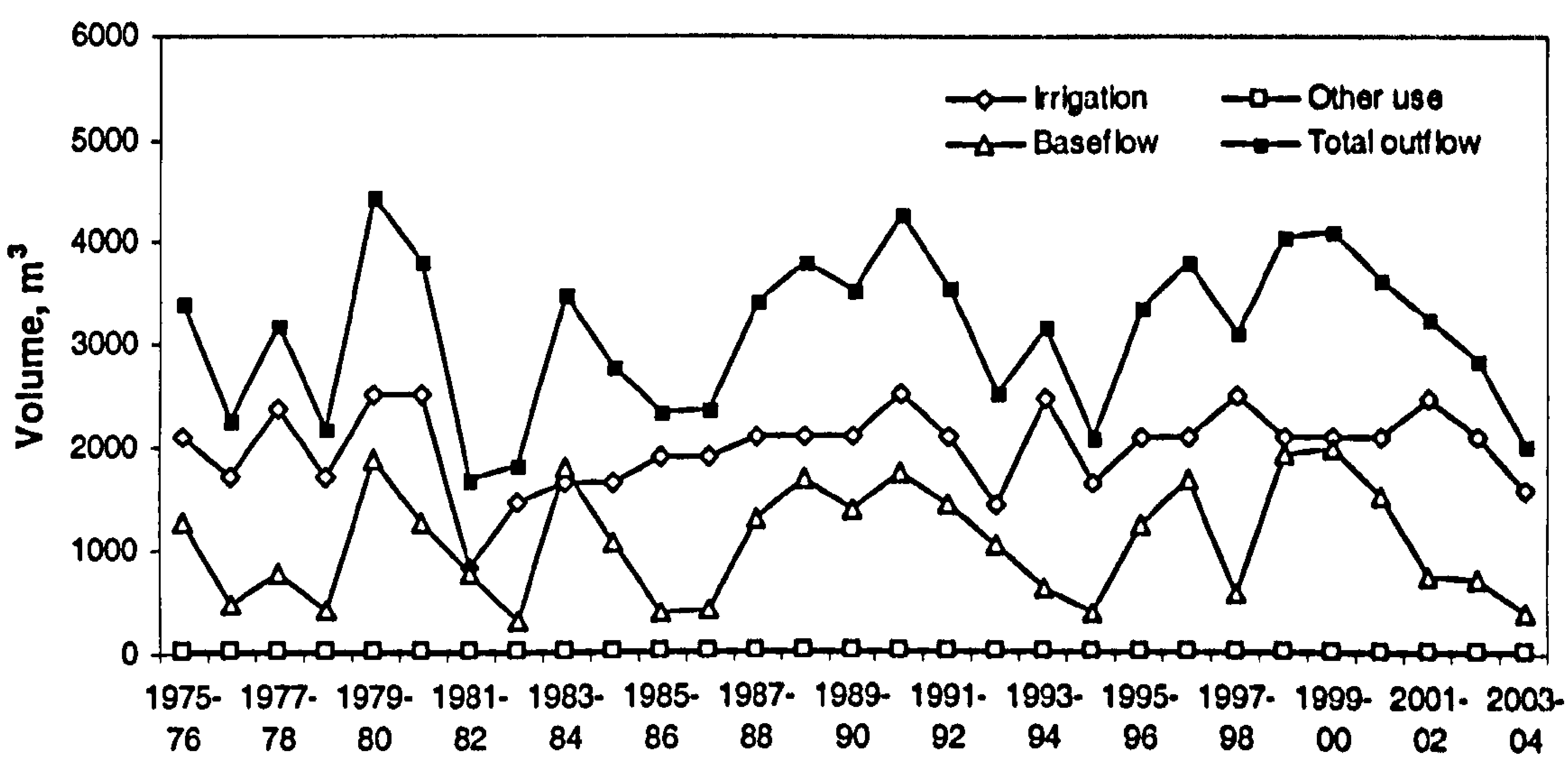


Figure 8.14: Groundwater withdrawal components for Pimpalgaon Ujjaini watershed

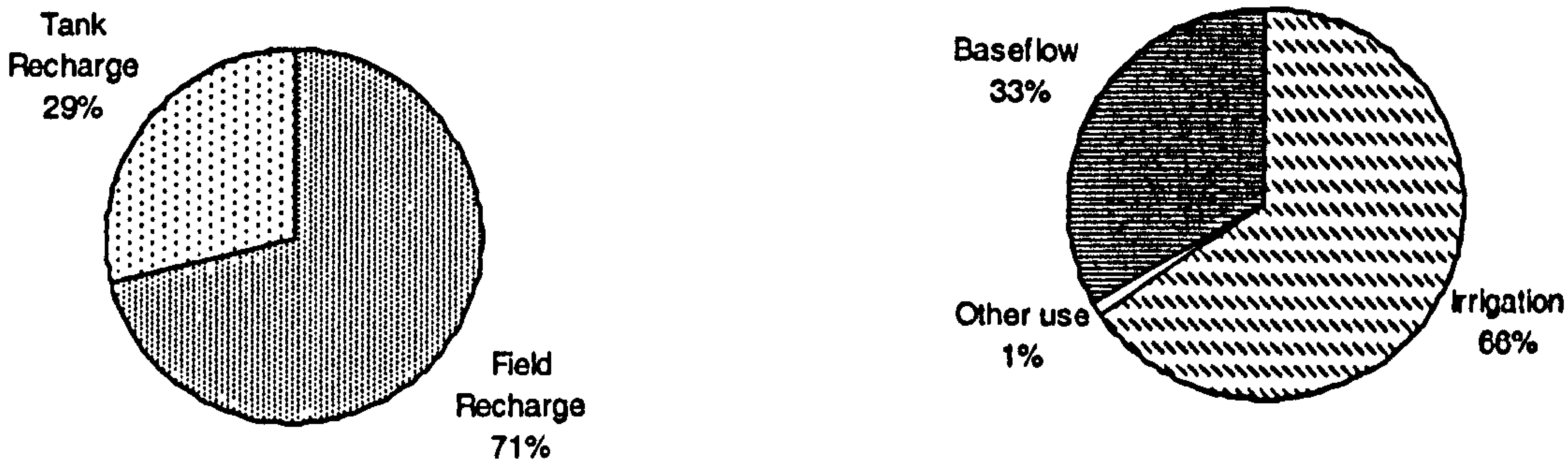


Figure 8.15 Contributions of groundwater recharge and withdrawal components for Pimpalgaon Ujjaini watershed

8.5.1.5 Catchment-storage-command relationship for Pimpalgaon Ujjaini watershed

It is difficult to identify the command area of a percolation tank. In this study the catchment and command area together was considered as the total command area of the tank (i.e. considering the tank as type-3). Table 8.13 gives the catchment and command areas of two tanks in the watershed. The CSR for tank No.1 is less than that for tank No.2. Subsequently the annual inflow was less than tank capacity (0.6) in tank No 1, whereas it was more (1.5) than the tank capacity in tank No 2.

Table 8.13 Catchment area, storage, command area, CSR, CCR for Pimpalgaon Ujjaini watershed

Tank No.	Catchment, ha	Storage, ha-m	Command, ha	CSR	CCR
1	270.6	69.6	694.0	3.9	0.4
2	213.6	21.7	883.6	9.8	0.2

8.5.1.6 Project economics

Project economics of the tank irrigation system was carried out by considering all costs and benefits of the project. Costs included initial costs, maintenance costs, and crop cultivation costs. Initial costs included costs of tank excavation, pipeline, wells, and pumps,. All the wells in the watershed were dug wells. 5 HP pumps were considered on these wells. Maintenance costs were taken as 4% of the initial costs. Benefits were through the crop production in the watershed. There was no horticultural plantation in the watershed and irrigations to field crops were by surface application (no drip irrigation). No trenches were taken in the watershed. Hence there was no initial cost towards horticultural plantations, drip system and trenches. The different costs considered for the economic analysis are given in Table 8.14. Annualised values of all initial costs were computed and are given in Table 8.15.

Table 8.11 gives the annualised values of costs and benefits. Annual crop cultivation costs and benefits are given in Table 8.16.

Table 8.14: Various costs considered in the economics analysis for PU watershed

Sr. No.	Item	Unit	Quantity	Rate, Rs	Value
1	Excavation for tanks	m^3	142799	30	4283953
2	Excavation for wells	m^3	16681	175	2920700
3	Pipeline, 110 mm, PVC, (including excavation), Model output	m	89092	73	6503737
4	Monoblock pump, 5 HP	1	85	12247	1040995

Table 8.15 Annualised values of costs and benefits for PU watershed

Initial cost Rs	Maintenance cost, Rs	Incremental crop cultivation cost, Rs (details below)	Total incremental cost Rs	Incremental benefits Rs (details below)	BC Ratio
1200984	48039	11035725	12284748	16455873	1.34

Table 8.16 Annual crop costs and benefits for Pimpalgaon Ujjaini watershed

Climate data Year	Crop cultivation cost, Rs	Crop benefits Rs
1975-76	11015789	16723213
1976-77	12150601	17694738
1977-78	12837900	17602580
1978-79	10605744	14532060
1979-80	12957961	19795516
1980-81	12950419	20414872
1981-82	4590744	5070016
1982-83	10284029	12428815
1983-84	9090267	14167778
1984-85	9090290	13581311
1985-86	11533419	15433297
1986-87	10818930	15444790
1987-88	11030607	16273565
1988-89	11030594	17211522
1989-90	11030607	18089220
1990-91	12834091	19700276
1991-92	11030353	16652252
1992-93	8131183	14308911
1993-94	12828907	19828560
1994-95	12044342	17181048
1995-96	11030607	17049546
1996-97	11030571	17576280
1997-98	12834855	18100652
1998-99	11030607	18296012
1999-00	11030607	16798412
2000-01	11030607	16912372
2001-02	12704546	18571084
2002-03	11030607	16678828
2003-04	10426232	15102791
Average	11035725	16455873

The incremental annual costs and benefits for the watershed were 12284748 and 16455873 giving the benefit cost ratio of1.34. Project costs and benefits were Rs 9264 and 12410 per hectare respectively.

8.5.1.7 Conclusion

Pimpalgaon Ujjaini watershed has two percolation tanks in the middle of the watershed. The watershed water balance study shows that about 58% of runoff was released downstream of the watershed. Inflow was less as compared to the tank capacities (especially for tank No 1). Hence any effort in catchment treatment (like CCTs) of these tanks will further reduce the inflow to the tanks. Seepage made major contribution to the water loss from the tanks. Irrigation was from the groundwater storage only and hence it formed a major (66%) outflow component in the groundwater balance. The BC ratio indicates the project economically feasible.

8.6 Comparison of tank systems in two watersheds

This section gives the comparison between the performance parameters of the two watersheds

8.6.1 Water balance of the tank systems

Summary of different water balance components of two watersheds is given in Table 8.17. Both these watersheds differ in size, land use, treatment and agroclimatic region. There was no significant difference between the runoff (as per cent of rainfall) between the two watersheds. Runoff was 19% in Akola and 21.5% in Pimpalgaon Ujjaini watershed. However field deep percolation was 10.6% in Akola and 20.5% in Pimpalgaon Ujjaini watershed. Some part of the Akola watershed was treated with CCTs and hence less field was available for field recharge from this watershed. Major difference was also found in the tank evaporation and seepage losses. Tank evaporation was 4% in Akola watershed whereas it was 13.6% in Pimpalgaon Ujjaini watershed. Tank seepage was 24% in Akola and 84% in Pimpalgaon Ujjaini watershed. The climate at Pimpalgaon Ujjaini watershed is drier and the rainfall is less as compared to Akola watershed. There was no irrigation from the tanks in Pimpalgaon Ujjaini watershed and water remained in the tank storage for a longer time. These differences must have contributed to the differences in evaporation and seepage losses at the two sites. Since groundwater is used for irrigation in both the watersheds seepage from these tanks can not be considered as loss as per the concept of IWSS. The seepage from percolation tanks (85% in Tank-1 and 74% in Tank-2) is similar to those obtained by Suraj et al (1999) for three tanks in Punjab similar to Pimpalgaon Ujjaini tanks.

Guerra *et al* (1990) studied the water balance for tanks in Philippines which were similar to tanks in Akola watershed. They found that farmers used stored water for rice crop that was about 30% of the total water outflow. Seepage and percolation losses were 45% and evaporation 25%. In Akola watershed the irrigation amount contributed about 6.5% and seepage and evaporation contributed about 24 and 4% respectively of the total tank outflow while remaining 65.5% went as overflow from the tanks.

Table 8.17 Summary of water balance components of two watersheds

Parameter	Akola watershed	Pimpalgaon Ujjaini watershed
Annual rainfall*, mm	792	541
Area, ha	28	1326
No of tanks	6	2
Purpose of tank	Storage and recharge	Recharge
Runoff in the watershed (per cent of rainfall)	19	21.5
Field recharge to groundwater (per cent of rainfall)	10.6	20.5
Inflow/Tank capacity ratio	9.4	0.82
DSR, %	65.6	58.5
Tank seepage (per cent of inflow)	23.8	83.6
Tank evaporation (per cent of inflow)	4	13.6
Tank irrigation (per cent of inflow)	6.5	0
Field Recharge (Per cent of total GW recharge)	54	71
Tank Recharge (Per cent of total recharge)	23.8	29
Trench Recharge (Per cent of total recharge)	22.2	0
Groundwater flow (Per cent of total outflow)	72.1	33.3
GW Irrigation (Per cent of total outflow)	25.7	65.5
Other use (Per cent of total outflow)	2.2	1.2
BC Ratio	1.71	1.34

(These are average annual rainfalls calculated with the data set used in this study. The average annual rainfalls reported in Chapter 7 are as obtained from the literature).*

8.6.2 Catchment-storage relationship for the tanks

As discussed in Chapter 4, it is difficult to standardize the norms about the catchment-storage relationship for tanks due to lack of data on these structures. Samra *et al* (2002) have compiled information at the country level and gave some guidelines based on the available data. These are discussed in detail in Chapter 4 (Section 4.3.6.2). From these guidelines it is felt that Akola watershed comes in assured rainfall region (792 mm) and the lands are relatively flatter and therefore catchment storage ratio of about 20-25 (i.e. 20-25 ha catchment area per ha-m storage) could be taken as reference for comparing the existing cases. In the present investigation the CSR for Akola watershed ranged from 38 to 78, which looks higher than these guidelines. The high inflow capacity ratio for these tanks and higher DSR (in spite of six tanks in the watershed) from the watershed also supplement these findings.

Pimpalgaon Ujjaini watershed comes in the scarcity region of Maharashtra where average annual rainfall is 541 mm. From the literature of Samra *et al* (2002), it is felt that for such regions the CSR may be taken as 40 (i.e. 40 ha catchment per ha-m storage capacity) as reference for comparing the existing cases. These norms were for storage or storage-cum-recharge structures. Such norms for only recharge structure (percolation tanks) were not available. However in the present study simulation was carried out with different management options (discussed in next Chapter) i.e. using the tanks as only recharge structures and as storage-cum recharge structures. It was found that tanks capacities are approximately halved when they are used as recharge cum storage structures than when they are used as recharge structures only. Therefore the reference criteria of CSR of 40 from Samra *et al* (2002) for storage-cum recharge structures can be modified as 20 for percolation tanks in the Pimpalgaon Ujjaini watershed. In the present study the CSR for tanks in the Pimpalgaon Ujjaini watershed ranged from 4 to 10, indicating that the CSR for tanks in this watershed are comparatively less. This finding is supplemented by the low inflow capacity ratios for these tanks obtained in the analysis.

8.6.3 Conclusion

From the analysis of the water balance of tank systems in two watersheds, it is concluded that tanks in the Akola watershed have more catchment per unit storage (higher CSR) resulting in high inflow capacity ratios for the tanks. The water use was also less in the watershed due to horticultural crops and irrigation by drip system. All these might have resulted into high DSR from the watershed. The capacities of six tanks in the watershed are less appropriate with the supply and demand parameters of individual tanks. The inflow to the tanks can be reduced by taking *in situ* RWH practices like trenches in the catchments of these tanks (as taken in the catchments of the tank No 2 and 3). On the contrary the catchment per unit tank capacity is less (lower CSR) in the case of tanks in the Pimpalgaon Ujjaini watershed giving less inflow capacity ratios for these tanks. It suggests that any *in situ* RWH treatment taken in the catchments of these tanks will further reduce the inflow to these tanks. As expected groundwater irrigation component was more in Pimpalgaon Ujjaini watershed compared to Akola watershed. In summary though the tank irrigation systems are beneficial in both the watersheds, tank capacities are less appropriate with the supply and demand parameters of these tanks in these watersheds.

The trench system analysis relating water harvesting potential with the monetary investment gives a useful tool for planning investment in trench system. By simulating the two cases i.e. 'with trenches' and 'without trenches' in Akola watershed the first hypothesis was proved and accepted.

It will be of interest to compare these tank strategies with other alternative tank strategies in the watershed to see the overall performance on the watershed water balance and the project economics. This is discussed in Chapter 9.

CHAPTER – 9

SIMULATION OF ALTERNATE TANK STRATEGIES IN THE WATERSHED

9.1 Summary

This chapter discusses the results of simulation of some specific tank strategies and management options in comparison to the existing tank strategies in the Akola and Pimpalgaon Ujjaini watershed. The hypothesis No 3 is also investigated and discussed in this Chapter.

9.2 Introduction

The existing tank systems for Akola and Pimpalgaon Ujjaini watershed were evaluated and discussed in Chapter 8. The results of evaluation gave some indicators about the water balance and the project economics of the watershed for the existing tank systems. These tank systems were based on the experience of the planners and the prevailing socioeconomic needs. The performance indicators of these systems are compared with those from the literature and conclusions about these tank strategies are drawn as discussed in Chapter 8. The performance of the tank system can be improved by changing the tank strategy in the watershed to limited extent (like number of tanks and their capacities can be increased but not decreased). The performance can also be improved by changing the management options like changing irrigation strategies, changing the source of water for irrigation (only groundwater or tank and groundwater both). It is necessary to study the performance indicators for the new tank strategy or management option. However at present in the absence of an analytical tool such kind of analysis is not possible. Literature is also lacking on the aspect of relative performance of different tank strategies and tank management options in the watershed. SOFTANK model developed in this research fills this gap. It is possible to simulate alternate tank strategies and management options and study the performance indicators of the new system.

Some common alternate tank strategies and management options for Akola and Pimpalgaon Ujjaini watershed are simulated to demonstrate the utility of the SOFTANK model for such kind of analysis. The performance of the new strategies and management options is compared the help of water balance and project economics of the new system with that of existing tank strategies and management options. Following paragraphs discuss the results of simulation of some alternate tank strategies and management options for Akola and Pimpalgaon Ujjaini (PU) watersheds.

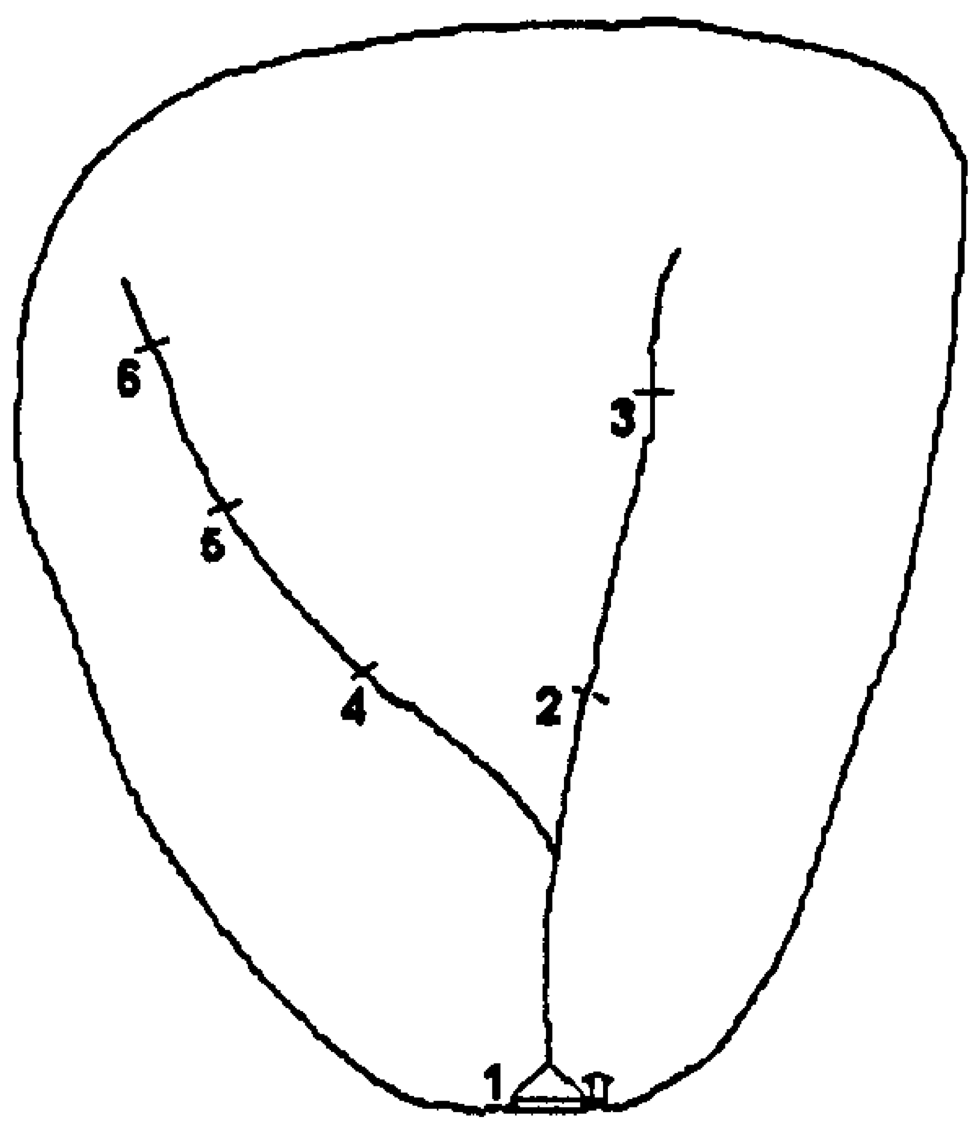
9.3 Simulation of alternate tank strategies for Akola watershed

In the Akola watershed, there are six small tanks and the source of water for irrigation in the watershed is tank as well as groundwater. This existing system was evaluated and discussed in Chapter 8. From the results of the simulation, it was found that the tanks in the watershed are under designed and much of the inflow goes as DSR from the watershed. It was also found that inflow capacity ratio was very less for tank 2 and 3 and tank capacities are less appropriate with the supply and demand parameters of these tanks as indicated by wide variation in the inflow capacity ratio for these tanks. Therefore some alternate tank strategies were simulated for this watershed to study their performance indicators in relation to the existing tank strategy.

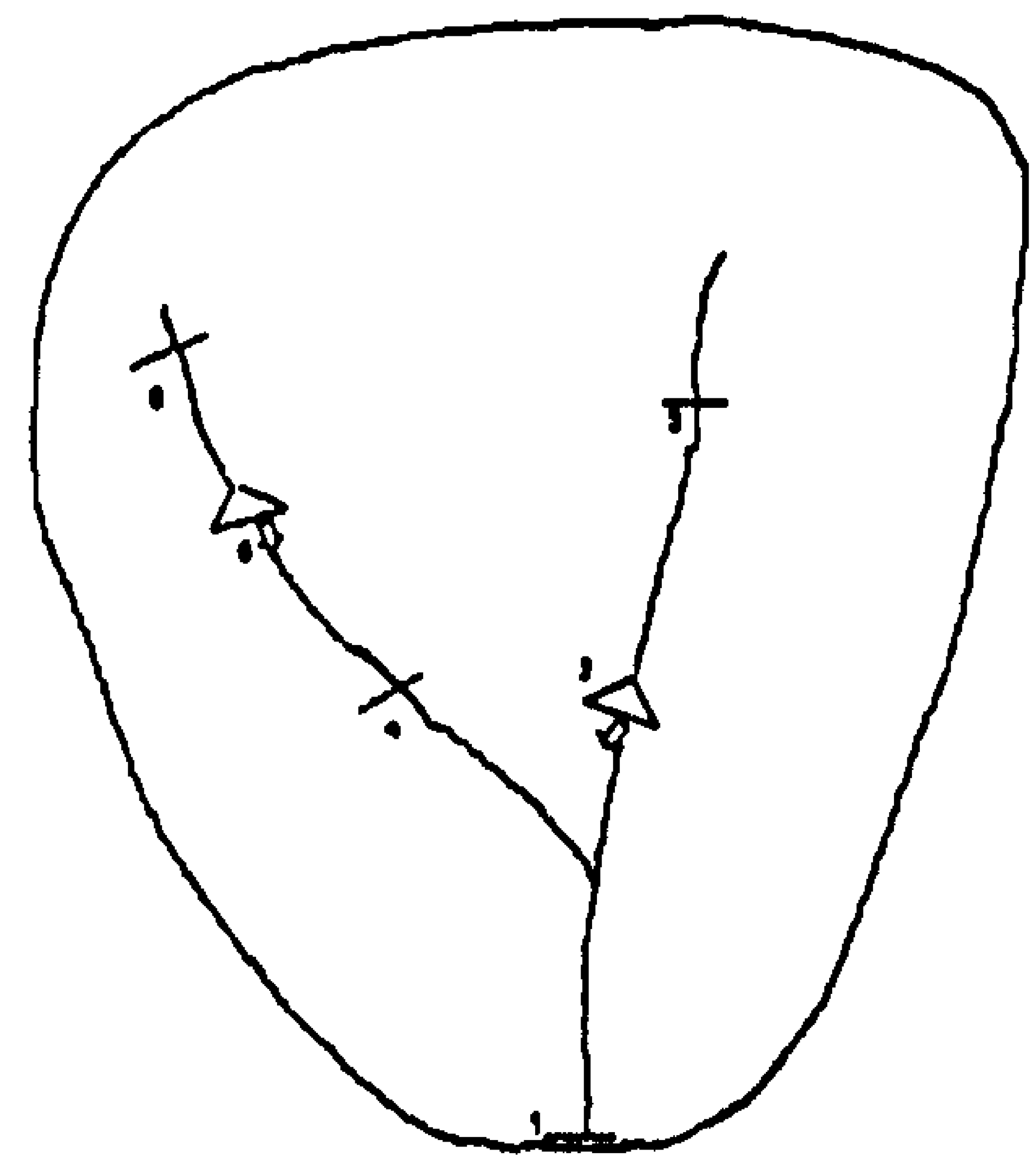
The tank strategies considered for simulation for Akola watershed are given in Table 9.1 and these strategies are shown in Fig 9.1 for ease of understanding. These tank strategies involve different number of tanks, their locations and their types. For example Tank Strategy No 1 involve only one tank at the outlet of the watershed; tank strategy No 50 and 58 involve two tanks in the middle of the watershed with type 1 tanks in strategy No 50 and type 3 tanks in strategy No 58. Tank strategy No 1805, 1926 and 2047 involve six tanks at six stream points with tank type 1, 2 and 3 respectively (except tank 1 which is always of type 2).

Table 9.1: Alternate tank strategies for Akola watershed

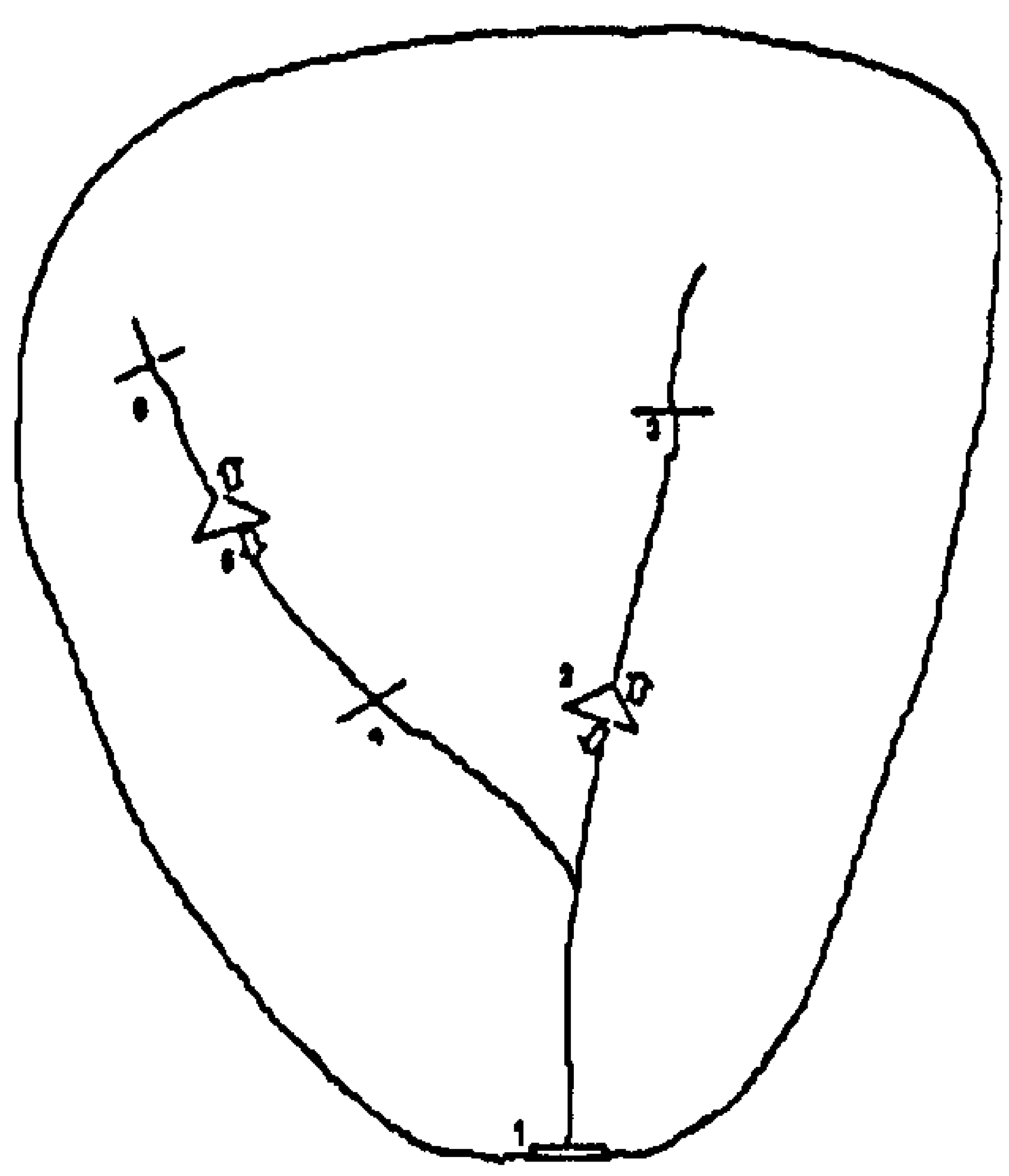
Tank strategy No	No. of tanks	Tank strategy details Tank No-Stream point No-Tank type	Tank strategy description
1	1	1-1-2	One tank at the outlet of the watershed type 2
50	2	1-2-1, 2-5-1	Two tanks of type 1 at stream point No 2 and 5
58	2	1-2-3, 2-5-3	Two tanks of type 3 at stream point No 2 and 5
1805	6	1-1-2, 2-2-1, 3-3-1, 4-4-1, 5-5-1, 6-6-2	One tank of type 2 at the outlet and five tanks of type 1 at other stream points
1926	6	1-1-2, 2-2-2, 3-3-2, 4-4-2, 5-5-2, 6-6-2	All six tanks of type 2 at six stream points
2047	6	1-1-2, 2-2-3, 3-3-3, 4-4-3, 5-5-3, 6-6-3	One tank of type 2 at the outlet and five tanks of type 3 at other stream points



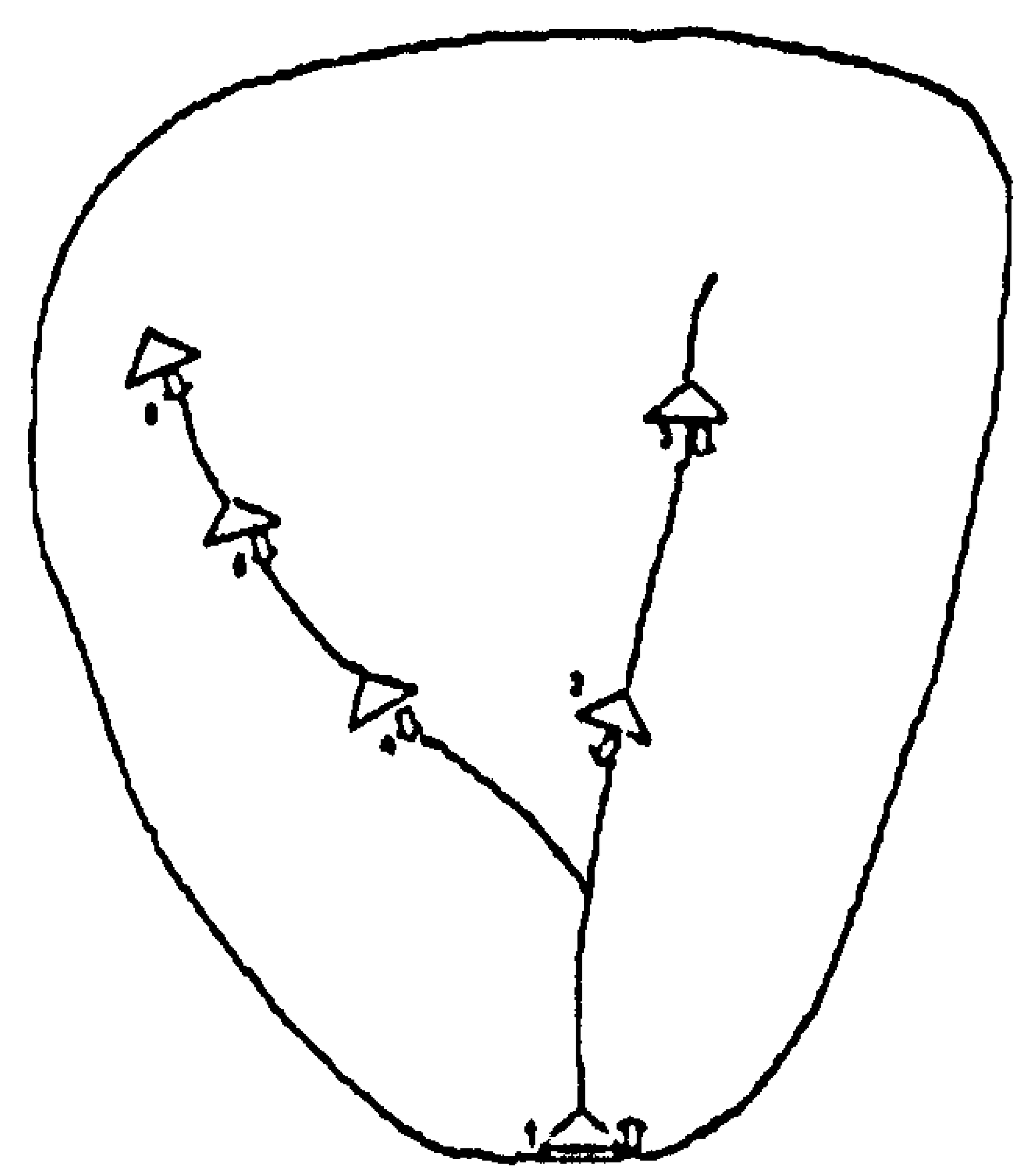
(a) Tank strategy No 1



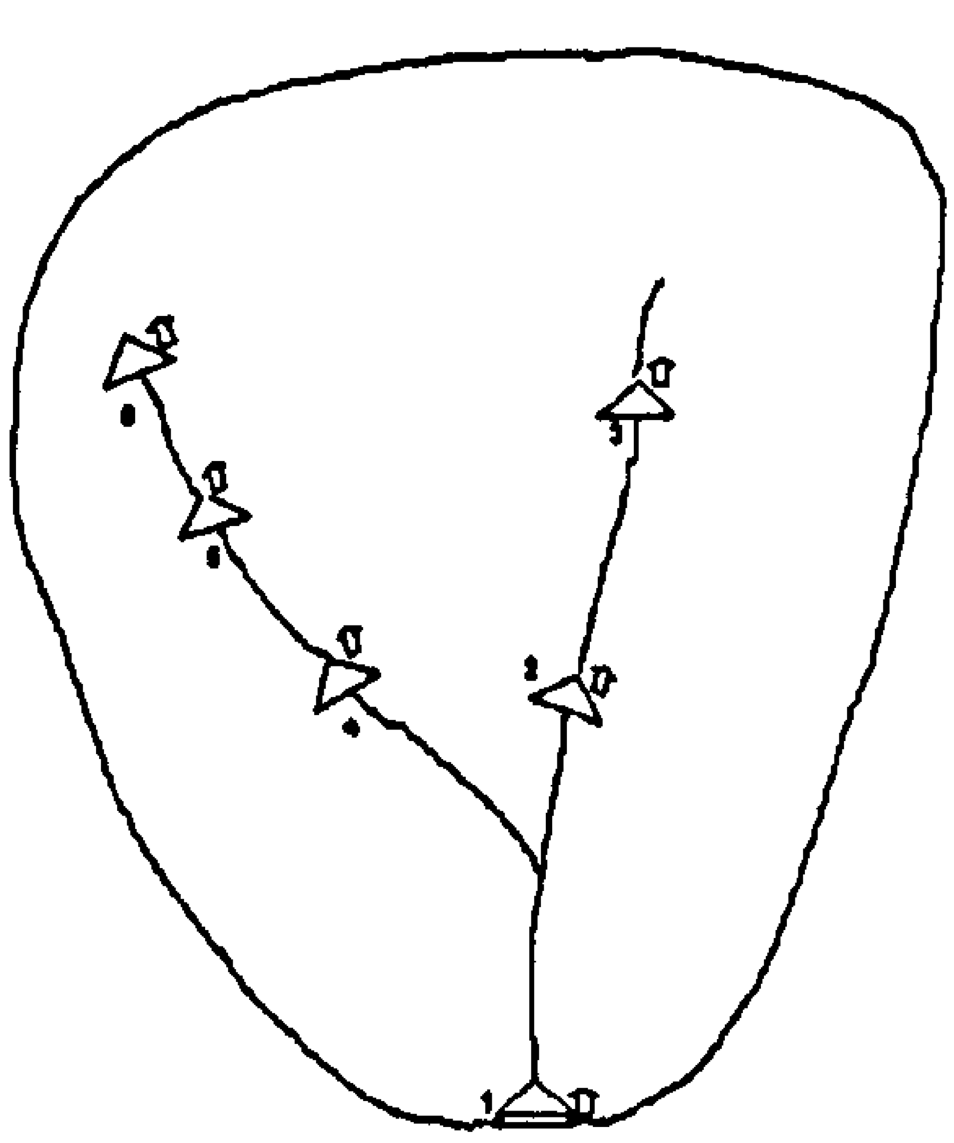
(b) Tank strategy No 50



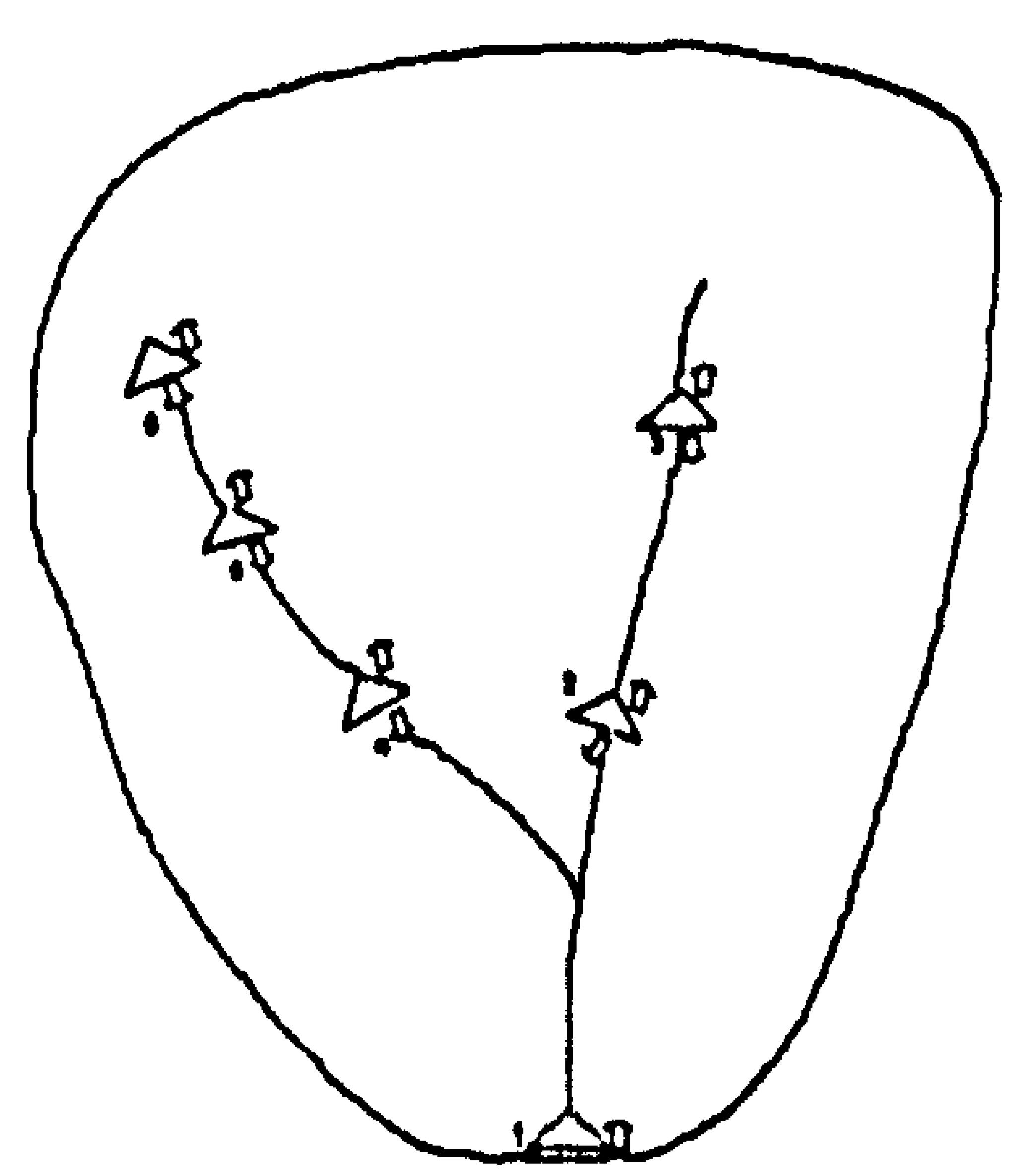
(a) Tank strategy No 58



(b) Tank strategy No 1805



(a) Tank strategy No 1926



(b) Tank strategy No 2047

Figure 9.1 Illustration of tank strategies for Akola watershed

The above described six tank strategies were simulated for Akola watershed. The data used for simulating the tank strategies were the same as that used for evaluation of tank strategies in Chapter-8. Only difference is that the tank sizes are optimised in the simulation mode whereas existing tank sizes were considered in the evaluation mode. The downstream release (DSR) obtained in the evaluation mode was 65.62%. Simulations were carried out by giving the DSR criterion of 65% with 5% deviation allowed in the DSR. The resulting DSR values were 64.11, 64.80, 64.81, 65.98, 65.96 and 66.01 for simulation of tank strategy No 1, 50, 58, 1805, 1926 and 2047 respectively. Following paragraphs discuss the water balance and project economics of these tank strategies in comparison to the existing tank strategy.

9.3.1 Field water balance

Important components of field water balance are given in Table 9.2. From the table it is observed that there is not much variation in the field water balance components among different strategies. Whatever variation occurs is due to changes in the tank sizes for different strategies making different areas available for field water balance. Area irrigated was about 12.79 ha among different simulated strategies as against 13.33 ha in evaluation study. Volume of irrigation water was less in the tank strategies which consist of tank type 1 (i.e. tank strategy No 50 and 1805) since only downstream area comes under tank command (property of tank type). Runoff and deep percolation were fairly uniform and they averaged 18.95 and 10.61% of rainfall in different simulated tank strategies whereas these components were 18.90 and 10.62% in the existing tank strategies indicating not much variation in these components in the alternative tank strategies.

Table 9.2 Field water balance components for Akola watershed

Strategy	Area Irrigated, ha	Irrigation volume, m^3	Runoff**	DP**
1	12.71	14703.30	18.90	10.70
50	12.97	12598.24	19.04	10.50
58	12.97	14826.73	19.04	10.55
1805	12.69	12493.88	18.90	10.61
1926	12.70	14680.34	18.91	10.67
2047	12.70	14676.12	18.91	10.66
1926 (Evaluation mode)	13.33	14767.32	18.90	10.62

(** per cent of rainfall)

9.3.2 Tank capacities

In simulation mode tank capacities are computed for the given tank strategy and management options like irrigation strategy and DSR criterion. These estimated tank capacities for different strategies are given in Table 9.3. From the table it is observed that in the case of six number of tanks which existed in the watershed (tank strategy No 1926), the existing tank capacities at stream point no. 1 and 4 were less than the optimum simulated sizes whereas tank capacities at stream point no 2 and 3 were higher than optimum simulated sizes. Trenches are present in the catchments of tanks at stream point no. 2 and 3 hence simulated optimum sizes are less. Though the total storage capacity in the simulated tank strategy No 1926 was 1.11 times existing storage capacity, the variation in individual tank capacities ranged from 0.12 to 1.95 times the existing tank capacities. Hence with the help of the proposed methodology it is possible to get more appropriate tank sizes for each stream point according to the conditions in the watershed around that stream point.

Table 9.3 Tank capacities for different strategies for Akola watershed

Strategy\Tank No.	Tank 1	Tank 2	Tank 3	Tank 4	Tank 5	Tank 6	Total storage capacity, m^3
1	6691.09	--	--	--	--	--	6691.09
50	--	965.48	--	--	6538.05	--	7503.53
58	--	963.99	--	--	6531.44	--	7495.44
1805	1429.50	144.19	129.98	1505.72	1210.69	835.92	5256.00
1926	1948.80	112.96	104.31	1357.12	1121.43	691.78	5336.40
2047	1399.33	147.45	137.25	1460.39	1311.67	843.79	5299.88
1926 (existing condition)	999.92	917.73	487.52	655.72	1185.59	577.95	4824.43

9.3.3 Tank system water balance

Tank system water balance components are given per unit tank capacity in Table 9.4. The tank water balance components in the existing and simulated tank strategy No 1926 show that there are little increases in all the water balance components in the simulated strategy over the existing one. The other tank strategies show that as the number of tanks in the watershed decreases, the irrigation volume per unit tank capacity increases and tank strategy No.1 which consists of one tank at the outlet of the watershed gives maximum irrigation volume among the different tank strategies.

It is also observed from Table 9.3 and Table 9.4 that tank capacities in the case of tanks in strategy No 50 and 58 are more and hence inflow per unit tank capacity is less as compared to other strategies. In these strategies tanks are located at stream points no 2 and 5 which are at the middle of the watershed. Tank sizes are optimised for the given DSR. In these strategies some runoff from the downstream of the tanks directly contributed to the DSR at the watershed outlet. Hence tank sizes get increased so that less overflow is allowed from these tanks to meet the DSR at the outlet of the watershed. Hence to satisfy the downstream release criterion of 65% these tank sizes get increased.

Table 9.4 Tank system water balance components (m^3/m^3) for Akola watershed

Strategy	Inflow*	Irrigation	Evaporation	Seepage
1	8.02	1.14	0.25	1.50
50	3.57	0.76	0.22	1.33
58	3.58	0.79	0.21	1.31
1805	9.40	0.34	0.41	2.49
1926	9.84	0.47	0.41	2.48
2047	9.14	0.37	0.41	2.46
1926 (EM**)	9.41	0.41	0.29	1.71

*(*Water balance components are expressed in volume per unit volume of tank capacity,**EM = evaluation mode)*

Inflow per unit tank capacity for different tanks in strategy No 1926 (Table 9.5) varied from 4.31 to 43.20 in the case of existing tank sizes whereas it varied from 17.12 to 26.97, with the proposed methodology indicating better tank sizes throughout the watershed.

Table 9.5 Inflow per unit tank capacity for individual tanks for strategy no. 1926

Tank No	Inflow /capacity (existing size)	Inflow/capacity (simulated size)
1	36.40	26.97
2	4.31	29.81
3	6.95	26.89
4	43.20	22.94
5	15.49	17.12
6	20.73	20.76

9.3.4 Groundwater balance

The table 9.6 shows the relative contribution of different inflows to and outflows from the groundwater reservoir. They are fairly uniform in all the strategies except in strategy 1 where there is significant contribution due to field recharge. In this strategy there is only one tank at the watershed outlet, hence field recharge is more and tank recharge is less as compared to other strategies.

Table 9.6 Groundwater balance components for Akola watershed

Strategy	FR	TR	TrR	Irrigation	Other use	Groundwater flow
1	61.27	12.99	25.74	20.87	2.32	76.81
50	53.39	24.00	22.62	17.67	2.24	80.09
58	53.81	23.51	22.68	21.41	2.19	76.39
1805	51.85	26.37	21.78	22.26	2.17	75.57
1926	53.03	24.80	22.16	25.59	2.14	72.27
2047	51.94	26.32	21.74	25.87	2.12	72.01
1926(EM)	54.04	23.76	22.19	25.74	2.17	72.09

(FR = Field recharge, TR = Tank recharge, TrR = Trench recharge, Recharge components are per cent of total groundwater recharge and outflow components are per cent of total groundwater outflow)

9.3.5 Project economics

Total annual costs, benefits and benefit-cost (BC) ratios for different tank strategies are given in given in Table 9.7. In the case of tank strategy No 1926 there is no significant difference in the BC ratio between the existing and simulated tank strategy. But when compared with other strategies then BC ratio increased with decreasing number of tanks. Tank strategy No 1 with one tank at the outlet of the watershed gave maximum BC ratio of 1.80. Therefore the analysis suggests that one tank at the outlet of the watershed would have given higher profits in the Akola watershed than the existing six small tanks. The economics show that the higher BC ratio for tank strategy No 1 is because of decreased cost of the project due to higher storage excavation ratio for the tank at the outlet (see Section 6.3.7.2 for discussion on storage excavation ratio).

Table 9.7 Project economics for different tank strategies for Akola watershed

Strategy	Incremental cost, Rs	Incremental benefits, Rs	Benefit cost ratio
1	173786	312656	1.80
50	179137	312262	1.74
58	179166	312262	1.74
1805	183424	308014	1.68
1926	183450	308124	1.68
2047	183453	308124	1.68
1926 (EM)	185657	317682	1.71

9.3.6 Conclusion

The comparative study of simulated tank strategies with the existing tank strategy in the Akola watershed has shown that there is no significant difference in the BC ratio between the simulated and existing tank strategy No 1926. However the tanks capacities in the simulated strategy are more appropriate than the existing tank capacities since these tank capacities are optimised for the watershed conditions around the tanks. When other simulated tank strategies are compared, tank strategy No 1 with one tank at the outlet of the watershed gave better BC ratio among the different strategies studied. Hence one tank at the outlet of the watershed with capacity of 6690 m^3 would have given higher net benefits than the existing strategy of six small tanks.

It is to be noted here that the analysis is presented above to show the utility of the SOFTANK model for such kind of analysis. In practice however when a tank system exists in the watershed, we have very limited options (or no options at all) to make changes in the physical tank system. Therefore it is always advisable to study the changes in the management options than the changes in the tank strategy. This aspect was considered for the Pimpalgaon Ujjaini watershed and the simulations were carried out with two options about the source of water for irrigation i.e. only groundwater and tank and groundwater both. The results are discussed in the next section.

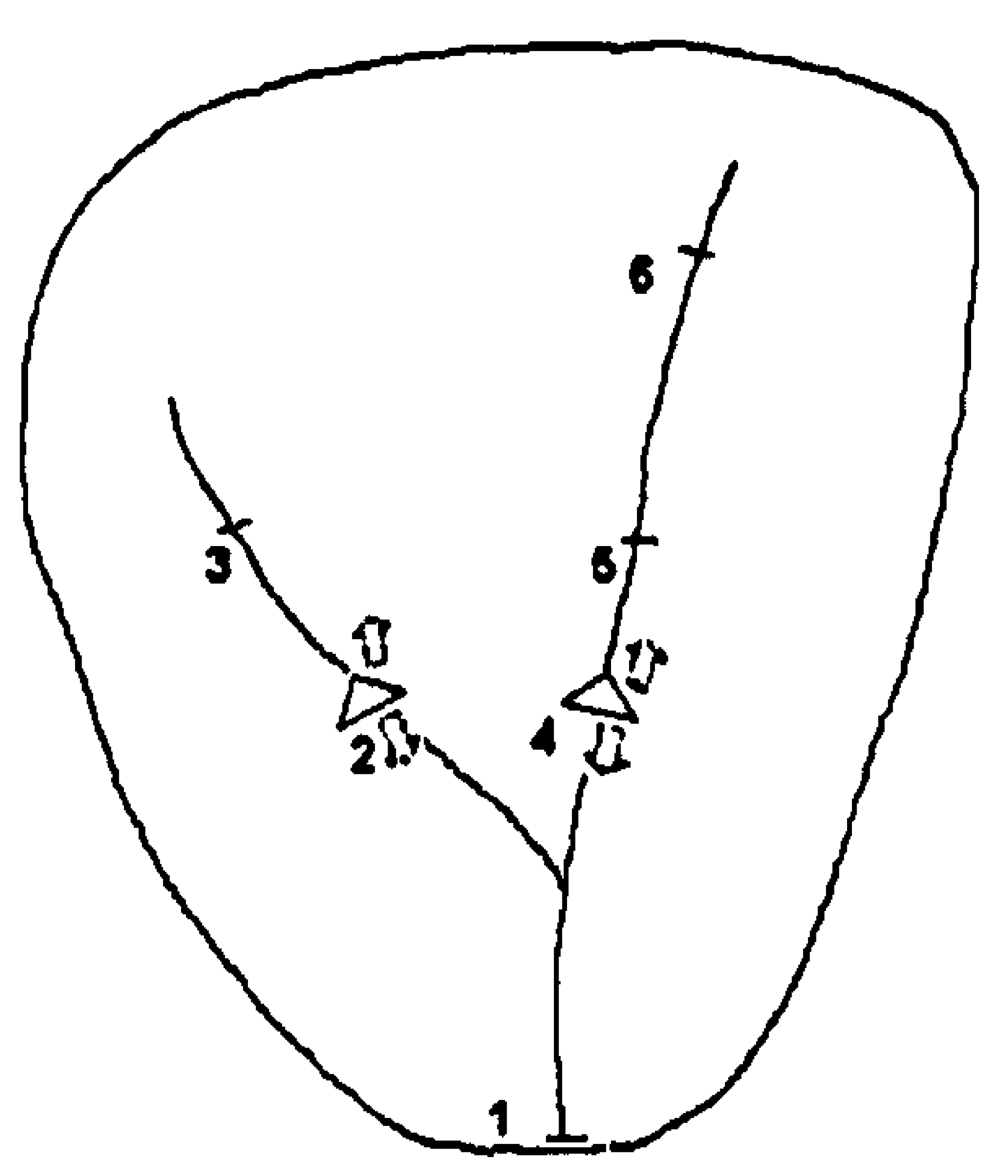
9.4 Simulation of alternate tank strategies for Pimpalgaon Ujjaini watershed

From the evaluation of the existing tank systems in the Pimpalgaon Ujjaini (PU) watershed, it was found that the tanks were over designed as the inflow capacity ratios were very less for these tanks. Six stream points were identified for the tanks and the tank strategies considered for simulation for Pimpalgaon Ujjaini watershed are given in Table 9.8. Only two tanks at different stream points were considered for the watershed. The tanks in the watershed are used for groundwater recharge only therefore two management options for the source of irrigation water were considered. One option was with the use of only groundwater (existing case) and other option with the use of both tank and groundwater. Hence there were three tank strategies and two management options resulting in six combinations. The description of the tank strategies is given in the table and the strategies are illustrated in Fig 9.2. Comparison of these strategies will help in deciding the proper location of the tanks in the watershed and the policy of managing the water resources for irrigation in the watershed.

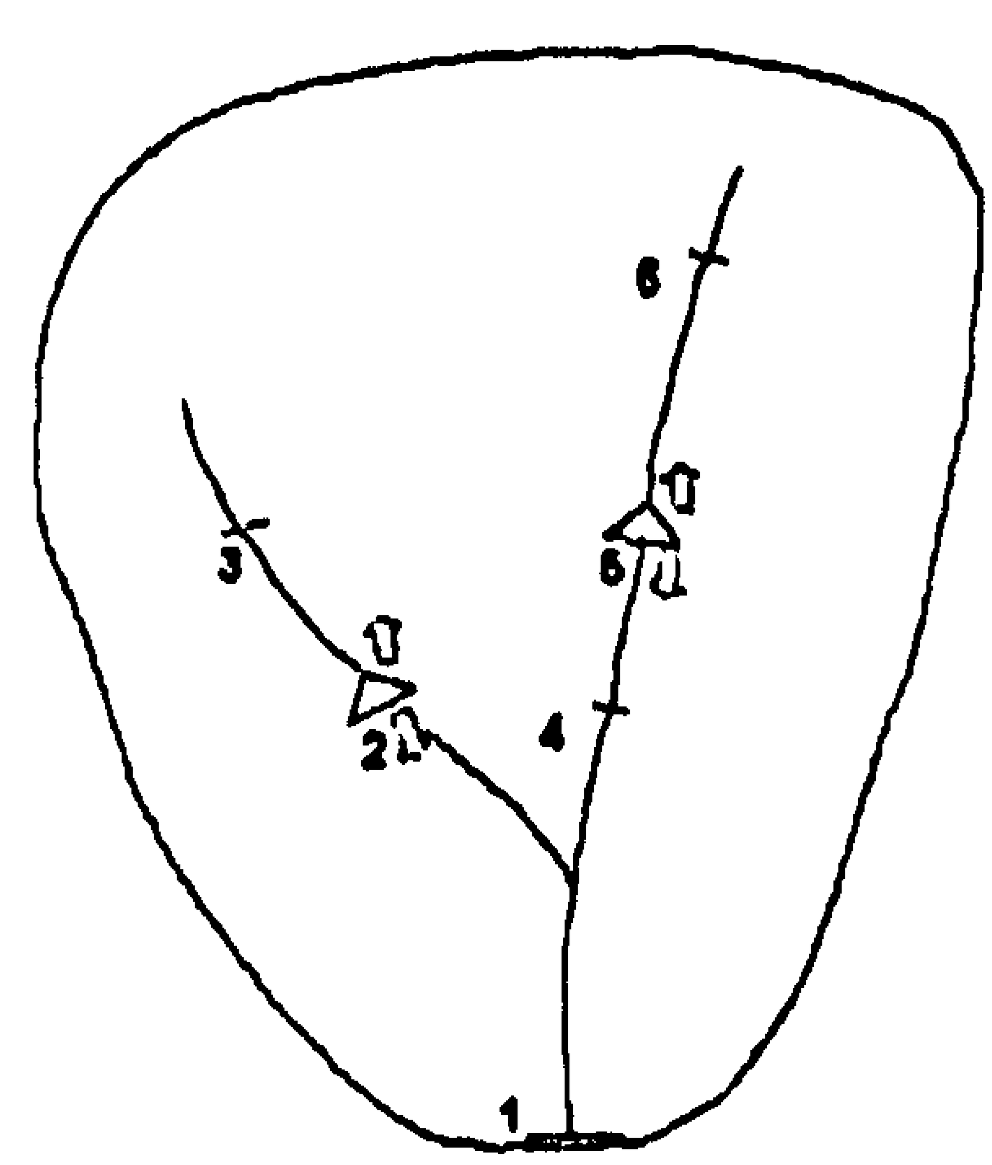
Table 9.8: Alternate tank strategies for Pimpalgaon Ujjaini watershed

Tank strategy No	No. of tanks	Tank strategy details Tank No-Stream point No-Tank type	Source of water for Irrigation	Tank strategy description
49gw*	2	1-2-3 2-4-3	Only groundwater	Two tanks of type 3 at stream point No 2 and 4
49gtw	2	1-2-3 2-4-3	Tank and groundwater both	Two tanks of type 3 at stream point No 2 and 4
58gw	2	1-2-3 2-5-3	Only groundwater	Two tanks of type 3 at stream point No 2 and 5
58tgw	2	1-2-3 2-5-3	Tank and groundwater both	Two tanks of type 3 at stream point No 2 and 5
94gw	2	1-3-3 2-6-3	Only groundwater	Two tanks of type 3 at stream point No 3 and 6
94tgw	2	1-3-3 2-6-3	Tank and groundwater both	Two tanks of type 3 at stream point No 3 and 6
94gw (EM)	2	1-3-3 2-6-3	Only groundwater	Two tanks of type 3 at stream point No 3 and 6

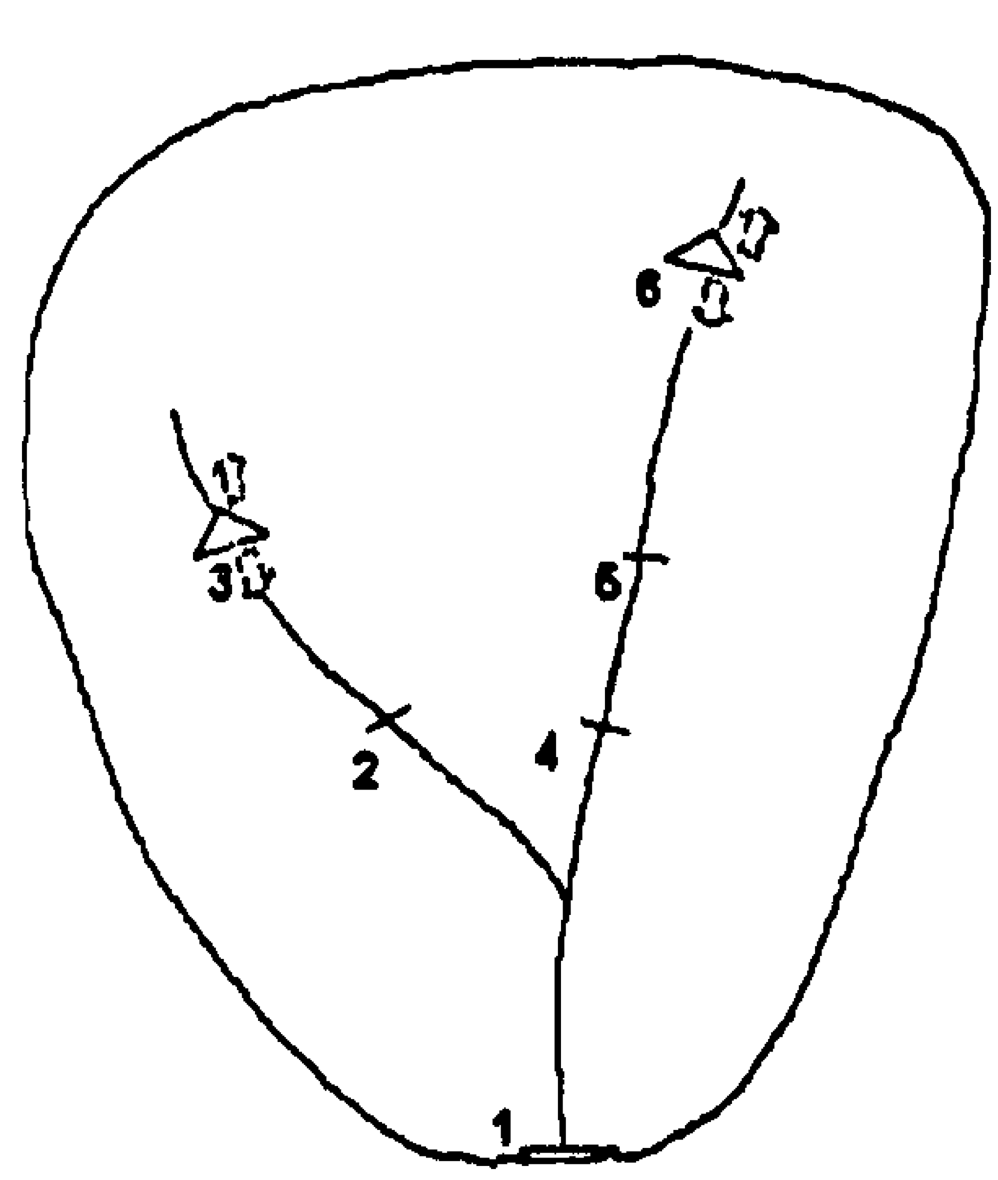
**(Tank strategy No is suffixed with management option for convenience of discussion)*



(a) Tank strategy No 49



(b) Tank strategy No 58



(c) Tank strategy No 94

Figure 9.2 Illustration of tank strategies for Pimpalgaon Ujjaini watershed

The above tank strategies were simulated for 29 years climatic data (1976-2004) for Pimpalgaon Ujjaini (PU) watershed. The DSR obtained in evaluation of the existing tank strategy was 58.52. Hence simulations were carried out for 58% DSR with 5% deviation allowed in the DSR value. The resulting DSR obtained for different simulated strategies were 58.01, 59.39, 57.45, 58.26, 61.84 and 61.87% for strategies 49gw, 49gtw, 58gw, 58tgw, 94gw, and 94tgw respectively. The data used for simulating the tank strategies were the same as that used for evaluation of tank strategies. Only difference is that the tank sizes are optimised in the simulation mode whereas existing tank sizes were considered in the evaluation mode. Following paragraphs discuss the water balance and project economics of these tank strategies in comparison to the existing tank strategy for the Pimpalgaon Ujjaini watershed. In the case of tank strategy No 94 tank sizes could be simulated only during 17 years out of the total 29 years due to the DSR criterion. The years in which DSR criterion was not satisfied, tank sizes were not simulated.

9.4.1 Field water balance

Important components of field water balance are given in Table 9.9. As mentioned earlier, in the case of tank strategy No 94, tank sizes could be simulated only for 17 years out of 29 years in order to meet the DSR criteria and therefore while comparing the indicators of these tank strategies with those in evaluation mode, data for only those years from evaluation study were considered for which tanks sizes were simulated in the simulation mode. These years were. 1975-76, 1977-78, 1980-81, 1981-82, 1983-84, 1984-85, 1987-88, 1988-89, 1989-90, 1990-91, 1991-92, 1995-96, 1996-97, 1999-2000, 2000-01, 2001-02, 2002-03. For other strategies tank sizes were simulated for all the years and hence evaluation results were also considered for all the years. From the table it is observed that the field water balance components are fairly uniform in all the strategies. Since percolation tanks were considered as type 3 tanks (tanks with command area on upstream and downstream side) in the methodology all the cultivable area in the watershed comes under the command of the tanks irrespective of their positions in the watershed.

Table 9.9 Field water balance components for PU watershed

Strategy	Area Irrigated, ha	Irrigation volume, m^3	Runoff**	DP**
49gw	727.62	2015535	21.42	20.89
49tgw	729.84	2055774	21.44	21.05
58gw	727.39	2014249	21.43	20.82
58tgw	729.35	2054713	21.45	21.01
94gw (17 yrs)	714.93	2098959	26.73	22.83
94tgw(17 yrs)	714.93	2003136	26.08	22.01
94gw (EM*)				
(29 years average)	712.74	1995317	21.51	20.52
(17 years average)	712.74	2056557	26.78	22.49

** EM: Evaluation mode ** per cent of rainfall*

9.4.2 Tank capacities

Tank capacities for different strategies were estimated in simulation mode and are given in Table 9.10. From the table it is seen that tank capacities are less for the tank strategy No 49 in which tanks are located in the lower part of the watershed. As tanks move upstream (as in strategy No 58 and 94) tank capacities increases to meet the DSR criterion. Storage capacities are more by 1.77 to 2 times when water in the tank is not used for irrigation as compared to when it is used for irrigation along with groundwater irrigation. In the case of strategy No 94 where the tanks are further upstream, tank capacities are found same for both the management options of groundwater use and tank and groundwater use for irrigation. This is due to the requirement of meeting the 58% DSR criterion. Storage capacity obtained by simulation is 1.27 times that of existing storage capacity in the case of tank strategy No. 94gw (existing strategy and management option). Major difference is found in the capacity of tank No 2 where the simulated tank capacity is about 2.5 times of the existing tank capacity. Inflow capacity ratios for simulated tank capacities are uniform for both tanks whereas they differ (0.61 and 1.51) in the existing tank system. This again indicates that in the proposed methodology tank capacities are more appropriate with the supply and demand parameters of the tank.

Table 9.10 Tank capacities for Pimpalgaon Ujjaini watershed

Strategy\Tank No.	Tank 1	Tank 2	Total storage capacity, m^3	Inflow/capacity ratio Tank-1	Tank-2
49gw	198100.36	313495.00	511595.36	2.93	2.86
49tgw	104665.57	147226.74	251892.31	6.03	6.18
58gw	259241.53	278848.49	538090.03	2.26	2.27
58tgw	150366.28	153193.01	303559.29	4.47	4.05
94gw (17 yrs)	654411.46	505664.21	1160075.67	0.74	0.81
94tgw(17 yrs)	654411.46	505664.21	1160075.67	0.74	0.81
94gw (Evaluation)	695876.69	216937.45	912814.14	0.61	1.51

9.4.3 Tank system water balance

Tank system water balance components per unit tank capacity are given in Table 9.11. All the balance components decrease as the tanks move upstream. Maximum irrigation water is available for the strategy No 49, in which tanks are in the downstream reaches of the watershed and used for irrigation. Evaporation and seepage are much less when water in the tanks is used for irrigation. Here it needs to be emphasized that since tank optimization is governed by the DSR as the tanks move upstream they are optimised such that the DSR at the watershed outlet is maintained at the assigned level. Hence tank capacities tend to increase from downstream to upstream of the watershed. (This is contrary to the intuition of less tank capacities at the upstream part of the watershed than at the downstream part). Due to increase in tank capacities the water balance components per unit tank capacity decreases as tanks move upstream in the watershed.

Table 9.11 Tank system water balance components (m^3/m^3) for PU watershed

Strategy\Tank No.	Overflow*	Evaporation	Seepage	Irrigation	Storage
49gw	1.32	0.20	1.08	0.00	0.04
49tgw	2.81	0.07	0.43	2.50	0.03
58gw	0.73	0.19	1.05	0.00	0.03
58tgw	1.38	0.07	0.41	2.13	0.02
94gw (17 yrs)	0.00	0.12	0.63	0.00	0.01
94tgw(17 yrs)	0.00	0.03	0.19	0.54	0.00
94gw (EM)	0.04	0.11	0.68	0.00	0.00

*(*Water balance components are expressed in volume per unit volume of tank capacity)*

9.4.4 Groundwater balance

Groundwater balance components for the watershed are shown in Table 9.12. From the table it is observed that field recharge is more (and tank recharge less) as the tanks are used for irrigation purpose since water remains for less time period in the tanks when they are used for irrigation. The water balance components for the existing strategy (Strategy No 94gw) and the simulated strategy do not show any difference. Water balance components for different strategies are uniform irrespective of the location of tanks in the watershed.

Table 9.12 Groundwater balance components for PU watershed

Strategy	FR*	TR	Irrigation	Other use	Groundwater flow
49gw	77.60	22.40	68.79	1.31	29.90
49tgw	94.58	5.42	58.07	1.38	40.55
58gw	77.06	22.94	68.74	1.31	29.95
58tgw	93.29	6.71	57.77	1.37	40.86
94gw (17 yrs)	72.66	27.34	63.15	1.15	35.71
94tgw(17 yrs)	88.73	11.27	52.82	1.27	45.91
94gw (EM)	71.08	28.92	65.53	1.21	33.26

(FR: Field recharge, TR: Tank recharge, Recharge components are per cent of total groundwater recharge and outflow components are per cent of total groundwater outflow)

9.4.5 Project economics

Abstract of economic analysis for different tank strategies is given in Table 9.13. The analysis was carried out by considering the life of project as 30 years and 1975-76 as the base year. From the table it is seen that BC ratios are higher when tanks are used for both irrigation and recharge than only for recharge. The BC ratios of simulated strategies are more than the existing strategy. BC ratio was found maximum (1.57) in the case of tank strategy No 49 when tanks are used for irrigation.

Table 9.13 Project economics for different tank strategies for PU watershed

Strategy	Initial cost, Rs	Maintenance cost, Rs	Incremental cultivation cost, Rs	Total incremental cost, Rs	Incremental benefits, Rs	BC ratio
49gw	889296	35572	10087557	11012425	17004343	1.54
49tgw	822410	32896	10050622	10905928	17089597	1.57
58gw	902221	36089	10068447	11006757	16995465	1.54
58tgw	842915	33717	10033915	10910547	17077597	1.57
94gw (17 yrs)	1046232	41849	9780512	10868593	16820405	1.55
94tgw (17 yrs)	1061280	42451	9698533	10802264	16820553	1.56
94gw (EM)	1200984	48039	11035725	12284748	16455873	1.34

Hence if the tanks were located at stream point No. 2 and 4 and both tanks were used for irrigation then it could have given higher benefits than existing strategy and management. The BC ratio of the tank strategy No 94gw is higher (1.55) in simulation mode than in the evaluation mode (1.34). For evaluation the data of all the climatic years were considered while in simulation, model simulated tank strategies only for 17 years. Hence they can not be compared with different length of data series.

9.4.6 Conclusion

The water balance analysis and project economics of the Pimpalgaon Ujjaini tanks show that tank location and capacities of the existing tank system are less appropriate with the supply and demand parameters. Tanks are oversized. Constructing the tanks further downstream at stream point No 2 and 4 with capacities of 104666 and 147227 m^3 and using the tanks for recharge as well as irrigation could have given higher BC ratio of 1.57 than the existing1.34.

9.5 Investigation of Hypothesis No 3.

In this study the concept of integrated water storage system (IWSS) was proposed in the first Chapter according to which three storage media in the watershed i.e. soil, tank and aquifer should be considered together to make optimum use of available water for crop production in the watershed. Though the approach of integrated watershed management (discussed in Chapter 2) is based on this concept, the practices are adopted with thumb rules and empirical guidelines. From the case studies described in Chapter 2, the integrated effect of these storages has been reported in terms of overall benefits in the watershed like rise in groundwater table, increase in number of wells, irrigated area and crop production in the watershed. But details on individual storages in the watershed were not reported. If effect of these storages on each other and the water balance in the watershed is known, then it will be possible to use them optimally. Since literature was lacking on this aspect a hypothesis was proposed in this research which states that -

"There is a need for integrating different storage systems (soil, tank and aquifer) while optimizing the use of available water for crop production and thus in turn for the optimum design of tank system".

Therefore an investigation was made in this study to see the effect of changes in one storage system on the other storage systems and the overall water balance in the watershed. Analysis was made by performing simulations for the following cases. The test case was Akola watershed and simulations were carried out for the year 2002-03 with the DSR of 65% (existing DSR in the watershed).

- Tank strategy
    - Tank strategy No 1 (T_1) and
    - Tank strategy No 1926 (T_{1926}) (existing tank strategy)

- Land uses:
    - Horticulture crops (L_H) (existing land use) and
    - Field crops (L_F)

- Drainable porosity
    - Drainable porosity = 0.1 ($P_{0.1}$) (existing drainable porosity) and
    - Drainable porosity = 0.05 ($P_{0.05}$)

These different cases were selected with the intention to induce changes in the properties of three storages in the watershed. Tank strategy affects the tank storage hence two tank strategies i.e. tank strategy No 1 and 1926 were selected. Tank strategy No 1 consists of only one tank at the outlet of the watershed whereas tank strategy No 1926 consists of six tanks at six stream points (all of type-2) in the watershed (existing case in the watershed). Land use affects soil storage, hence two land use cases of field crops and horticultural crops (existing land use) were selected. Drainable porosity is the volume of water that will drain from a fully saturated material under the influence of gravity. Thus aquifers with different drainable porosity values will have different aquifer storage Hence two drainable porosity values i.e. 0.1 (existing) and 0.05 were selected for the analysis. The results are discussed below in terms of different water balances in the watershed.

9.5.1 Tank water balance

Tank water balance components are given in Table 9.14. From the table it is seen that tank storage was found more in the case of tank strategy No 1 than the tank storage in tank strategy No 1926 for both land uses and drainable porosity values. It was more by about 1.7 times in the case of tank strategy No 1 than that of tank strategy No 1926 for land use of field crops where as it was more by 1.3 times in the case of horticulture. Drainable porosity did not affect the tank storage capacity. Tank storage was 6784 and 3842 m^3 for tank strategy No 1 and 1926 respectively for field crops whereas these values were 4766 and 3631 for horticulture crops. Tank irrigation was found more by a factor of 3 in the case of strategy No 1 than that of strategy 1926 for both the land use. Drainable porosity had no effect on the tank irrigation. Tank seepage and evaporation losses were more in the case of tank strategy No 1926 than tank strategy No 1.

Table 9.14: Tank water balance components for different storage treatments in Akola watershed

Treatment	Total tank storage capacity (m^3)	Inflow (m^3)	Overflow (m^3)	Evaporation (m^3)	Seepage (m^3)	Irrigation (m^3)
$T_1 L_F P_{0.1}$	6784	45036	27138	871	5542	11485
$T_{1926} L_F P_{0.1}$	3842	44927	32508	1166	7330	3923
$T_1 L_H P_{0.1}$	4766	29042	16606	914	5774	5748
$T_{1926} L_H P_{0.1}$	3631	29426	19281	1127	7160	1858
$T_1 L_F P_{0.05}$	6784	41323	23642	834	5362	11485
$T_{1926} L_F P_{0.05}$	3812	41339	29195	1107	6993	4045
$T_1 L_H P_{0.05}$	4766	29042	16606	914	5774	5748
$T_{1926} L_H P_{0.05}$	3631	29426	19281	1127	7160	1858

9.5.2 Field water balance

Field water balance components are presented in Table 9.15. From the table it is seen that irrigation applied is about 4 times more in the case of field crops than that of horticultural crops. Irrigation volume available was more in the case of tank strategy No 1 than that of tank strategy No 1926. Drainable porosity did not affect the irrigation volume. Runoff was about 1.5 times more in field crops than the runoff in horticultural crops. Evapotranspiration was more in field crops than that in horticultural crops. Drainable porosity affected the deep percolation from field. Deep percolation was 1.3 times more when drainable porosity was 0.1 than the deep percolation when drainable porosity was 0.05 for field crops.

Table 9.15: Field water balance components for different storage treatments in Akola watershed

Treatment	Irrigation (m^3)	Runoff (m^3)	Evapotranspiration (m^3)	Deep percolation (m^3)
$T_1 L_F P_{0.1}$	53858	43463	148782	24456
$T_{1926} L_F P_{0.1}$	50328	42954	145261	27216
$T_1 L_H P_{0.1}$	13278	27742	142931	13932
$T_{1926} L_H P_{0.1}$	13259	27645	142601	13798
$T_1 L_F P_{0.05}$	41042	39763	147343	18577
$T_{1926} L_F P_{0.05}$	36610	39412	141198	22813
$T_1 L_H P_{0.05}$	13278	27742	142931	13932
$T_{1926} L_H P_{0.05}$	13259	27645	142601	13798

9.5.3 Groundwater balance

Ground water balance components are presented in Table 9.16. From the table it is seen that recharge through field and tank were more in tank strategy No 1926 than these recharges in tank strategy No 1 for both the land use and drainable porosity. Combine field and tank recharge was 33781 m^3 in tank strategy No 1926 whereas it was 27227 m^3 in tank strategy No 1 for field crops. Effect of drainable porosity on field and tank recharge was found in field crops but not in horticulture crops. Groundwater irrigation was more in tank strategy No 1926 than that in tank strategy No1.

Table 9.16: Groundwater balance components for different storage treatments in Akola watershed

Treatment	Field recharge (m^3)	Tank recharge (m^3)	Trench recharge (m^3)	Irrigation (m^3)	Other use (m^3)	Groundwater flow (m^3)
$T_1 L_F P_{0.1}$	24456	2771	0	42373	1095	9408
$T_{1926} L_F P_{0.1}$	27216	6565	0	46405	1095	10715
$T_1 L_H P_{0.1}$	13932	2887	5788	7530	1095	31139
$T_{1926} L_H P_{0.1}$	13798	6225	5770	11401	1095	30696
$T_1 L_F P_{0.05}$	18577	2681	0	29557	1095	4001
$T_{1926} L_F P_{0.05}$	22813	6295	0	32565	1095	6447
$T_1 L_H P_{0.05}$	13932	2887	5788	7530	1095	20291
$T_{1926} L_H P_{0.05}$	13798	6225	5770	11401	1095	19858

9.5.4 Trench water balance

Trenches were present with the land use of horticulture in the micro-catchments 2 and 3. However there was no effect of changes in tank storage and drainable porosity on the trench water balance. Inflow to the trench was 12315 m^3 and deep percolation from the trench was 5770 m^3.

9.5.5 Economics

Land use and tank strategy affected the BC ratio. BC ratio was 1.80 for horticultural crops whereas it was 1.27 for field crops when tank strategy was 1. These values were 1.72 and 1.15 respectively for tank strategy No 1926.

9.5.6 Conclusion

From the above findings, it is observed that any change in one storage system affects the other storage systems and consequently the water balances in the watershed. For example when land use changes from horticulture to field corps irrigation requirement is increased. This increased irrigation requirement affects the tank and groundwater storages and is met differently when tank strategy changes. When tank strategy changes it affects the groundwater storage through changes in field and tank recharge. Changes in drainable porosity, affects the recharge to groundwater. Therefore any change in one storage system affects the other two storage systems. Hence these storages should be considered together in order to make the efficient use of harvested rainwater in the watershed. Therefore the hypothesis that "there is a need for integrating different storage systems (soil, tank and aquifer) while optimizing the use of available water for crop production and thus in tern for the optimum design of tank system" is accepted.

9.6 Closure

The 'simulation' utility of the SOFTANK model is demonstrated with the help of two case study watersheds in this Chapter. Alternate tank strategies were simulated for Akola watershed and alternate tank strategies and management options were simulated for Pimpalgaon Ujjaini watershed. Findings of the study suggested that there is scope to improve the performance of tank systems in both the watersheds. With the simulation mode, the investigation of hypothesis-3 was performed and the hypothesis - "there is a need for integrating different storage systems (soil, tank and aquifer) while optimizing the use of available water for crop production and thus in turn for the optimum design of tank system" was accepted.

When tank systems are constructed many times circumstances change during the course of time. For example in situ RWH systems are constructed in the catchments, of these tanks, upstream-downstream conflict for water availability occurs, groundwater extraction becomes unsustainable (at present there is no restriction on groundwater use in India), changes in the land use pattern due to increased water availability etc. With the help of simulation utility of the SOFTANK model it is possible to analyse these changes in the watershed. Therefore it is concluded that the simulation utility of the SOFTANK model enables the analysis of different scenarios (or changes) which affect the tank system in the watershed. Such analysis is important especially to improve the performance of the existing tank systems as discussed in this Chapter or to adapt to the changes in the watershed. Next chapter discusses the optimum tank strategies for these watersheds.

Chapter-10

OPTIMIZATION OF TANK SYSTEMS FOR THE WATERSHEDS

10.1 Summary

This chapter discusses the optimum tank systems for Akola and Pimpalgaon Ujjaini watersheds as derived with the SOFTANK model. Optimum tank systems are derived and discussed for existing conditions for both the watersheds.

10.2 Introduction

Optimum tank systems are the best tank systems for the watershed under given conditions. Optimum tank systems were derived for the existing land use, land treatment and the way tanks are used for both the Akola and Pimpalgaon Ujjaini (PU) watersheds. The details about the different aspects of these watersheds are presented in Chapter 7 and 8. A quick review of both the watersheds is presented below.

Akola watershed is a small watershed of 28 ha with six small tanks. Land use in the watershed mainly consists of horticulture and silvipasture plantations. Irrigations to the horticultural crops are given through drip system. No irrigation is given to the silvipasture plantations. Field crops are taken on small area where irrigation is provided by surface methods. Source of irrigation is both the tank water and groundwater. Continuous contour trenches are present in the catchments of tank No 2 and 3. In the evaluation study it was found that with the existing tank system and water use the downstream release (DSR) from the watershed was around 66%. The tank capacities were found less appropriate with the supply and demand parameters of the tanks. When alternate tank strategies were simulated for this watershed, it was found that one tank at the outlet of the watershed would have given higher net benefits than the existing tank system of six tanks in the watershed.

Pimpalgaon Ujjaini (PU) watershed is a large watershed with 1326 ha area. There are two percolation tanks at the middle of the watershed. Land use in the watershed consists of common field crops. There are no *in situ* RWH systems in the catchments of the tanks. Tanks are used for recharging the groundwater hence water from the tanks is not used for irrigating the crops in the watershed. Source of irrigation is mainly groundwater. In the evaluation study it was found that with the present tank system and water use pattern, the DSR from the watershed was about 59%. In the evaluation study it was found that both the tanks in the watershed were over designed. Alternate tank strategies and management options were simulated for the watershed and it was found that alternate locations of tanks and use of tanks for both irrigations and groundwater recharge would have given higher net benefits than the existing tank locations and management.

10.3 Optimization of tank systems

As discussed in Chapter 6, the optimum tank systems for the watershed were derived by repetitive simulation (see Section 6.4.1). Optimum tank systems for the watershed were derived by running the 'SOFTANK' model in Simulation-Optimization mode. This consists of obtaining the optimum tank strategy for each climate year and then evaluating the optimum tank strategy of each climatic year for remaining climatic years (optimization mode). By performing this, the net benefits/DSR for each climate year were obtained for the optimum tank strategy of all the climatic years. The average of the net benefit and DSR values obtained over the entire climate series for optimum tank strategy of particular climatic year were considered as the net benefit/DSR values of this tank strategy. However if the average DSR in the optimization mode was within the input DSR with deviation (e.g. 30 ± 10%) the strategy was selected as the optimum strategy. If it was not within the range of input DSR then the strategy with next highest maximum net benefits (in simulation mode) was considered and again the strategy was evaluated for all the climatic data years in the optimization mode. The process was repeated till the output DSR was within the range of input DSR. Thus the model gave 28 optimum tank strategies for 28 years for Akola watershed and 29 optimum tank strategies for 29 years for Pimpalgaon Ujjaini (PU) watershed. If a particular tank strategy repeated as the optimum tank strategy for different years, it was treated as different tank strategy for the optimization purpose since the dimensions of the tanks were different (though the strategy was the same). Finally the tank strategy giving maximum average net benefits was selected as the optimum tank strategy for the given DSR. The process was repeated for a range of DSR values between 0 and 100%. It is suggested to avoid the DSR values of 0 and 100 % for simulation since these are the extreme cases. In the case of zero DSR tank sizes are optimised so that all the rain and runoff are harvested. This results in exceptionally high and unrealistic tank sizes. For example when the SOFTANK was run for zero DSR in the present investigation it resulted into a tank capacity of 264589 m^3 for a watershed of 28 ha! This is equivalent to storing rainfall of 945 mm falling over the watershed at one time. Though I got such sizes during high rainfall years (rainfall more than 900 mm), the tank sizes obtained were unrealistic.

The case of 100% DSR means no water is harvested and hence tank system is not necessary. Therefore it is suggested to avoid these extreme cases. And I have not rigorously tested SOFTANK to handle these extreme cases.

10.3.1 Optimum tank system for Akola watershed

Optimum tank strategy for Akola watershed was derived by running SOFTANK model in Simulation-Optimization mode as described in previous section. The yearly optimum strategies derived are given in Table 10.1. Final optimum strategy was selected from these yearly strategies that gave maximum average net benefits for 28 years. From the table it is seen that tank strategy No 1 is the most frequently occurring strategy for almost all the years and all the DSR levels. The optimum tank strategies obtained for different DSR levels for Akola watershed are given in Table 10.2.

Table 10.1 Yearly optimum tank strategies for different DSR for Akola watershed

Year	Rainfall, mm	DSR values,%									
		10*	20	30	40	50	60	70	80	90	95
1976-77	760.4	1	1	1	1	1	1	1	1	1	1
1977-78	1075.3	1	1	1	1	1	1	1	1	1	13
1978-79	914.5	1	1	1	1	1	1	1	1	1	1
1979-80	840.7	1	1	26	1	1	1	1	1	1	1
1980-81	707.9	1	1	1	1	1	1	1	13	1	1
1981-82	967.7	1	1	26	26	1	1	1	13	1	1
1982-83	551.9	1	1	1	1	1	1	1	1	1	1
1983-84	842.5	1	1	1	1	1	1	1	1	1	1
1984-85	538.0	1	1	1	1	1	1	1	1	1	1
1985-86	700.5	1	1	1	26	1	1	1	1	1	1
1986-87	817.4	1	1	1	392	27	1	1	1	1	1
1987-88	739.3	1	1	1	1	1	1	1	1	1	1
1988-89	1372.0	1	1	1	69	405	26	1	13	1	1
1989-90	747.3	1	1	1	1	1	1	1	1	1	1
1990-91	1019.3	1	1	1	376	1	1	1	1	1	1
1991-92	454.0	1	1	1	1	1	1	1	1	1	1
1992-93	977.4	1	1	28	1	1	1	1	1	1	1
1993-94	893.2	1	1	1	1	1	1	1	13	1	13
1994-95	1011.2	1	1	1	1	1	1	1	1	1	1
1995-96	562.4	1	1	1	1	1	1	1	1	1	1
1996-97	710.4	1	1	1	1	1	1	1	1	7	7
1997-98	827.8	1	1	22	1	1	1	1	1	1	1
1998-99	870.2	1	1	1	1	1	1	1	1	1	1
1999-00	976.5	1	1	29	1	1	1	1	1	1	1
2000-01	646.4	1	1	1	1	1	1	1	1	1	1
2001-02	634.10	1	1	1	1	1	1	1	1	1	1
2002-03	639.10	1	1	1	1	1	1	1	1	1	1
2003-04	380.80	1	1		1	1	1	1	1	7	7

*(*These are input(or target) DSR values and the output DSR for which these tank strategies are derived varies within the range of input DSR ± 10%)*

Table 10.2 Optimum tank strategies for different DSR levels for Akola watershed.

Input DSR	Actual output DSR,%	Tank Strategy No.	Net benefits, Rs
10	11	1	432720
20	18	1	433952
30	26	1	435767
40	40	1	438623
50	47	1	439826
60	55	1	441095
70	68	1	442938
80	72	1	443422
90	86	1	445007
95	92	1	445682

10.3.1.1 Optimum tank Strategy No 1 for Akola watershed

In this tank strategy there is only one tank at the outlet of the watershed. The tank is of type 2 i.e. the entire catchment of the tank is its potential command area (Fig 10.1). Water is lifted from the tank for irrigating the crops in the catchment. Normally the site conditions for construction of tanks are favourable in terms of topography and storage excavation ratio at the outlet of the watershed. Hence many times outlet of the watershed is a preferred tank location. Tank dimensions for tank strategy No 1 for different DSR are given in Table 10.3. From the table it is seen that as expected the tank capacity decreases as the DSR increases.

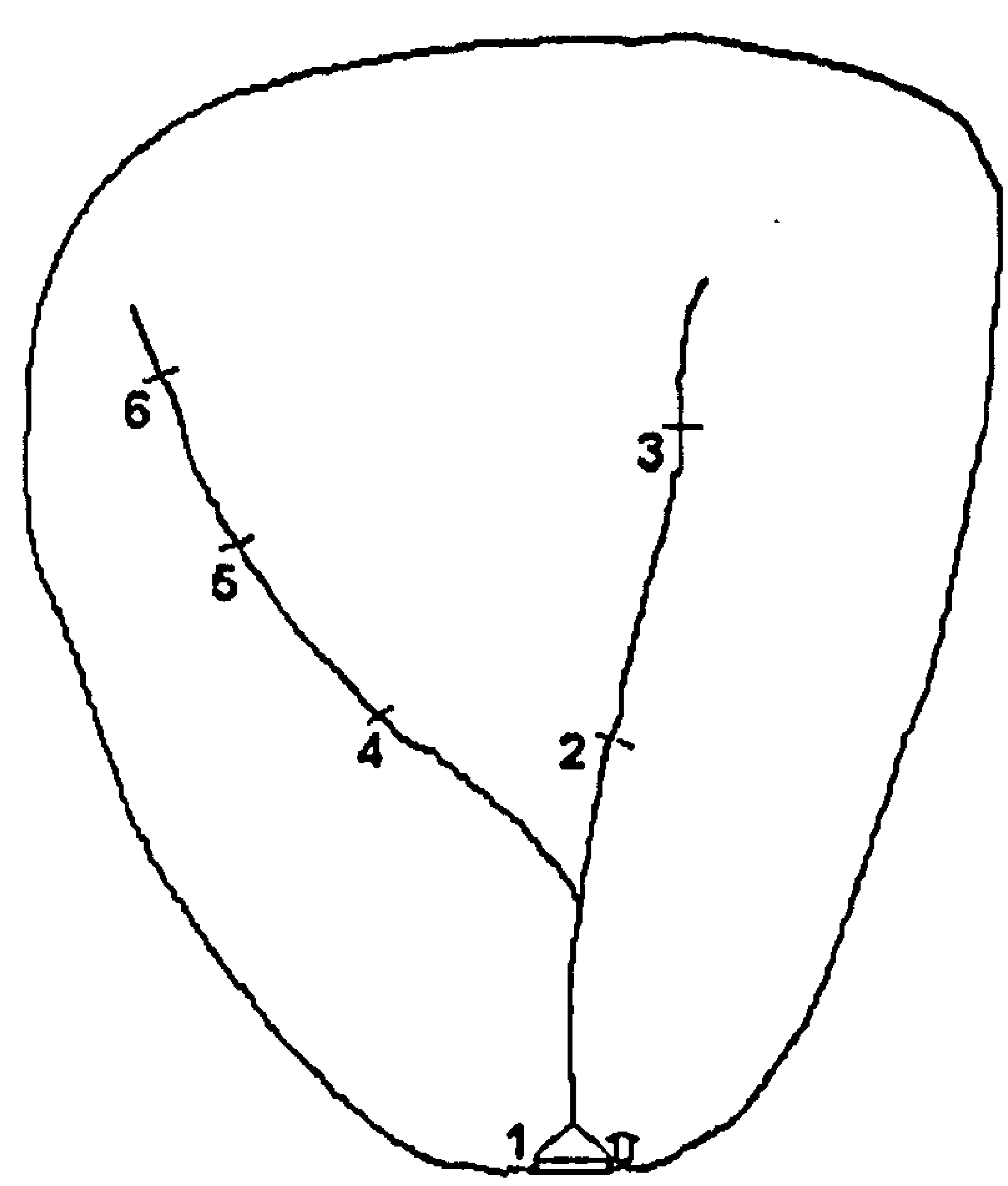


Figure 10.1 Tank strategy No.1

Table 10.3 Dimensions of tanks for tank strategy No 1 for different DSR

Output DSR	Tank capacity, m^3	Bottom length, m	Bottom width, m	Top length, m	Top width, m	Depth, m
11	25071	69.9	69.9	77.7	77.7	3.9
18	22382	67.0	67.0	74.5	74.5	3.8
26	19349	63.4	63.4	70.5	70.5	3.5
40	14395	57.5	57.5	63.8	63.8	3.2
47	11915	53.9	53.9	59.9	59.9	3.0
55	9618	50.0	50.0	55.5	55.5	2.8
68	5991	42.1	42.1	46.7	46.7	2.3
72	4996	39.8	39.8	44.2	44.2	2.2
86	1982	29.0	29.0	32.2	32.2	1.6
92	780	22.1	22.1	24.5	24.5	1.2

10.3.1.2 DSR vs net benefits for Akola watershed

The graph of DSR vs net benefits is shown in Fig. 10.2. From the figure it is seen that the net benefits from the watershed are increasing as the DSR increases. As the DSR increases less water is stored and used in the watershed. This should have resulted into reduction of net benefits but the graph has shown the opposite trend. It thus indicates that tank plus groundwater irrigation is not economical in the Akola watershed. To understand this finding it needs to be recalled that in the Akola watershed land use consists of horticultural and silvipasture crops. Out of total area of 27 ha, horticulture comprises 11 ha area and silvipasture 10 ha area. Irrigation is not given to the silvipasture crops and irrigation is given by drip system for horticultural crops. Irrigation is not given to the horticultural crops for 2 months during summer season. Field crops are taken on 2.5 ha area for which irrigation is given by surface method. An area of 3.5 ha is barren. Akola watershed comes in assured rainfall zone and the average annual rainfall is about 792 mm. Moreover there are trenches in catchment 2 and 3 in the watershed. Therefore land use of horticulture and the land treatment of trenches along with assured rainfall all help in recharging the groundwater. The demand for water is less as compared to supply. Out of total irrigation volume of 14767 m^3, 12787 m^3 (87%) is given through groundwater irrigation and only 1980 m^3 (13%) is given through tank irrigation. Recharge to groundwater through field is 24504 m^3 and through trenches is 9537 m^3. About 38% of the recharge water is reused through groundwater irrigation. As per Keller (2002) typically groundwater recovery under artificial recharge averages 75% of the recharge volume. The groundwater extraction in the present case for Akola watershed is much less than this average. The groundwater recharge from trenches and field is sufficient to meet deficit created by groundwater irrigation for the crops. About 75% recharge takes place through field and trenches which is sufficient to meet the groundwater deficit. Construction of tanks therefore does not look economical for the watershed. This is also supplemented with the fact that the base flow is a major outflow (72%) from the groundwater table. Since irrigation needs are met by groundwater, any additional investment in tank system becomes uneconomical.

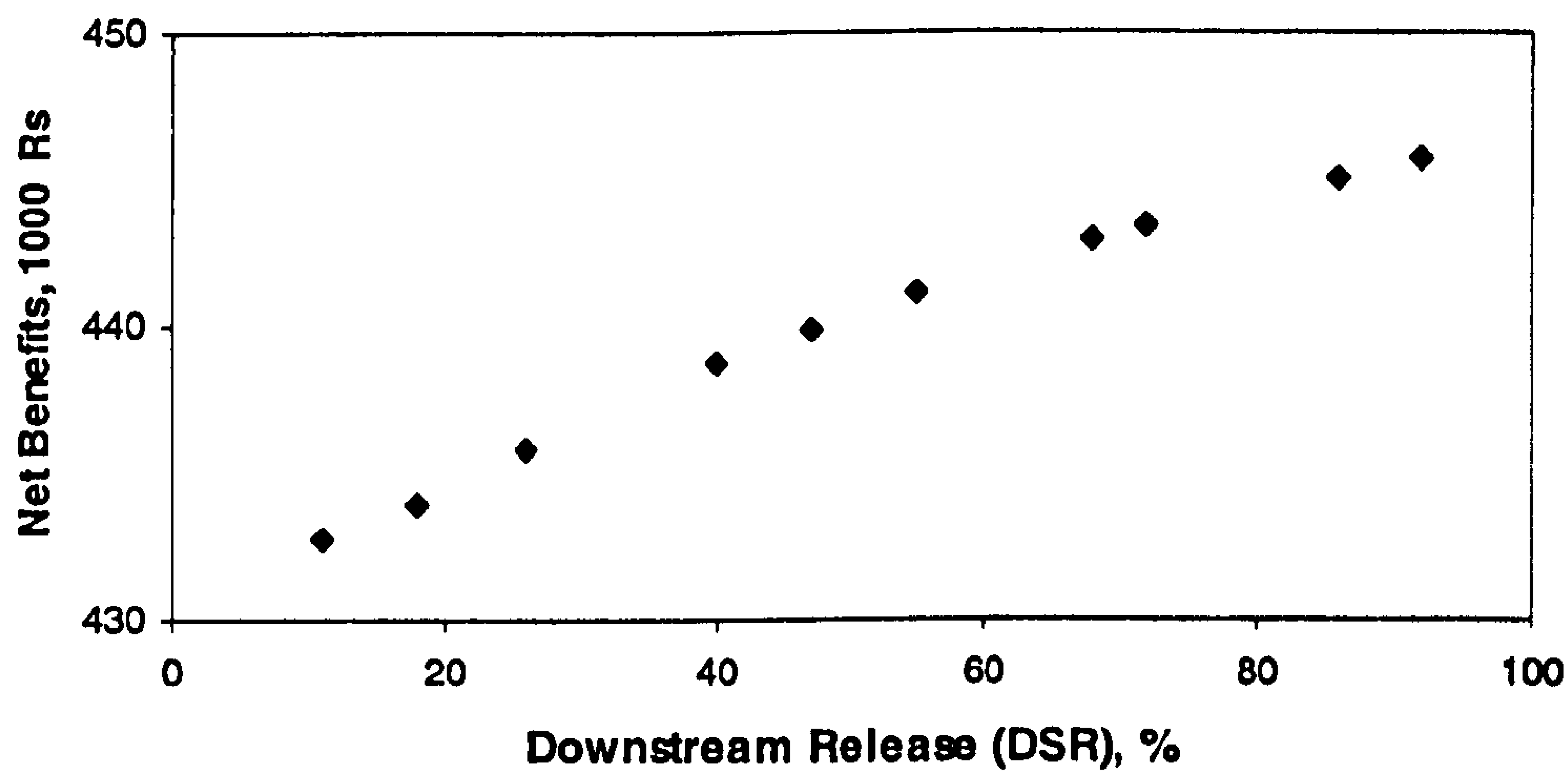


Figure 10.2 Net benefits vs DSR for Akola watershed

10.3.1.3 Conclusion

The Akola watershed has six small tanks (ponds) in the watershed for runoff harvesting in addition to the trenches in the catchments of tank 2 and 3. The analysis for the optimum tank strategy for the watershed was carried out for different DSR levels. It was found that the as the DSR increases, the net benefits in the watershed increases thereby suggesting that tanks are not economical. This finding is supported with the facts that major share of irrigation requirement is met by groundwater and recharge from field and trenches is sufficient to recharge the groundwater since only 38% of the recharge water is used for irrigation in the watershed. Also the finding support that using water efficiently can make more water available for downstream uses thus minimizing the upstream-downstream water related conflicts.

10.3.2 Optimum tank system for Pimpalgaon Ujjaini watershed

Optimum tank strategy for Pimpalgaon Ujjaini watershed was derived in the same way as that for Akola watershed. First yearly optimum tank strategies were derived based on the maximum net benefits and the output DSR. During some of the years the optimum strategies were not obtained since the output DSR did not match the input DSR. The yearly tank strategies are given in Table 10.4. From the table it is seen that some of the tank strategies are the frequently occurring tank strategies during the climatic data period. When these tank strategies were run for other climatic data series it was found that that the frequently occurring tank strategies are not the strategies giving the maximum net benefits. But their frequent occurrence does suggest their stable nature for the climatic series and need consideration in deriving optimum tank strategy. Hence it is suggested that optimum tank strategies may be selected either on the basis of most frequently occurring tank strategies or the strategies giving the maximum net benefits. Here optimum tank strategy has been derived based on the maximum average net benefits during the climatic data set. One optimum tank strategy was derived for each DSR from 20 to 90. Optimum tank strategy was not found for the DSR of 10%. Since the percolation tanks comes under type 3 tanks there are limitations on the positioning of the tanks at stream points in the watershed. For example there can not be a tank at the outlet of the watershed since there is no command on the downstream side of the tank. Hence tanks are to be placed at some point in the watershed where command area is available on both sides of the tank. This drastically reduces the feasible number of tank strategies in the watershed. When tank moves upstream some portion of watershed comes below the tank as its command. This command directly contributes runoff to the outlet of the watershed as DSR. If this value is greater than or equal to the input DSR ± deviation (e.g. 30 ± 10%) then tank strategy is not derived. (This further reduces the number of feasible tank strategies). The SOFTANK then searches for next tank strategy. In this way optimum tank strategies were obtained for different DSR.

10.3.2.1 DSR vs net benefits for Pimpalgaon Ujjaini watershed

The optimum tank strategies for different DSR along with their economics are given in Table 10.5. The benefit cost ratio for different strategies was found to be around 2.5. The graph of net benefits vs DSR is given in Fig 10.3. Net benefits are minimum for DSR of 20%. Benefits then rise sharply for DSR of 30%. Maximum net benefits are obtained for the DSR of 40%. The net benefits beyond this maximum decreases gradually towards 95 % DSR. Thus the tank strategy giving the maximum net benefits is strategy No 85 (corresponding to DSR of 40%). Thus for the DSR from 0 to 40%, the tank strategy No. 85 (i.e. for DSR of 40%) should be considered as the optimum tank strategy for the watershed and for the DSR values grater than 40%, the tank strategies corresponding to the desired DSR should be obtained from the graph and considered as the optimum tank strategy for that DSR level. The existing tank strategy (tank strategy No 94) and the optimum tank strategy (tank strategy No

85) are shown in Fig. 10.4. The trend of the graph suggests that there is not much decrease in the net benefits as DSR increases. This is supported by the fact that field deep percolation contributes about 70% of the total groundwater recharge whereas tank seepage contributes remaining 30% of the groundwater recharge. And the source of irrigation is groundwater since tanks are used for percolation purpose only.

Table 10.4 Yearly optimum tank strategies for different DSR for Pimpalgaon Ujjaini watershed

Year	Rainfall, mm	DSR*							
		20	30	40	50	60	70	80	90
1975-76	674.4	1804	49	85	913	994	373	58	16
1976-77	383.3	1804	400	265	NIL	NIL	94	1075	49
1977-78	514.7	1804	994	85	49	58	94	58	58
1978-79	332.8	346	76	76	NIL	NIL	94	373	265
1979-80	872.9	1804	994	319	85	994	67	67	16
1980-81	589.6	1804	994	49	85	49	67	94	16
1981-82	262.7	NIL	NIL	NIL	NIL	481	76	49	58
1982-83	596.6	NIL	238	NIL	NIL	NIL	94	76	58
1983-84	434.7	1804	58	58	265	265	373	94	16
1984-85	331.5	1804	994	913	319	58	67	67	16
1985-86	387.0	1804	76	NIL	NIL	454	1804	1804	373
1986-87	649.4	1804	427	76	NIL	NIL	238	265	265
1987-88	663.7	1804	1804	346	49	58	67	94	94
1988-89	687.3	319	58	58	1804	400	49	67	16
1989-90	827.6	1804	1804	346	58	85	67	67	16
1990-91	522.2	913	994	454	85	94	454	121	16
1991-92	443.9	1804	319	58	85	85	76	94	7
1992-93	628.4	1804	NIL	319	832	994	994	94	94
1993-94	369.2	1804	373	319	373	58	1804	319	1804
1994-95	587.9	238	346	NIL	NIL	NIL	94	454	994
1995-96	776.5	832	49	85	238	319	319	67	16
1996-97	519.7	1804	58	58	85	67	481	94	NIL
1997-98	812.6	832	994	319	58	76	265	85	94
1998-99	676.2	1804	994	913	319	58	67	67	16
1999-00	652.2	1804	58	58	994	994	373	94	16
2000-01	536.1	913	49	454	58	67	85	13	16
2001-02	389.0	1804	NIL	265	238	265	265	58	94
2002-03	324.5	1804	373	238	49	58	265	265	292
2003-04	674.4	1804	427	265	NIL	NIL	49	49	58

*(*These are input (or target) DSR values and the output DSR for which these tank strategies are derived varies within the range of input DSR ± 10%)*

Table 10.5: Cost economics of optimum tank strategies for different DSR for Pimpalgaon Ujjaini watershed

Input DSR, %	Output DSR, %	Tank Strategy	Initial cost Rs	Maint. Cost Rs	Crop cultivation cost Rs	Total cost, Rs	Gross Benefits, Rs	Net Benefits, RS	Bene cost ratio
20	28	319	1111520	44461	12547334	13703315	34044029	20340714	2.47
30	37	58	1086906	43476	12564275	13694658	34348596	20653939	2.50
40	49	85	1012107	40484	12612237	13664828	34358057	20693229	2.50
50	60	49	833295	33332	12665042	13531669	34196250	20664581	2.52
60	67	58	805677	32227	12649486	13487390	34153068	20665678	2.52
70	72	49	768920	30757	12669951	13469628	34134524	20664897	2.52
80	80	58	758688	30348	12659341	13448376	34104325	20655949	2.53
90	90	58	720598	28824	12659109	13408530	34023329	20614799	2.52

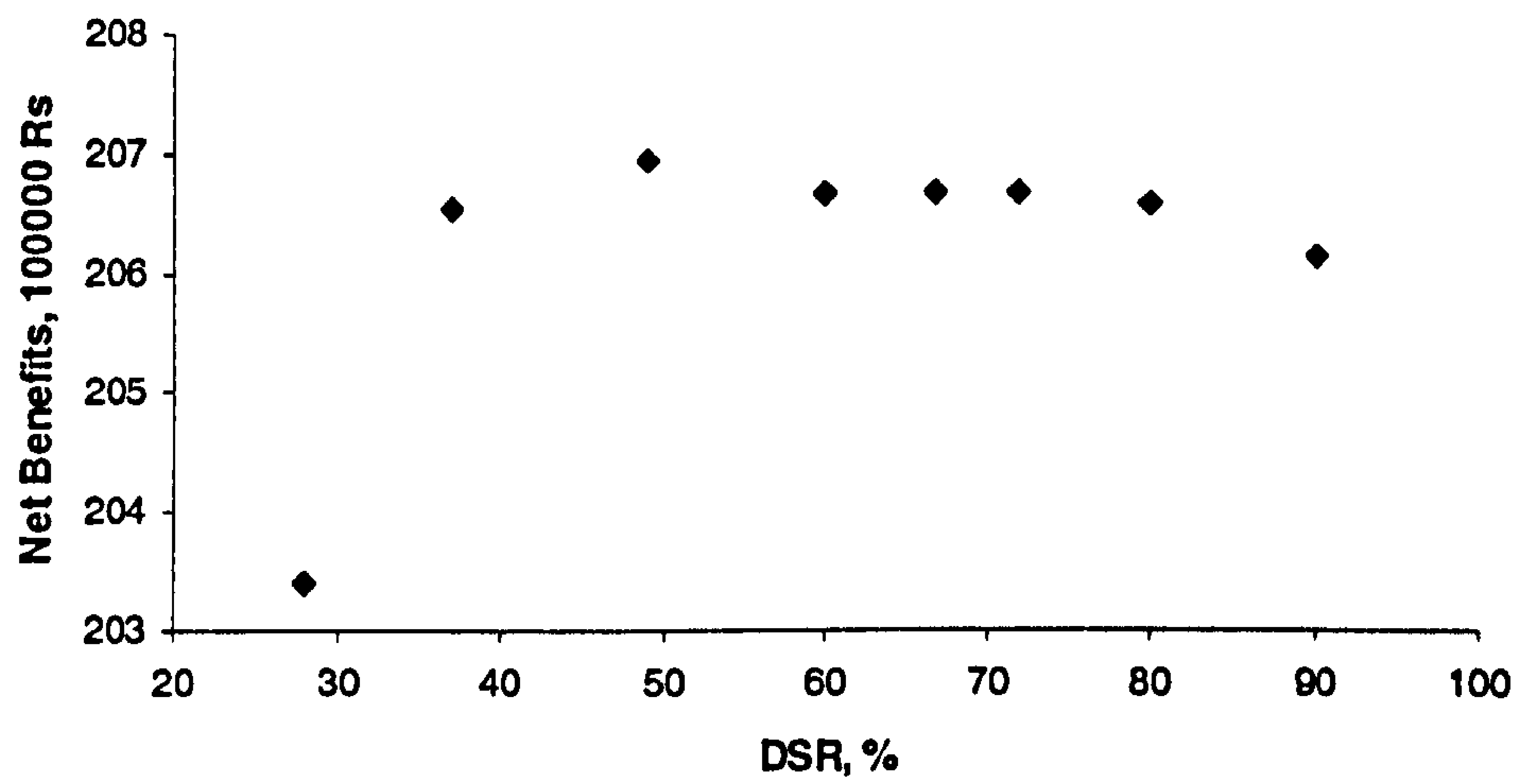
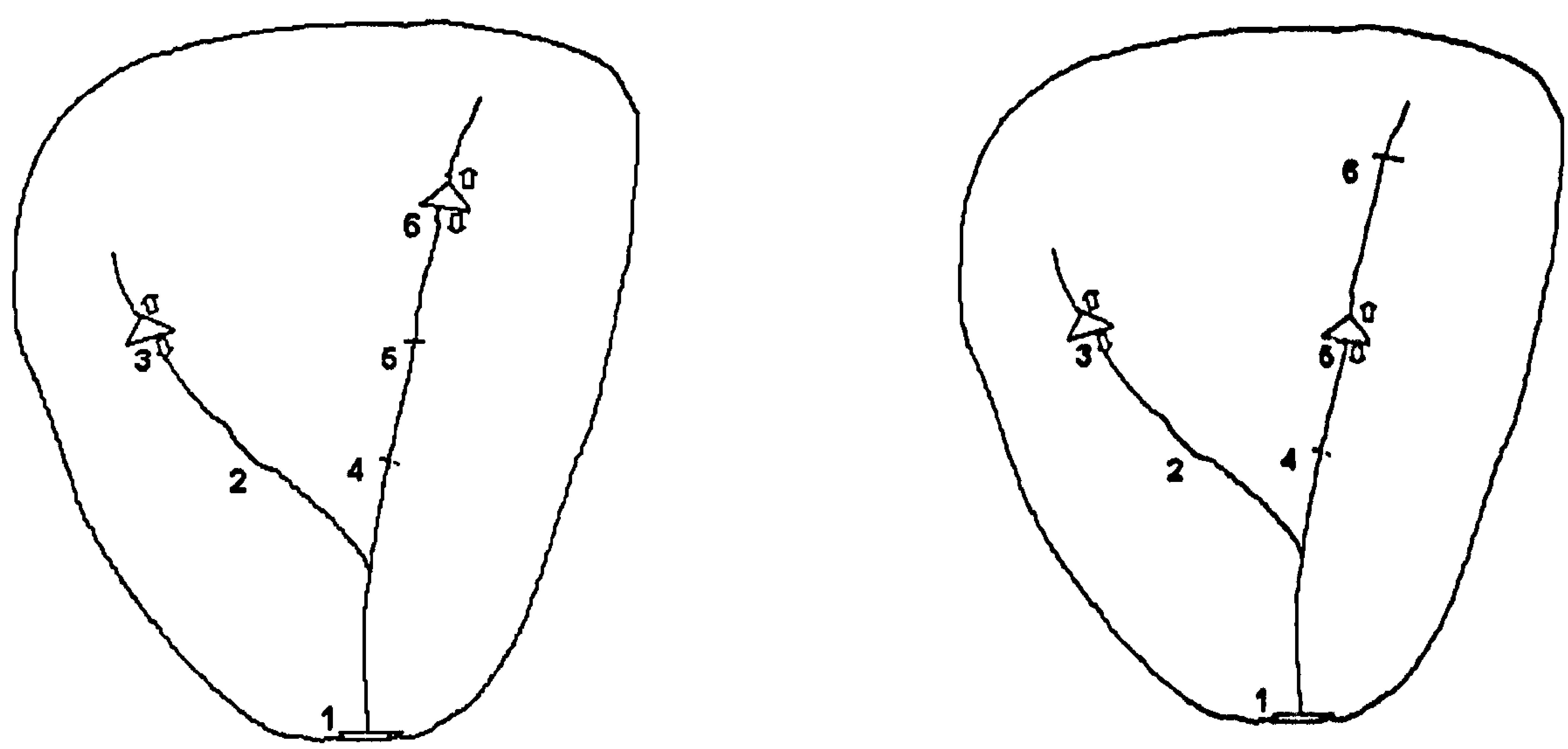


Figure 10.3: Net benefits vs DSR for Pimpalgaon Ujjaini watershed



(a) Tank strategy No 94 (existing strategy) (b) Tank strategy No 85(optimum strategy)

Figure 10.4: Existing and optimum tank strategies for Pimpalgaon Ujjaini watershed

10.3.2 Tank capacities for different DSR for Pimpalgaon Ujjaini watershed

Tank capacities for different DSR are presented in Table 10.6 and the tank dimensions for optimum tank strategy are presented in Table 10.7. From Table 10.6 it is seen that tank capacities decrease as the DSR increases. Total storage capacity of tanks of the optimum tank strategy is insignificantly more than the existing tank strategy but there are significant differences in the individual tank capacities. In Chapter-8 (Section 8.5.1.3) it was shown that the annual inflow to tank-1 was less than its capacity and there was no overflow from this tank. This suggests that tank was over designed. In the optimum tank strategy this capacity is reduced and the tank capacity of second tank is increased since tank moves further downstream than its position in the existing tank strategy (see Fig. 10.4). Hence in the optimum tank strategy tanks capacities are more appropriate with the supply and demand parameters of the tank.

Table 10.6 Tank capacities at different DSR for Pimpalgaon Ujjaini watershed

DSR	Tank Strategy No.	Tank capacity, m^3			
		Tank-1	Tank-2	Tank-3	Total capacity
20	319	544529	208442	575081	1328052
30	58	645424	682515	--	1327939
40	85	361333	568359	--	929693
50	49	136344	195785	--	332130
60	58	129709	136051	--	265760
70	49	59135	103122	--	162257
80	58	49682	55029	--	104711
90	58	17205	18669		35873
58	Existing (94)	695877	216937	--	912814

Table 10.7 Dimensions of optimum tank strategy (strategy No 85) for Pimpalgaon Ujjaini watershed

Tank No	Capacity, m^3	Top length, m	Top width, m	Bottom length, m	Bottom width, m	Depth, m
1	361333	200	200	180	180	10
2	568359	232	232	208.6	208.6	11.7

10.3.2.3 Conclusion

Tanks were found economical for Pimpalgaon Ujjaini watershed. Since the source of irrigation was only groundwater and fields played major role in the groundwater recharge the difference between the net benefits at maximum and minimum DSR is not very significant as observed from graph of DSR vs net benefits. For Pimpalgaon Ujjaini watershed it was found that tank strategy No 85 is the optimum tank strategy for the existing conditions and practices in the watershed giving maximum net benefits of Rs 20693229 (Rs 15605 per ha) with DSR of 40%.

10.4 Closure

The application of the SOFTANK model for the two watersheds has demonstrated the utility of the model to derive optimum tank systems for the watersheds. The novelty of the approach lies in the fact that optimum tank systems can be derived for any desired level of DSR. This feature of the SOFTANK model puts it at an advantage in the growing upstream downstream conflicts in the watershed projects.

At present the watershed projects in India are carried out without any consideration of how much water will be harvested by the development activities. The approach is to harvest as much rain as possible. Hence there is growing debate on the upstream downstream water conflicts. It will be possible to address this issue with the help of SOFTANK model. The inclusion of DSR criterion thus allows better distribution of upstream-downstream benefits. By adopting the approach of IWSS and by optimizing tank systems at different DSR levels it also becomes evident whether the tank system is economical or not for the watershed. Accordingly optimum tank systems were determined for the case study watersheds and discussed in this Chapter. This chapter closes the discussion on application of the proposed methodology for the case study watersheds. Next Chapter presents the conclusions of the research.

Chapter-11

CONCLUSIONS

11.1 Summary:

This Chapter presents the conclusions and findings of this research carried out to investigate the optimum tank system for the watershed. The conclusions are discussed in the light of proposed hypotheses. Findings of the application of SOFTANK model for the case study watersheds are also presented. Suggestions for future work are given at the end.

11.2 Introduction

This research work was undertaken with the aim of "Optimum design of tank irrigation system for the watersheds in semi arid and sub-humid tropics of India". The background and need of research along with the hypotheses and objectives of research are presented in Chapter 1. In the chapter it has been discussed that watershed based rainwater harvesting has been adopted as the most appropriate approach for sustaining the crop production in semiarid and sub-humid regions of India where construction of big reservoirs is not feasible. Watershed development implies the construction of *in situ* and *ex situ* RWH systems to maximize the rainwater harvesting and make efficient use of harvested rainwater in the watershed. Review and discussion on *in situ* and *ex situ* RWH systems are presented in Chapters 2, 3 and 4. At present these systems are designed with experience and empirical knowledge. Therefore a methodology was developed to study one *in situ* RWH system i.e. continuous contour trenches (CCT) and is presented in Chapter 3. Existing approaches for design of tank systems along with the need of new approach are discussed in Chapter 5. The detail methodology and the resulting simulation model 'SOFTANK' for design of optimum tank system has been presented in Chapter 6. Two case study watersheds from the semiarid region of Maharashtra state of India were selected for demonstrating the applicability of the developed methodology. The details of these case studies along with calibration of the SOFTANK model are discussed in Chapter 7. The existing tank systems in these watersheds were evaluated and the results are discussed in Chapter 8. Chapter 9 discusses the utility of the SOFTANK model in simulating different scenarios in the watershed. The optimum strategies for both the watersheds were derived and are discussed in Chapter 10. This chapter presents the conclusions of this research as per the hypotheses proposed in the first chapter.

11.3 Conclusions

The conclusions of the research are discussed below as per the hypothesis proposed in the first Chapter.

11.3.1 Hypothesis-1:

In situ RWH systems influence the storages of downstream ex situ RWH systems (tanks) and hence both *in situ* and *ex situ* RWH systems *should be considered together in the methodology for optimum design of tank system in the watershed*

To verify this hypothesis, literature on the *in situ* rainwater harvesting (RWH) practices was reviewed along with the case studies of integrated watershed management. These are discussed in Chapter 2. Most of the reviews and case studies were drawn from the work carried out in India. All the reviews in the Chapter indicated that these *in situ* RWH systems store significant volumes of runoff thereby reducing the flow to the downstream and increasing the soil profile moisture and groundwater recharge. Their effectiveness varies according to the climate, soil, topography and land use and different results are obtained by different workers which are discussed in the Chapter. For example tillage enhanced infiltration by 28.63% (Dongale, 1987), sowing crop across the slope reduced runoff by 18.7% (Patil and Bangal, 1991), runoff in mulched plot was far less than that of non-mulched plot (Bhatt and Khera, 2005). About 60-80% rainfall could be harvested with continuous contour trenches (Deoulgaonkar 2004). Therefore literature strongly supports that the *in situ* RWH systems harvest considerable volumes of runoff and thus affects the storage systems downstream in the watersheds.

This was further verified by simulating the tank system in the Akola watershed with and without continuous contour trenches. Results are discussed in Chapter 8. In one case, trenches were laid in catchments of tank 2 and 3 whereas in other case trenches did not exist in these catchments. Results suggested that inflow to tank 2 and 3 was reduced by half due to the existence of trenches in these catchments and the tank capacities were reduced by about 5 times than the tank capacities when trenches did not exist. Due to the presence of trenches there was increase in groundwater recharge by about 12%. Therefore the findings of the study also support the findings of other workers as reviewed from the literature and therefore the hypothesis that "*in situ* RWH systems influence the storages of downstream *ex situ*

RWH systems (tanks) and hence they should be considered together in the methodology for optimum design of tank system in the watershed" is accepted.

11.3.2 Hypothesis 2:

Rational design of tank system for the watershed should be obtained by investigating different scenarios that result from the combination of number of tanks, their locations and types (defined by tank strategy) as tank strategies affect greatly the outputs from the system (such as water available for consumptive use, crop production, benefits).

For investigating this hypothesis a new classification of the tank system was proposed based on the orientation of command area around the tank. This is discussed in detail in Section 4.3.2. There are different combinations of number of tanks, their locations and tank types in the watershed. Each of these combinations was defined as 'a tank strategy'. A procedure was developed to determine the number of such possible combinations (i.e. tank strategies) for a watershed based on the number of stream points in the watershed (A stream point is defined as the location on the drainage line where tank construction is preferred). The procedure is discussed in Section 6.3.3. This procedure was included in the SOFTANK model to generate tank strategies for watersheds. Some commonly observed tank strategies are simulated for Akola and Pimpalgaon Ujjaini watersheds and the results are discussed in Chapter 9. Findings of the simulation suggest that the water balance in the watershed changes as the tank strategies in the watershed changes. For example contribution to groundwater recharge through field, tanks and trenches were 61, 13 and 26% respectively in tank strategy No 1 whereas these contributions were 54, 24 and 22% respectively for tank strategy No 1926 (existing strategy) in Akola watershed. Therefore if all the possible combinations (i.e. tank strategies) are simulated then the optimum tank strategy can be selected for the desired criteria for the watershed. This analysis was carried out for Akola watershed and it was found that construction of tanks is not economical for the watershed. Since there are horticultural crops in the watershed, crop water requirement is low and the source of groundwater is sufficient to meet this requirement. Hence tanks were not found economical for the Akola watershed.

For Pimpalgaon Ujjaini watershed the optimum tank strategy was derived by simulating all the tank strategies for the watershed. At present the two tanks are located at stream point No 3 and 6 in the watershed. Results indicated that the optimum strategy consists of two tanks at stream point No 3 and 5. Findings of the study therefore indicate that optimum tank system can be obtained by simulating all the possible tank strategies for the watershed. Therefore the hypothesis "*rational design of tank system for the watershed should be obtained by investigating different scenarios that result from the combination of number of tanks, their locations and types (defined by tank strategy) as tank strategies affect greatly the outputs from the system (such as water available for consumptive use, crop production, benefits)*" is accepted.

11.3.3 Hypothesis 3:

There is a need for integrating different storage systems (soil, tank and aquifer) while optimizing the use of available water for crop production and thus in turn for the optimum design of tank system.

The concept of integrated water storage system (IWSS) was introduced in the first Chapter. The watershed based rainwater harvesting approach being adopted in India attempts to make integrated use of these three storages (i.e. soil, tank and aquifer). Many successful case studies on integrated watershed management were reviewed in Chapter 2. All these studies (Maheshwari, 1990, Urade and Sagare, 1993, Singh, 1995, Gaur *et al,* 1995, Rao, 1996, Goyal *et al.*, 1997, and Mittal and Samra, 2001) reported the positive effects of integrated watershed development on the availability of water in the watershed. As a result there was rise in groundwater table, number of wells, and crop yield in the watershed over a period of 5 to 10 years as a result of the integrated effect of different *in situ* and *ex situ* RWH practices in the watershed. But these studies did not report the details on individual storages and their effects on each other in the watershed.

Therefore an investigation was carried out for the Akola watershed where two land uses (horticulture and field crops), two tank strategies (tank strategy with one tank at the outlet of the watershed (T1) and tank strategy with six tanks at six stream points of type-2 (T1926)) and two values of drainable porosity (0.1 and 0.05) were considered for simulation. Simulations were carried out for the resulting eight combinations of these parameters. Results are discussed in Chapter 9. Findings of the analysis suggested that any change in one storage system affects the other storage systems and consequently the water balances in the watershed. For example when land use changes from horticulture to field crops the irrigation requirement is increased. This increased irrigation requirement affects the tank and groundwater storages and is met differently when the tank strategy changes. When the tank strategy changes it affects the groundwater storage through changes in field and tank recharge. Changes in drainable porosity, affects the recharge to groundwater. Therefore any change in one storage system affects the other two storage systems. Hence these storages should be considered together in order to make the efficient use of harvested rainwater in the watershed. Therefore the hypothesis that "*there is a need for integrating different storage systems (soil, tank and aquifer) while optimizing the use of available water for crop production and thus in turn for the optimum design of tank system*" is accepted.

11.3.4 Hypothesis 4:

It is possible to design the optimum tank system for the watershed for a desired downstream release of water (from the watershed).

In the watershed projects in India, there is debate on 'upstream-downstream conflict' of the watershed projects. Therefore the above hypothesis was introduced in this research to see the possibility of designing the optimum tank system for the desired down stream release from the watershed. Therefore this aspect was included in the methodology of tank system design in this research. Accordingly tank systems are designed for any desired downstream release (DSR). When all the tank strategies for the watershed are simulated for downstream releases between 0 and 100, then one best tank strategy for each DSR level is obtained. The plot of net benefits *vs* DSR level gives the optimum tank strategy for that watershed (i.e. strategy giving maximum net benefits). The trend of the graph also suggests whether tank system for the watershed is economical or not. Accordingly this analysis was carried out for Akola and Pimpalgaon Ujjaini watershed and the findings suggested that tank system is not economical for the Akola watershed whereas it was economical for Pimpalgaon Ujjaini watershed. On the basis of the analysis an optimum tank strategy for the Pimpalgaon Ujjaini watershed is suggested. If such graph is prepared for the watershed under development then optimum tank system for any desired DSR level can be selected for that watershed. Therefore the hypothesis "*It is possible to design the optimum tank system for the watershed for a desired downstream release of water (from the watershed)*" is accepted.

11.3.5 Hypothesis 5:

The variability in supply and demand parameters influences the design of tank system.

To derive the optimum tank system for the watershed all the possible tank strategies were simulated for a particular year. The methodology gave optimum tank strategy for that year. But since there is yearly variation in the climate, this tank strategy needed to be evaluated for other climatic years. When this was done the output DSR from the tank strategy may or may not match with the desired (input) DSR. This means that the climate influences the tank strategy. This aspect was considered in the analysis and if the output DSR matched with the input DSR the tank strategy was selected else the tank strategy with the next highest net benefits was selected for evaluation. In this way all the yearly optimum tank strategies were evaluated against other climatic data series and the strategy giving maximum net benefits was selected as the optimum tank strategy for that DSR level for the watershed. The results are discussed in Chapter 10. From the investigation it is concluded that climate influences the supply and demand parameters of the tank system and therefore the hypothesis "*The variability in supply and demand parameters influences the design of tank system*" is accepted.

11.4 Findings of the research

The findings of the research are presented in this section.

11.4.1 Methodology for optimum design of tank system for watershed

As a part of this investigation a comprehensive methodology has been developed for the optimum design of tank system for the watershed. The methodology is based on three important water balances in the watershed i.e. field water balance, tank water balance and groundwater balance. The tank system for the watershed is optimised for maximum net benefits. Novel features of the methodology (which were not observed in the earlier approaches of tank design as discussed in Chapter 5) are

1. Tank system is optimised for the watershed and not for a single tank (as done by earlier researchers) though single tank can also be designed considering its catchment and command area.

2. A new tank classification system based on the orientation of its command area has been introduced which defined the 'tank type' in this research.

3. The concept of 'tank strategy' has been introduced which is a combination of number of tanks, their locations and types in the watershed.

4. Field allocation for the catchment and command area of a tank is a dynamic process and changes with the tank strategy

5. Methodology accounts for the effect of *in situ* RWH practices like trenches in the catchments of tanks while optimising the tank system

6. Three storage systems i.e. soil, tank and aquifer have been integrated into the methodology of tank system design.

7. An important aspect of down stream release (DSR) has been introduced in optimising the tank system for the watershed.

11.4.2 Development of SOFTANK model

The comprehensive methodology of optimum design of tank system was converted into computer code in C language which resulted into computer model SOFTANK. This model provides an analytical tool for studying different aspects related with tank system design in the watershed. Many such aspects have been widely addressed in this research.

11.4.3 Assessment of water harvesting potential of CCT

For the performance assessment of water harvesting potential of continuous contour trenches (CCT) two indicators i.e. Gross WHP and net WHP have been introduced. Gross WHP indicates reduction in runoff to the downstream tanks due to the existence of trenches in their catchments whereas net WHP indicates the groundwater recharge due to the trenches. In the Akola watershed, where trenches (of cross section 0.3 x 0.6 m spaced at 5 m interval) are present in the catchments of tank No 2 and 3 these indicators were found as

Gross WHP = 82%
Net WHP = 47%

The methodology can also be used to design the trench system for a desired water harvesting potential or for the desired monetary investment.

11.4.4 Evaluation and performance improvement of the existing tank systems

The SOFTANK model can be used to evaluate the existing tank system and to suggest measures (changes in the tank system or changes in the management) to improve the tank system performance in the watershed. Accordingly the tank systems in Akola and Pimpalgaon Ujjaini watershed were evaluated and the findings are given below.

11.4.4.1 Akola watershed

In Akola watershed, it is observed that, about 34% runoff is harvested in the watershed and 66 % went out of the watershed. Recharge to groundwater takes place trough field (54%), tank (24%) and trenches (22%). Trenches reduced the inflow to the tanks and contributed to groundwater recharge. Baseflow is the major groundwater outflow component. When other tank strategies were simulated for the watershed it was found that tank No 2 and 3 which included trenches in their catchments were over designed. It was also found that one tank at the outlet of the watershed (with capacity 6690 m^3) would have given higher net benefits than the existing tank system of six tanks with total storage capacity of 4825 m^3.

11.4.4.2 Pimpalgaon Ujjaini watershed

In Pimpalgaon Ujjaini watershed 42% runoff is harvested by the tanks and 58% went out of the watershed. Since the source of irrigation was groundwater, it formed the major (66%) outflow component from the groundwater storage. Tanks in the watershed were over designed as inflow capacity ratio was very less for the tanks. Seepage was the major (84%) outflow component from the tanks. Recharge from tanks and field was 29 and 71% respectively. In this watershed there are two tanks at stream point No 3 and 6 with capacities of 695877 and 216937 m^3 (total storage capacity 912814 m^3) and these tanks are used for groundwater recharge only. When alternate tank strategies and management options were simulated it was found that if tanks were located at stream point No 2 and 4 and they were used for both recharge and irrigation then the system would have given higher net benefits than the existing system. The resulting tank capacities were 104666 and 147227 m^3 for tank 1 and 2 respectively with total storage capacity of 251893 m^3 (3.6 times less than the existing storage capacity).

11.4.5 Optimum tank systems for the watersheds

Optimum tank systems for the Akola and Pimpalgaon Ujjaini watersheds were derived for the existing conditions and practices in the watershed. The findings are given below.

11.4.5.1 Akola watershed

For Akola watershed it was found that the tank system is not economical. The land use in the watershed consists of horticulture and silvipasture systems. Irrigation is not given to the silvipasture system whereas irrigations are given by drip system to the horticultural crops. Therefore the source of groundwater is sufficient to meet the irrigation water requirement of these crops. Additional investment in tanks is not economical.

11.4.5.2 Pimpalgaon Ujjaini watershed

For Pimpalgaon Ujjaini watershed, tank system was found economical and optimum tank system was derived. The details of the existing and optimum tank system are given below

Parameter	Existing system	Optimum system
No of tanks	2	2
Tank locations	Stream point No 3 and 6	Stream point No 3 and 5
Tank capacities, m^3	695877 and 216937	361333 and 568359
Total storage capacity, m^3	912814	929693
Net benefits, Rs	17868067	20693229
Increase in net benefits per ha, Rs		2130

11.5 Suggestions for future work

During the course of this research, many research aspects cropped up in the mind but could not be completed. Some of the aspects do need mention here. Hence it is suggested that the following research works may be continued in future.

11.5.1 Optimum tank systems for different management options in the watershed

The management options changes the water balance in the watershed and affects the three storages in the watershed. Therefore it is suggested that the optimum tank systems may be determined for different management options in the watershed. The possible management options are as below

11.5.1.1 Source of water for irrigation

Source of water for irrigation in the watershed is normally only groundwater as in the case of Pimpalgaon Ujjaini watershed and tank and groundwater both as in the case of Akola watershed. Therefore if the optimum tank systems are determined for such management options then it is possible to select the most profitable management option and the corresponding tank system.

11.5.1.2 Irrigation strategy

Irrigation strategy consists of scheduling irrigations at different time intervals and applying varying depths of water. If the combinations of different irrigation interval and irrigation depth are studied then it will be possible to select the most profitable irrigation strategy combination and the corresponding tank system for the watershed.

11.5.2 Research on other in situ RWH systems

In this study the effect of only CCT is studied on the storage capacity of tanks downstream. But there are many other *in situ* practices like bunds, terraces, ridges etc which are commonly adopted in the catchments of the tanks. These practices differ in their geometry and specifications and need to be studied individually.

11.5.3 Field experiments

Watershed development projects are an ongoing process in India. It is suggested that for one watershed which is taken for development, the optimum tank system may be derived with the SOFTANK model. The derived tank system may be implemented in the watershed and data on water balances may be collected for a period of 3 to 5 years. This will facilitate the validity of the SOFTANK model by comparing the simulated and observed water balances in the watershed.

11.6 Concluding remarks

Countries in the semiarid and sub humid regions face the water scarcity problems more due to the uneven distribution of rainfall in space and time than due to the low cumulative annual rainfalls. We can not increase the rainfall or change the rainfall pattern but we can manage it in a better way to increase the economic benefits. An effort was made in this research to contribute to the literature on rainwater harvesting in general and design of tank irrigation system in particular. The research provided an analysis for optimizing the tank system to get maximum benefits from the available rainfall. Research showed that net benefits from the available water can be increased by optimizing the tank system design in the watershed. The literature on rainwater harvesting suggest that there is a great scope to make more water available for the productive use from the same rainfall if it is properly managed. And therefore it is literally true that "Sky is the only limit for rainwater harvesting".

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Appendix A3-1

Equations for estimation of evaporation and evapotranspiration

A) Equation for evaporation-Penman (1948) equation:

Following Penman equation was used for estimating evaporation from open water surfaces

$$E_0 = 0.35\left(1+9.8x10^{-3}u_2\right)\left(e_s - e_d\right) \quad \text{(A3-1.1)}$$

Where
E_0 = Evaporation from open water surface mm/day
u_2 = Wind velocity at 2 m height mile/day
e_s = Vapour pressure at the avaporating surface, mm Hg
e_d = Vapour pressure in the atmosphere above, mm Hg

B) Equation for estimation of evapotranspiration

Following Penman-Monteith equation was used for estimating reference crop evapotranspiration

$$\chi \mathrm{ET0} = \frac{\Delta(R_n - G) + \ell C_p(e_a - e_d)1/\gamma_a}{\Delta + \gamma(1+\gamma_c/\gamma_a)} \quad \text{(A3-1.2)}$$

To facilitate analysis,
ET0 = $ET_{rad} + ET_{aero}$

where, χ ETO = latent heat flux of evaporation, $KJm^{-2}s^{-1}$,
Δ = Slope of vapour pressure curve, KPa^0c^{-1},
Rn = Net radiation flux at surface, $KJm^{-2}s^{-1}$,
G = Soil heat flux, $KJm^{-2}s^{-1}$,
ℓ = Atmospheric density, kgm^{-3},
Cp = Specific heat moist air, $KJkg^{-10}C^{-1}$,
(e_a-e_d) = Vapour pressure deficit, Kpa,
γ_a= aerodynamic resistance, m^{-1},
γ_c=crop canopy resistance, m^{-1},
γ=psychometric constant, KPa^0C^{-1},
χ = Latent heat of vaporization, MJ kg^{-1},

Recommended combination formula for reference evapotranspiration (ET_0) :

$$ET_0 = \frac{0.408\Delta(Rn-G)+\gamma\frac{900}{T+273}U_2(e_a-e_d)}{\Delta+\gamma(1+0.34U_2)} \quad \text{(A3-1.3)}$$

Where,

$ET0$ = Reference crop evapotranspiration, mmd^{-1},
Rn = Net radiation at crop surface, MJ $m^{-2}d^{-1}$,
G = Soil heat flux, MJ $m^{-2}d^{-1}$,
T = Average temperature, ^0C,
U_2 = Wind speed measured at 2 m height, ms^{-1},
(e_a-e_d) = Vapour pressure deficit, KPa,
Δ = Slope of vapour pressure curve, KPa^0C^{-1},
γ =Psychometric constant, KPa^0C^{-1},
900 = KJ^{-1} kg K

Step 1 is calculation of Δ
Step 2 is calculation of Rn
Step 3 is calculation of G
Step 4 is calculation of
Step 5 is calculation of T,
Step 6 is calculation of U_2,
Step 7 is calculation of $(e_a - e_d)$,

STEP 1 :
Calculation of Δ

$$\Delta = \frac{4098e_a}{(T+237.3)^2}$$

where, T = Air temperature, 0C,
ea = Saturation vapour pressure at temperature T, KPa,
Now,

$$ea = 0.611.\exp[\frac{17.27T}{T+237.3}]$$

Thus for calculation of step 1 temperature (^0C) as data input is required. Now, lets move directly to step 7 in which we will be calculating (e_a-e_d) of which e_a has been already been calculated,

e_d = actual vapour pressure, KPa.

$$e_d = \frac{RH_{mean}}{\left[\frac{50}{e_a(T_{min})}+\frac{50}{e_a(T_{max})}\right]}$$

$$RH_{mean} = \frac{RH_{max}-RH_{min}}{2.0}$$

Thus, for calculating e_d we require minimum and maximum values of temp. and relative humidity.

STEP 2 : Calculation of Rn;

$$Rn = Rns - Rnl$$

a) $Rns = 0.77\,(0.19 + 0.38\,\frac{n}{N})\,Ra$

b) $Rnl = 2.45 \times 10^{-9}\,(0.9\,\frac{n}{N} + 0.1)\,(0.34 - 0.14\,\sqrt{e_d}\,)\,(T_{kx}^4 + T_{kn}^4\,)$

Now, consider **step 2a** : That is,

$$Rns = 0.77\,(0.19 + 0.38\,\frac{n}{N})\,Ra$$

Here, $\frac{n}{N}$ = relative sunshine fraction,

n = bright sunshine hours per day, hr

N = maximum day light hours, hr

Ra = Extra terrestrial radiation.

$N = 7.64\,\omega_s$

We have to give input value of n as no standard empirical or any other type of equation so as to calculate bright sunshine hours per day is available.

Now as we will move ahead to calculate Ra the question of to calculate N will be solved

$$Ra = 37.6\,dr\,(\omega_s\,\sin\Psi\sin\delta + \cos\Psi\cos\delta\sin\omega_s)$$

Here,

dr = Relative distance between earth and Sun,

$dr = 1 + 0.033\cos(0.0172\,J)$

where, J = Number of the day in the year,

$$J = (275\,\frac{M}{9} - 30 + D) - 2,$$

Here, M = month number,

D = day of the month

If M < 3, then J = J+2,

If leap year and M > 2, then J = J + 1,

ω_s = Sunset hour angle, rad

ψ = latitude, rad

δ = solar declination, rad

$\delta = 0.409\sin(0.0172J - 1.39)$

$\omega_s = \arccos(-\tan\psi\ .\tan\delta\,)$

The value of latitude in degrees, minute, second will be given as input data.

[180^0 = radians = 3.1415927

therefore, x^0 = how many radians ?

$$rad = \frac{x^0 3.1415927}{180}\ ]$$

Now, consider **Step 2b**:

$$Rn1 = 2.45 \times 10^{-9} (0.9 \frac{n}{N} + 0.1)(0.34 - 0.14 \sqrt{e_d})(T_{kx}^4 + T_{kn}^4)$$

All parameters required to calculate Rn1 have already been calculated except,

$T_{kx} = T^0C_{max} + 273$

$T_{kn} = T^0C_{min} + 273$

STEP 3 : Calculation of G

$G = 0.14 (T_{month\,n} - T_{month\,(n-1)}) \approx 0$

STEP 4 : Calculation of γ

$$\gamma = 0.00163 \frac{P}{\chi}$$

χ =2.45 or $2.501 - (2.361 \times 10^{-3})\,T$

$$P = 101.3 \left(\frac{293 - 0.00652Z}{293}\right)^{5.26}$$

Z = elevation, m

STEP 5 : Calculation of T

T is our input data.

STEP 6 : Calculation of U_2

$$U_2 = \frac{4.87 Uz1}{\ln(67.8z1 - 5.82)}$$

U_{z1} = wind speed measured at height z1, ms^{-1},

Therefore, we need two more input values U_{z1} and z1

Input values required :

i) Temp., 0C
ii) Minimum temp.
iii) Maximum temp.
iv) Relative humidity, minimum %
v) Relative humidity, maximum %
vi) No of bright sunshine hours, hr
vii) Latitude, degree, minute, sec
viii) Altitude, m
ix) Wind speed measured at height Z1, m/s at m.

Appendix A3-2

Determination of Green Ampt parameters from Infiltration test data

Procedure for determination of G-A parameters

Following paragraphs describe the procedure for estimating the G-A model parameters from measure infiltration data.

Green Ampt infiltration equation can be written as

$$f=\frac{A}{F}+B \qquad \text{(A3-2.1)}$$

Where

f = Infiltration rate in cm/h
F = Cumulative infiltration, cm
$A = K_s \cdot M \cdot CP$
K_s = Saturated hydraulic conductivity of the soil, cm/h
$M = \theta_s - \theta_i$
θ_s = Saturated moisture content cm³/cm³
θ_i = Initial moisture content cm³/cm³
CP = Capillary potential, cm
$B=K_s$

Equation 3.5 can be written as

$$f=A\cdot G+B \qquad \text{(A3-2.2)}$$

where, $G=\frac{1}{F}$

With the help of observed data of infiltration rate, plot the curve of f vs G. Plot the best-fit straight line through the scatter. The intercept on Y-axis gives the value of B and slope of the curve gives the value of A.

$K_s = B$ and

$$CP = \frac{A}{K_s \cdot M}$$

Use these values of parameters for the estimation of infiltration rate by the Green Ampt equation.

Calculations for determination of G-A parameters for the Akola watershed

Time	Infiltration rate, (f), mm/h	Time, h	Incremental time, h	Incremental infiltration, mm	Cumulative infiltration (F), mm	1/F (G)
1	120.00	0.02	0.02	2.00	2.00	0.50
3	90.00	0.05	0.03	3.00	5.00	0.20
5	60.00	0.08	0.03	2.00	7.00	0.14
10	30.40	0.17	0.08	2.53	9.53	0.10
20	20.50	0.33	0.17	3.42	12.95	0.08
30	15.00	0.50	0.17	2.50	15.45	0.06
60	12.50	1.00	0.50	6.25	21.70	0.05
90	11.00	1.50	0.50	5.50	27.20	0.04
130	10.30	2.17	0.67	6.87	34.07	0.03
260	10.10	4.33	2.17	21.88	55.95	0.02
350	10.10	5.83	1.50	15.15	71.10	0.01

The graph of f vs. G is shown in Fig A31-1

Slope of the curve (A) = 253.43

Y-intercept (B) = 7.0185

Therefore $K_s = B = 7.0185$ mm/h

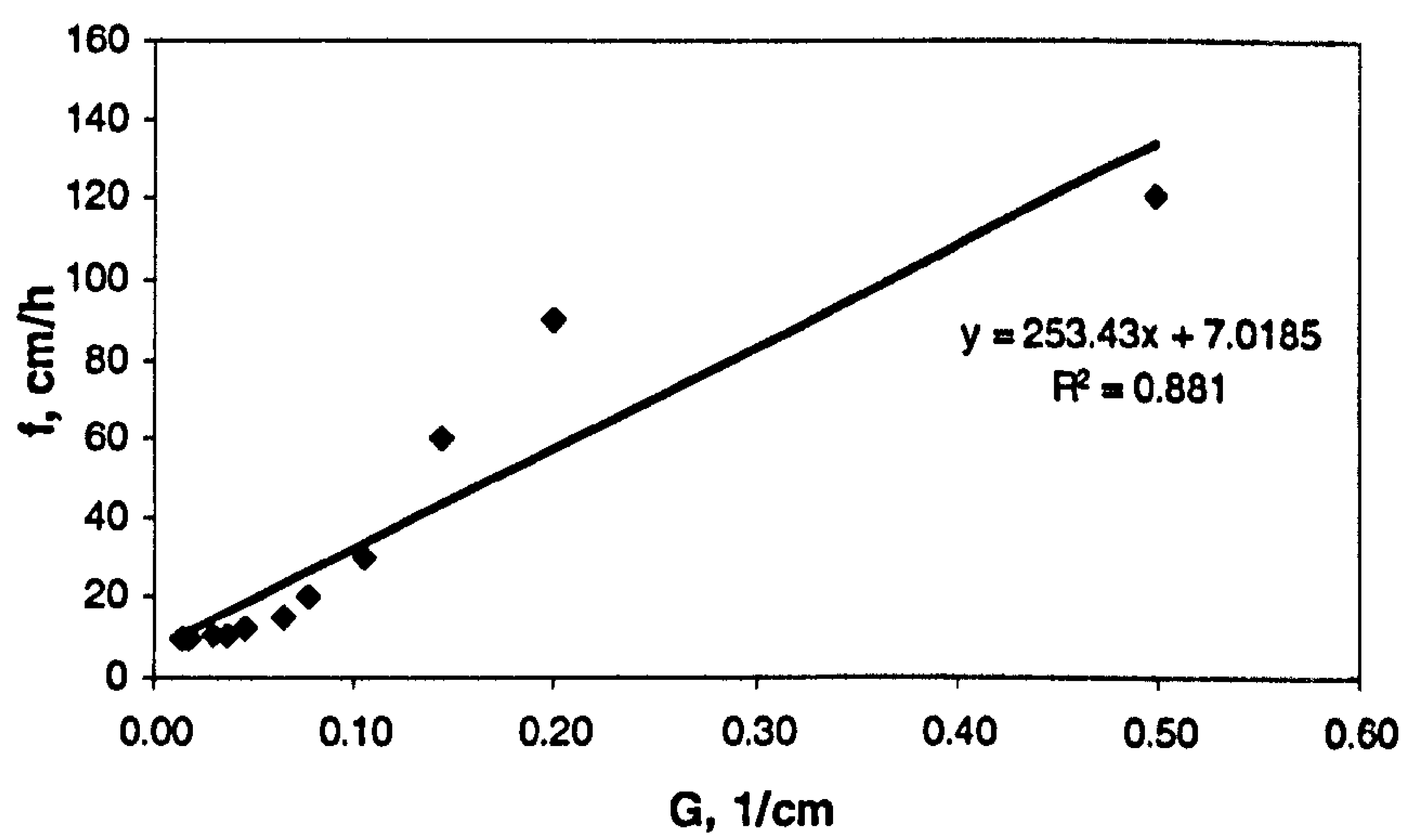

Figure A31-1 Graph of f vs. G for a soil in Akola watershed

$$CP = \frac{A}{K_s \cdot M}; \qquad \theta_s = 46.86; \quad \theta_i = 21.44; \qquad M = \theta_s - \theta_i = 25.42$$

$$CP = \frac{253.43}{7.0185 \times 25.42} = 142.06 \text{ mm/h}$$

Use these values of K_s and CP for the estimation of infiltration rate by the Green Ampt equation. The graph of observed and estimated infiltration rate with the calibrated parameters is shown in Fig. A31-2

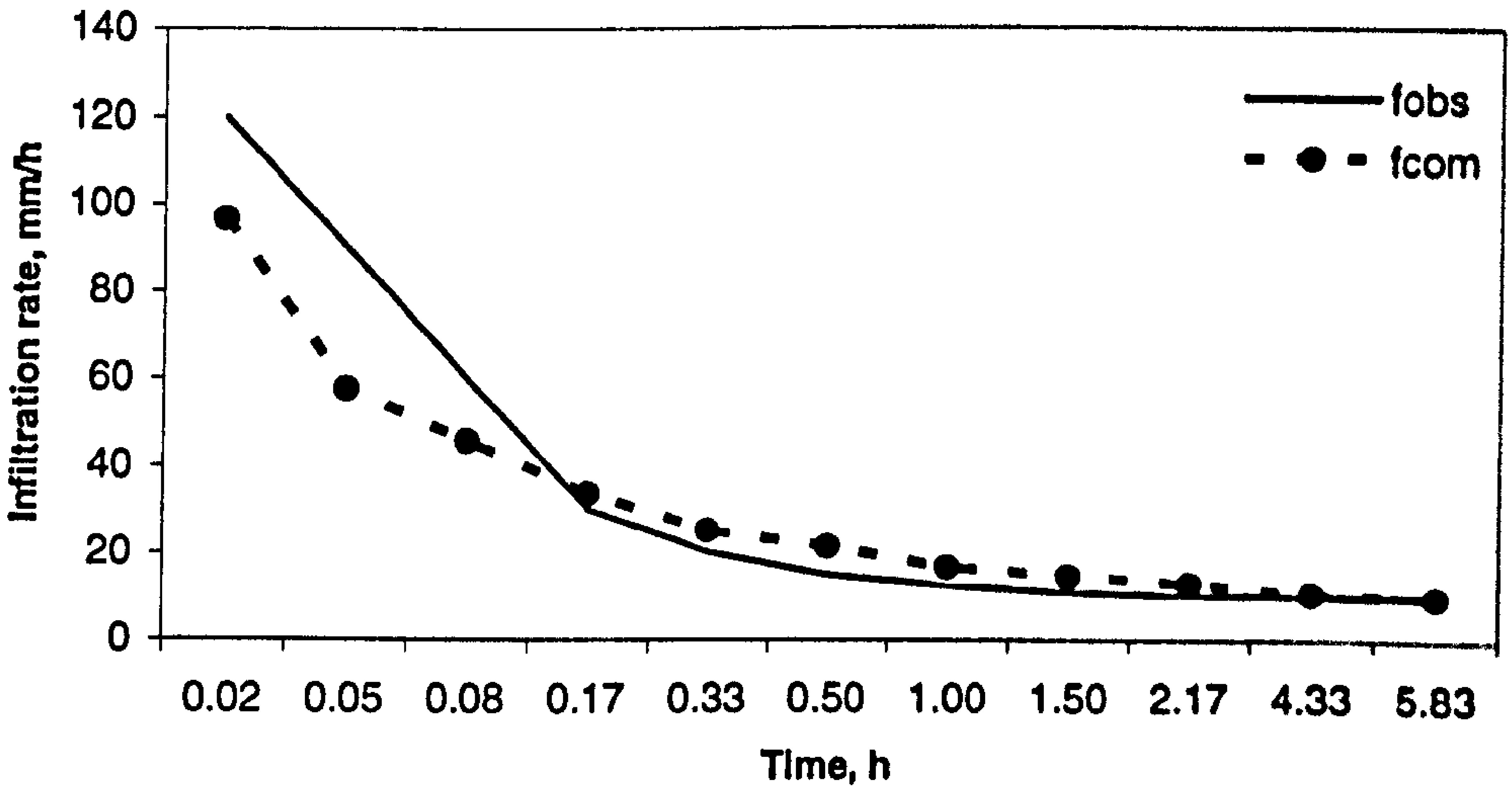

Figure A31-2 Graph of observed vs estimated infiltration rates

Appendix A 6-1

Lagrange formulations for optimum tank dimensions

Rectangular prism

A ratio (r) of width to length is required to define the rectangular shapo. Tank dimensions are optimized for discrete values of 'r' ranging from 0.1 to 0.9 with increments of 0.1.

$$
\begin{aligned}
&Min \quad 2\left[r\,l^2+(1+r)\,l\,d\right] \\
&st \\
&r\,l^2 d \;=\; V
\end{aligned}
\qquad \text{(A6-1.1)}
$$

Where
l, and d are the length and depth

The Lagrange function L is given as:

$$L \;=\; 2\left[r l^2+(1+r)\,l\,d\right]-\lambda\left(r l^2 d-V\right) \qquad \text{(A6-1.2)}$$

After solving

$$d=\sqrt[3]{\frac{V}{c_1}} \qquad \text{(A6-1.3)}$$

$$l=c_2\,d$$

Where c_1 and c_2 are the values of constants that arise in the equation for difforont ratios (r) as given in the following table

Ratio	Coefficient	Donominator
0.1	16.5	27.23
0.2	3.0	1.8
0.3	2.17	1.41
0.4	1.75	1.22
0.5	1.5	1.125
0.6	1.33	1.06
0.7	1.21	1.02
0.8	1.125	1.01
0.9	1.05	0.99

Inverted truncated pyramid (Trapezoidal)

$$Min \quad 2\left[ld\left(z^2+1\right)^{1/2}+zd^2\left(z^2+1\right)^{1/2}\right]+2\left[bd\left(z^2+1\right)^{1/2}+zd^2\left(z^2+1\right)^{1/2}\right]+lb$$

st

$$lbd+lzd^2+bzd^2+2z^2d^3 \quad = \quad V$$

(A6-1.4)

where,

l	=	the base length, m
b	=	the base breadth, m
d	=	the depth, m
z	=	side slope
V	=	the required quantity to be stored in the reservoir, m^3

The Lagrange function L is given as:

$$L \quad = \quad 2\left[ld\left(z^2+1\right)^{1/2}+zd^2\left(z^2+1\right)^{1/2}\right]+2\left[bd\left(z^2+1\right)^{1/2}+zd^2\left(z^2+1\right)^{1/2}\right]+lb$$
$$\lambda\left(lbd+lzd^2+bzd^2+2z^2d^3-V\right)$$

(A6-1.5)

After solving

$$4\left(z^2+1\right)^{1/2}d-2\lambda bd-2\lambda zd^2 = \quad 0$$

$$4\left(z^2+1\right)^{1/2}b+8z\left(z^2+1\right)^{1/2}d-\lambda b^2-4z\lambda bd-6\lambda z^2d^2 \quad = \quad 0$$

(6.14)

$$-b^2d-2zbd^2-2z^2d^3+V \; = \; 0$$

These three equations are then solved to obtain the values of l, b and d.

Cylindrical

$$Min \quad \left(2\,\frac{\pi}{4}h^2+\pi hd\right)$$

st (A6-1.6)

$$\frac{\pi}{4}h^2d \quad = \quad V$$

where,

h = the diameter, m

d = the depth, m

V = the required quantity to be stored in the reservoir, m^3

The Lagrange function L is given as:

$$L = \left(\pi hd + 2\frac{\pi}{4}h^2\right) - \lambda\left(\frac{\pi}{4}h^2 d - V\right) \quad \text{(A6-1.7)}$$

After solving

$$h = d$$

$$d = \sqrt[3]{\frac{4V}{\pi}}$$

Hemi-spherical

$$Min \left(\frac{\pi d^2}{2}\right)$$

$$st \quad \text{(A6-1.8)}$$

$$\frac{\pi}{12}d^3 = V$$

Where

d = diameter of spherical tank, m

The Lagrange function L is given as:

$$L = \frac{\pi d^2}{2} - \lambda\left(\frac{\pi}{12}d^3 - V\right) \quad \text{(A6-1.9)}$$

After solving

$$d = \sqrt[3]{\frac{12\ V}{\pi}} \quad \text{(A6-1.10)}$$

Appendix A6-2

Storage Excavation ratios considered in the study

Tank capacity, m^3	Storage excavation ratio
Less than 1000	1
1000-5000	2
5000-50000	3
50000-100000	5
100 000-500000	7
500000-1000000	9
1000000-1500000	12
1500000-2000000	15
2000000-2500000	18
more than 2500000	20

Appendix A6-3

Estimation of depth of rainfall required for initiating crop sowing
(This depth is used in the sowing criteria No 3 discussed in Section 6.3.8.1)

Assumption
For estimating the depth of rainfall for initiating crop sowing it is assumed that sowing takes place when the top 10 cm of soil layer attains moisture at field capacity

Computations of depth of rainfall required for initiating crop sowing in Akola and Pimpalgaon watersheds are shown below.

Akola watershed

Soil No.	Field capacity %	Wilting point, %	Bulk density, gm/cm^3	Sowing Depth, cm	Depth of water cm/m	Total depth of water, cm	Fraction of soils in the watershed	Depth required for the fraction of soils, cm
1	32.2	15.1	1.42	10	24.28	2.43	0.17	0.42
2	32.5	19.19	1.4	10	18.63	1.86	0.20	0.38
3	32.5	15.08	1.38	10	24.04	2.40	0.03	0.07
4	21.58	10.15	1.38	10	15.77	1.58	0.01	0.02
5	24.34	12.2	1.34	10	16.27	1.63	0.01	0.02
6	25.79	13.5	1.31	10	16.10	1.61	0.01	0.02
7	31.3	16.1	1.27	10	19.30	1.93	0.01	0.03
8	29.2	15.3	1.22	10	16.96	1.70	0.01	0.02
9	20.9	15.1	1.25	10	7.25	0.73	0.01	0.01
10	31.1	16.7	1.25	10	18.00	1.80	0.01	0.02
11	29.1	15.2	1.32	10	18.35	1.83	0.11	0.20
12	28.98	15.2	1.39	10	19.15	1.92	0.39	0.75
Total								1.97

Rainfall required for sowing: 1.97 cm = 19.7 mm = 20 mm

Pimpalgaon Ujjaini watershed

Soil Id	Field capacity %	Wilting point, %	Bulk density, gm/cm^3	Sowing Depth, cm	Depth of water cm/m	Total depth of water, cm	Fraction of soils in the watershed	Depth required for the fraction of soils, cm
1	24	12	1.35	10	16.20	1.62	0.05	0.09
2	32	15	1.35	10	22.95	2.30	0.01	0.02
3	18	10	1.5	10	12.00	1.20	0.02	0.03
4	18	10	1.5	10	12.00	1.20	0.13	0.16
5	20	10	1.35	10	13.50	1.35	0.03	0.04
6	32	15	1.35	10	22.95	2.30	0.00	0.00
7	20	10	1.35	10	13.50	1.35	0.15	0.20
8	24	12	1.35	10	16.20	1.62	0.09	0.15
9	18	10	1.5	10	12.00	1.20	0.03	0.04
10	32	15	1.35	10	22.95	2.30	0.05	0.12
11	32	15	1.35	10	22.95	2.30	0.12	0.27
12	32	15	1.35	10	22.95	2.30	0.07	0.15
13	32	15	1.35	10	22.95	2.30	0.00	0.00
14	32	15	1.35	10	22.95	2.30	0.24	0.55
							Total	1.82

Rainfall required for sowing: 1.82 cm = 18.2 mm = 20 mm

Appendix A6-4

Depth of Irrigation application

Depth of irrigation application in the case of irrigation scheduled as per fix depth fix interval criteria is estimated as below.

Akola watershed

Soil Id	Field capacity %	Wilting point, %	Bulk density, gm/cm^3	Soil Depth, cm	Depth of water cm/m	Total depth of water, cm	Area for soils	Fraction of soils in the watershed	Depth required for the fraction of soils, cm
1	32.2	15.1	1.42	118	24.28	28.65	4.70	0.17	4.99
2	32.5	19.19	1.4	117	18.63	21.80	5.50	0.20	4.44
3	32.5	15.08	1.38	74	24.04	17.79	0.80	0.03	0.53
4	21.58	10.15	1.38	20	15.77	3.15	0.40	0.01	0.05
5	24.34	12.2	1.34	20	16.27	3.25	0.35	0.01	0.04
6	25.79	13.5	1.31	20	16.10	3.22	0.34	0.01	0.04
7	31.3	16.1	1.27	76	19.30	14.67	0.36	0.01	0.20
8	29.2	15.3	1.22	81	16.96	13.74	0.36	0.01	0.18
9	20.9	15.1	1.25	83	7.25	6.02	0.35	0.01	0.08
10	31.1	16.7	1.25	80	18.00	14.40	0.34	0.01	0.18
11	29.1	15.2	1.32	79	18.35	14.49	2.90	0.11	1.56
12	28.98	15.2	1.39	60	19.15	11.49	10.60	0.39	4.51
								Total	**16.79**

Depth of irrigation = 16.79 cm
Depth of irrigation at 50% depletion = 8.40 cm
Application efficiency = 0.7
Depth of irrigation application = 11.99 cm= 12 cm = **120 mm**

Pimpalgaon Ujjaini Watershed

Soil Id	Field capacity %	Wilting point, %	Bulk density, gm/cm^3	Soil Depth, cm	Depth of water cm/m	Total depth of water, cm	Fraction of soils in the watershed	Depth required for the fraction of soils, cm
1	24	12	1.35	25	16.20	4.05	0.05	0.22
2	32	15	1.35	25	22.95	5.74	0.01	0.04
3	18	10	1.5	25	12.00	3.00	0.02	0.07
4	18	10	1.5	25	12.00	3.00	0.13	0.40
5	20	10	1.35	25	13.50	3.38	0.03	0.10
6	32	15	1.35	25	22.95	5.74	0.00	0.00
7	20	10	1.35	25	13.50	3.38	0.15	0.51
8	24	12	1.35	25	16.20	4.05	0.09	0.37
9	18	10	1.5	25	12.00	3.00	0.03	0.09
10	32	15	1.35	45	22.95	10.33	0.05	0.54
11	32	15	1.35	90	22.95	20.66	0.12	2.47
12	32	15	1.35	90	22.95	20.66	0.07	1.37
13	32	15	1.35	90	22.95	20.66	0.00	0.02
14	32	15	1.35	25	22.95	5.74	0.24	1.38
							Total	**7.59**

Depth of irrigation =7.59 cm
Depth of irrigation at 50% depletion = 3.795 cm
Application efficiency = 0.7
Depth of irrigation application = 5.42 cm= **55 mm**

Appendix A 6-5

Estimation of initial cost (per ha) of horticultural plantations

	Spacing	Life	Seedlings cost	Total No of Seedling	Total seedling cost	Cost of pits	Plantation cost, Rs/ha
Gooseberry	5x5m	15	10	400	4000	378	4378
Mango	10x10 m	20	15	200	3000	320	3320
Sapota	10x10 m	20	30	200	6000	320	6320
Guava	5x5m	15	5	400	2000	378	2378
Cus. Apple	5x5m	10	5	400	2000	378	2378
Coconut	10x10 m	20	25	200	5000	320	5320
Pomgranate	5x5m	10	5	400	2000	378	2378
Lime	5x5m	10	2	400	800	378	1178
Fig	5x5m	10	30	400	12000	378	12378
Orange	5x5m	15	20	400	8000	378	8378
Ziziphus (Ber)	5x5m	10	2	400	800	378	1178

Appendix A6-6

Estimation of drip system cost (per ha)

Cost of Drip Irrigation unit for crop having spacing 5 x 5 m

Sr. No	Name of the Component	Quantity	Rate (Rs.)	Cost/Fixed capital (Rs.)	Life (L) Years
1	Centrifugal pump set & accessories	1	7000	7000	20
2	Sand filter with pr.guage	1	6378	6378	20
3	Screen filter	1	2500	2500	20
4	Back flush assembly	1	196.2	196.2	20
5	Sub main flush valve	1	73	73	12
6	Fertilizer tank	1	3943	3943	20
7	By pass assembly	1	841	841	20
8	PVC pipe, (63 mm)	150 m	27.8/ m	4170	12
11	PVC End cap (63 mm)	1	40	40	12
12	PVC threaded flushing cap (63 mm)	1	40	40	12
13	PVC Ball valve, (63 mm)	1	801	801	12
14	PVC Elbow (.63 mm)	1	22	22	12
15	Pressure gauge	1	107.5	107.5	12
16	LDPE lateral (16 mm)	2000 m	6.2/ m	12400	12
17	GTO for lateral (16mm)	40	2.75 each	110	6
19	Drippers (8 LPH)	2000	2.35 each	4700	6
22	Miscellaneous charges			400	6
23	Installation charges			400	6

Cost of Drip Irrigation unit for crop having spacing 10 x 10 m

Sr. No	Name of the Component	Quantity	Rate (Rs.)	Cost/Fixed capital (Rs.)	Life (L) Years
1	Centrifugal pump set & accessories	1	7000	7000	20
2	Sand filter with pr.guage	1	6378	6378	20
3	Screen filter	1	2500	2500	20
4	Back flush assembly	1	196.2	196.2	20
5	Sub main flush valve	1	73	73	12
6	Fertilizer tank	1	3943	3943	20
7	By pass assembly	1	841	841	20
8	PVC pipe, (63 mm)	150 m	27.8/ m	4170	12
11	PVC End cap (63 mm)	1	40	40	12
12	PVC threaded flushing cap (63 mm)	1	40	40	12
13	PVC Ball valve, (63 mm)	1	801	801	12
14	PVC Elbow (.63 mm)	1	22	22	12
15	Pressure gauge	1	107.5	107.5	12
16	LDPE lateral (16 mm)	2000 m	6.2/ m	12400	12
17	GTO for lateral (16mm)	40	2.75 each	110	6
19	Drippers (8 LPH)	800	2.35 each	1880	6
22	Miscellaneous charges			400	6
23	Installation charges			400	6

Appendix-A7-1

Input Data File Formats

1. Field Data File:

Sr. No.	Parameter	Type	Default Value
1	Number of Fields	Integer	
2	Field Id	Integer	
3	Stream Id	Integer	
4	Field X-Coordinate	Double	
5	Field Y-Coordinate	Double	
6	Field Z-Coordinate	Double	
7	Field Area	Double	
8	Field Landuse	Integer	
9	Field Treatment	Integer	1 – Row 2 – Contoured 3 – Contour & Terraced
10	Field Hydrologic Condition	Integer	1 – Poor 2 – Fair 3 – Good
11	Field Soil Id	Integer	
12	Field Trench	Boolean	0 – No Trench 1 – Trench
13	Field Trench Id	Integer	

2. Stream Data File:

Sr. No.	Parameter	Type	Default Value
1	Number of Streams	Integer	
2	Number of Stream Points	Integer	
3	Stream Point Id	Integer	
4	Stream Point X-Coordinate	Double	
5	Stream Point Y-Coordinate	Double	
6	Stream Point Z-Coordinate	Double	
7	Tank Shape Id	Integer	1 – Square prism 2 – Rectangular prism 3 – Truncated pyramid 4 – Cylindrical 5 – Hemispherical 6 – Parabolic
8	Stream Id	Integer	
9	Number of Inflow Stream Points	Integer	
10	Inflow Stream Point Id	Integer	
11	Outlet Stream Point Id	Integer	

3. Field-Crop Data File:

Sr. No.	Parameter	Type	Default Value
1	Field Id	Integer	
2	Field Type	Integer	1 – Single crop 2 – Double crop 3 – Triple crop 4 – Horticulture 5 – Agro-forestry 6 – Bare field
3	Crop Id	Integer	

4. Crop Data File:

Sr. No.	Parameter	Type	Default Value
1	Number of Crops	Integer	
2	Crop Id	Integer	
3	Crop CN Id	Integer	
4	Crop name	String	
5	Sowing date	Date	
6	Harvest date	Date	
7	Initial root zone depth	Double	
8	Maximum root zone depth	Double	
9	Days to attain maximum root zone depth	Integer	
10	Crop growth stage	Integer	
11	Number of growth stages	Integer	1 for Stage 2 for Equation
	Crop stage duration Crop stage coefficient	Integer Double	
12	Number of yield response stages	Integer	
	Yield response stage duration Yield response stage coefficient	Integer Double	
13	Maximum yield (irrigated) Maximum yield (rainfed)	Double Double	
14	Maximum depletion	Double	
15	Ratio of by produce	Double	
16	Rate of main produce (irrigated), Rs/Qtl Rate of main produce (rainfed), Rs/Qtl	Double Double	
17	Rate of by produce, Rs/Kg	Double	
18	Irrigated cost of cultivation (Rs/ha) Rainfed cost of cultivation (Rs/ha)	Double Double	

5. Horticulture Data File:

Sr. No.	Parameter	Type	Default Value
1	Number of Horticulture Crops	Integer	
2	Plant Id	Integer	
3	Plant CN Id	Integer	
4	Plant name	String	
5	Spacing (Row to Row)	Double	
6	Spacing (Plant to Plant)	Double	
7	Plant root depth, mm	Double	
8	Plant coefficient	Double	
9	Plant factor	Double	
10	Plant life, years	Integer	
11	Initial plantation cost	Double	
12	Net benefit	Double	
13	Irrigation interval	Integer	
14	Drip irrigation option Plant factor	Integer Double	1 for Plant factor
15	Drip irrigation efficiency	Double	
16	Drip installation cost	Double	

6. Soil Data File:

Sr. No.	Parameter	Type	Default Value
1	Number of Soils	Integer	
2	Soil Id	Integer	
3	Layer number	Integer	
4	Field capacity moisture content (%)	Double	
5	Wilting point moisture content (%)	Double	
6	Bulk density (g/cm^3)	Double	
7	Soil depth (cm)	Double	
8	Saturation hydraulic conductivity (mm/hr)	Double	
9	Capillary potential (mm)	Double	
10	Soil porosity	Double	
11	Saturation moisture content (%)	Double	

7. Curve Number Data File:

Sr. No.	Parameter	Type	Default Value
1	Number of curve numbers	Integer	
2	Landuse code	Integer	
3	Field treatment code	Integer	1 – Row 2 – Contoured 3 – Contour & Terraced
4	Field hydrologic condition code	Integer	1 – Poor 2 – Fair 3 – Good
5	Hydrologic soil group	Integer	1 – HSG A 2 – HSG B 3 – HSG C 4 – HSG D
6	Curve number	Integer	

8. Other Data File:

Sr. No.	Parameter	Type	Default Value
1	Tank design runoff depth, mm	Integer	
2	DSR, %	Integer	
3	DSR deviation, %	Integer	
4	Bedrock level, m	Double	
5	Initial groundwater table height, m	Double	
6	Drainable porosity, fraction	Double	
7	Domestic/other groundwater use, m^3/day	Double	
8	Surface irrigation application efficiency, %	Double	
9	Irrigation supply pipe-length (m per ha)	Double	
10	Tank pump discharge, m^3/h	Double	
11	Tank pump electrical rate Rs/KWH	Double	
12	Well pump discharge, m^3/h	Double	
13	Well pump electrical rate, Rs/KWH	Double	

9. Economics Data File:

Sr. No.	Parameter	Type	Default Value
1	Earthwork labour cost, Rs/m^3	Integer	
2	Well drilling/digging cost, Rs/m^3	Integer	
3	Pipe cost, Rs/m	Integer	
4	Irrigation labour cost, Rs/ha	Double	
5	Life of pumps, years	Integer	
6	Life of system, years	Integer	
7	Interest rate, %	Double	
8	Inflation rate, %	Double	
9	Number of tank pumps	Integer	
10	Pump number	Integer	
11	Tank Id	Integer	
12	Tank pump cost, Rs	Double	

10. Ground Water Calibration Data File:

Sr. No.	Parameter	Type	Default Value
1	Number of wells	Integer	
2	Number of observations	Integer	
3	Initial ground water table height, m	Double	
4	Bed rock level, m	Double	
5	Drainable Porosity, fraction	Double	
6	Initial well water height, m	Double	
7	Observation date	Date	
8	Observed well water level, m	Double	

11. Infiltration Calibration Data File:

Sr. No.	Parameter	Type	Default Value
1	Number of soils	Integer	
2	Soil Id	Integer	
3	Number of observations	Integer	
4	Observation time (min)	Integer	
5	Observed rate of infiltration (mm/hr)	Double	

12. Tank Dimension Data File:

Sr. No.	Parameter	Type	Default Value
1	Number of tanks	Integer	
2	Tank Id	Integer	
3	Tank shape Id	Integer	1 – Square prism 2 – Rectangular prism 3 – Truncated pyramid 4 – Cylindrical 5 – Hemispherical 6 – Parabolic
4	Tank top length side one, m	Double	
5	Tank top length side two, m	Double	
6	Tank top width side one, m	Double	
7	Tank top width side two, m	Double	
8	Tank bottom length side one, m	Double	
9	Tank bottom length side two, m	Double	
10	Tank bottom width side one, m	Double	
11	Tank bottom width side two, m	Double	
12	Tank depth, m	Double	

13. Well Data File:

Sr. No.	Parameter	Type	Default Value
1	Number of wells	Integer	
2	Average well distance from field	Double	
2	Well Earth Work Rate	Double	
3	Well Id	Integer	
4	Field Id	Integer	
5	Well diameter, m	Double	
6	Well depth, m	Double	
7	Well pump cost, Rs	Double	

Appendix-A7-2

Input Data Files for Akola watershed

Please refer to Appendix A7-1 for the format of these tables. The rows in Appendix A7-1 correspond to the columns in this appendix

1. Field Data File (Calibration and Evaluation Mode):

19											
1	1	9.00	16.50	314.40	1.80	11	1	3	1	1	2
2	1	12.00	13.50	311.30	1.20	11	1	3	2	1	2
3	1	12.00	13.50	311.30	0.80	11	1	3	3	1	2
4	1	15.80	5.50	305.40	3.20	11	1	3	2	1	2
5	1	14.10	4.00	305.30	1.00	11	1	3	1	0	
6	1	16.20	4.00	304.50	1.00	11	1	3	2	0	
7	1	16.20	2.50	304.00	1.90	11	1	3	1	0	
8	2	12.50	4.00	306.50	2.85	11	1	3	11	0	
9	2	12.50	4.00	306.50	0.05	2	2	3	11	0	
10	2	12.20	7.80	308.50	0.34	2	2	3	10	0	
11	2	12.20	8.50	308.90	0.35	2	2	3	9	0	
12	2	12.20	9.20	309.10	0.36	2	2	3	8	0	
13	2	12.10	10.00	309.50	0.36	2	2	3	7	0	
14	2	12.00	10.80	309.90	0.34	2	2	3	6	0	
15	2	12.00	11.50	309.90	0.35	2	2	3	5	0	
16	2	12.00	12.40	310.90	0.40	2	2	3	4	0	
17	2	8.40	5.50	312.30	6.70	11	1	3	12	0	
18	2	5.20	15.50	313.90	0.40	11	1	3	12	0	
19	2	5.20	15.50	313.90	3.50	1	1	1	12	0	

2. Stream Data File:

2								
6								
1	16.2	2.5	304.0	3	1	2	2	4
2	15.8	5.5	305.4	3	1	1	3	
3	12.0	13.5	311.3	3	1	0		
4	12.5	4.0	306.5	3	2	1	5	
5	8.4	5.5	311.3	3	2	1	6	
6	5.2	15.5	313.9	3	2	0		
1								

3. Field-Crop Data File (Calibration and Evaluation Mode):

1	4	8
2	4	7
3	4	3
4	5	12
5	4	6
6	4	2
7	4	7
8	4	4
9	1	2
10	1	2
11	1	2
12	1	2
13	1	2
14	1	16
15	1	16
16	1	16
17	5	12
18	4	10
19	6	

4. **Crop Data File:**

1	2	PearlMillet	09/08/2001	08/11/2001	100	2	4	0.339	5	21 - 0	2500	0.5	1.68	6.50	0.3	640
					1000			0.6696		20 - 0.2	1000			5.20		520
					40			2.1468		20 - 0.55						
								-3.14928		20 - 0.45						
								0.07891		11 - 0.2						
3	2	Sorghum_R	01/10/2001	31/01/2001	100	2	4	0.339	5	21 - 0	4000	0.5	2.41	7.50	1.5	497
					1000			0.6696		30 - 0.2	1600			6.00		497
					50			2.1468		20 - 0.55						
								-3.14928		40 - 0.45						
								0.07891		11 - 0.2						
4	2	Wheat	15/11/2001	14/03/2002	50	1	5	15 - 0.3	6	15 - 0	3500	0.5	1.79	8.00	0.125	530
					900			25 - 0.85		25 - 0.25	1680			6.40		530
					50			20 - 1		20 - 0.5						
								40 - 0.8		30 - 1						
								20 - 0.5		18 - 0.8						
										12 - 0						
5	4	Gram	24/10/2001	10/02/2002	150	2	4	0.427	5	20 - 0	2500	0.5	1.5	15.50	0.5	1030
					800			0.36585		25 - 0.5	1750			12.40		1036
					55			7.29		20 - 0.9						
								-14.51822		25 - 0.7						
								6.5766		20 - 0.2						
6	4	Pigeon Pea	18/06/2001	11/10/2002	150	1	5	10 - 0.45	5	10 - 0	2500	0.5	1.3	16.00	0.5	676
					1000			25 - 0.75		25 - 0.5	1000			12.80		676
					50			40 - 1.15		40 - 0.9						
								25 - 0.85		25 - 0.7						
								16 - 0.7		16 - 0.2						
7	4	Soybean	25/06/2001	27/10/2001	150	1	4	20 - 0.35	5	20 - 0	2500	0.5	1.11	13.00	0.25	700
					1000			25 - 0.75		25 - 0.5	1000			10.40		700
					50			50 - 1.1		25 - 0.9						
								30 - 0.75		25 - 0.7						
										30 - 0.2						

Crop Data File Contd...:

8	2	Sunflower_K	15/07/2001	15/10/2001	150	1	5	10 - 0.35	5	10 - 0	1500	0.5	2	12.00	0	800
					1000			30 - 0.75		30 - 0.25	600			9.60		800
					60			25 - 1.15		25 - 0.5						
								15 - 0.75		15 - 1						
								13 - 0.4		13 - 0						
9	2	Sunflower_R	15/10/2001	15/01/2002	150	1	5	10 - 0.35	5	10 - 0	1500	0.5	2	12.00	0	800
					1000			30 - 0.75		30 - 0.25	600			9.60		800
					60			25 - 1.15		25 - 0.5						
								15 - 0.75		15 - 1						
								13 - 0.4		13 - 0						
10	2	Safflower	15/09/2001	20/01/2002	150	1	4	15 - 0.35	5	15 - 0	1500	0.5	2.86	18.00	0	1300
					1000			40 - 0.7		40 - 0.25	1050			14.40		1300
					60			50 - 1.1		35 - 0.5						
								23 - 0.25		20 - 1						
										18 - 0						
11	4	Green gram	30/06/2001	10/09/2001	150	1	4	11 - 0.4	5	10 - 0	1200	0.5	1.57	22.00	0.5	1333
					800			25 - 0.75		18 - 0.5	840			17.60		1333
					55			25 - 1.05		15 - 0.9						
								12 - 0.5		20 - 0.7						
										10 - 0.2						
12	4	Black gram	30/06/2001	10/09/2001	150	1	4	11 - 0.4	5	10 - 0	1200	0.5	1.5	22.50	0.5	1382
					800			25 - 0.75		18 - 0.5	840			18.00		1382
					55			25 - 1.05		15 - 0.9						
								12 - 0.5		20 - 0.7						
										10 - 0.2						
13	4	Groundnut	30/06/2001	30/10/2001	150	2	4	0.367	5	13 - 0	2000	0.5	2.49	22.00	0.5	1382
					1000			0.42008		30 - 0.2	1400			17.60		1382
					40			4.56019		40 - 0.8						
								-7.91878		30 - 0.6						
								3.1713		10 - 0.2						
14	2	Maize_K	28/06/2001	08/10/2001	100	1	5	16 - 0.4	5	16 - 0.4	5000	0.5	1.59	6.50	0.1	416
					1000			27 - 0.8		27 - 0.4	2000			5.20		416
					50			41 - 1.15		20 - 1.5						
								10 - 0.85		30 - 0.5						
								9 - 0.6		10 - 0.5						

Crop Data File Contd...:

15	2	Maize_R	30/10/2001	15/02/2002	100	1	5	16 - 0.4	5	10 - 0.4	5000	0.5	1.59	6.50	0.1	416
					1000			30 - 0.8		30 - 0.4	2000			5.20		416
					50			44 - 1.15		20 - 1.5						
								10 - 0.85		40 - 0.5						
								9 - 0.6		9 - 0.5						
16	2	Cotton	20/06/2001	10/11/2001	200	1	5	16 - 0.45	5	9 - 0.2	3000	0.5	2.86	25.00	0.03	1765
					1000			32 - 0.75		20 - 0.5	900			20.00		1765
					75			40 - 1.15		25 - 0.5						
								32 - 0.85		30 - 0.75						
								24 - 0.7		60 - 0.2						
17	2	Onion	15/10/2001	14/02/2002	100	1	5	31 - 0.5	3	31 - 0.45	30000	0.5	0.94	3.00	0	100
					400			30 - 0.75		61 - 0.8	12000			2.40		100
					30			31 - 1.05		31 - 0.3						
								17 - 0.9								
								14 - 0.8								
18	2	Tomato	15/10/2001	14/02/2002	120	1	4	17 - 0.45	4	27 - 0.4	30000	0.5	0	3.00	0	100
					450			25 - 0.75		20 - 0.6	7500			2.40		100
					35			15 - 1.15		31 - 1.1						
								66 - 0.8		45 - 0.6						
19	4	Fodder	01/11/2001	31/02/2002	100	1	2	43 - 0.4	2	43 - 0.4	30000	0.5	0	1.50	0	50
					1000			80 - 1		80 - 1	15000			1.20		50
					30											

5. Horticulture Data File:

12

1	11	Fig	5	5	1000	0.65	0.40	10	12378	60878	2	1	0.3	0.9	10250
2	11	Pomegranate	5	5	1000	0.65	0.40	10	2378	63000	2	1	0.3	0.9	10250
3	11	Ber (Ziziphus)	5	5	1500	0.60	0.40	10	1178	27000	2	1	0.3	0.9	10250
4	11	Orange	5	5	1500	0.75	0.40	15	8378	76650	2	1	0.3	0.9	10250
5	11	Lime	5	5	1500	0.65	0.40	10	1178	41645	2	1	0.3	0.9	10250
6	11	Guava	5	5	800	0.70	0.40	15	2378	37059	2	1	0.3	0.9	10250
7	11	Custard_Apple	5	5	1500	0.60	0.40	10	2378	5812	2	1	0.3	0.9	10250
8	11	Gooseberry	5	5	1500	0.70	0.40	15	4378	60819	2	1	0.3	0.9	10250
9	11	Coconut	10	10	1000	0.70	0.40	20	5320	46868	2	1	0.3	0.9	9580
10	11	Mango	10	10	1200	0.70	0.40	20	3320	39615	2	1	0.3	0.9	9580
11	11	Sapota	10	10	1200	0.75	0.40	20	6320	42160	2	1	0.3	0.9	9580
12	11	Silvipasture	5	5	1300	0.75	0.40	20	15000	7000	2	1	0.3	0.9	0

6. Soil Data File:

12								
1								
1	32.2	15.10	1.42	118	7.0	142.0	0.40	43.0
3								
2								
1	32.5	19.19	1.40	117	1.5	218.5	0.40	43.0
3								
3								
1	32.5	15.08	1.38	74	1.5	218.5	0.40	43.0
3								
4								
1	21.58	10.15	1.38	20	29.9	61.3	0.44	40.1
3								
5								
1	24.34	12.2	1.34	20	29.9	61.3	0.44	40.1
3								
6								
1	25.79	13.50	1.31	20	29.9	61.3	0.44	40.1
3								
7								
1	31.30	16.10	1.27	76	1.5	218.5	0.40	33.0
3								
8								
1	29.20	15.30	1.22	81	10.9	110.1	0.45	41.2
3								
9								
1	20.90	15.10	1.25	83	29.9	61.3	0.44	40.1
3								
10								
1	31.10	16.70	1.25	80	1.5	218.5	0.40	33.0
3								
11								
1	29.10	15.20	1.32	79	10.9	110.1	0.45	41.2
3								
12								
1	28.98	15.20	1.39	60	10.9	110.1	0.45	41.2
3								

7. Curve Number Data File:

1	1	1	1	77
1	1	1	2	86
1	1	1	3	91
1	1	1	4	94
2	1	1	1	72
2	1	1	2	81
2	1	1	3	88
2	1	1	4	91
2	1	3	1	67
2	1	3	2	78
2	1	3	3	85
2	1	3	4	89
2	2	1	1	70
2	2	1	2	79
2	2	1	3	84
2	2	1	4	88
2	2	3	1	65
2	2	3	2	75
2	2	3	3	82
2	2	3	4	86
2	3	1	1	66
2	3	1	2	74
2	3	1	3	80
2	3	1	4	82
2	3	3	1	62
2	3	3	2	71
2	3	3	3	78
2	3	3	4	81
3	1	1	1	65
3	1	1	2	76
3	1	1	3	84
3	1	1	4	88
3	1	3	1	63
3	1	3	2	75
3	1	3	3	83
3	1	3	4	87
3	2	1	1	63
3	2	1	2	74
3	2	1	3	82
3	2	1	4	85
3	2	3	1	61
3	2	1	2	73
3	2	1	3	81
3	2	1	4	84
3	3	1	1	61
3	3	1	2	72
3	3	1	3	79
3	3	1	4	82

3	3	3	1	59
3	3	3	2	70
3	3	3	3	78
3	3	3	4	81
4	1	1	1	66
4	1	1	1	77
4	1	1	1	85
4	1	1	1	89
4	1	3	1	58
4	1	3	2	72
4	1	3	3	81
4	1	3	4	85
4	2	1	1	64
4	2	1	2	75
4	2	1	3	83
4	2	1	4	85
4	2	3	1	55
4	2	3	2	69
4	2	3	3	78
4	2	3	4	83
4	3	1	1	63
4	3	1	2	73
4	3	1	3	80
4	3	1	4	83
4	3	3	1	51
4	3	3	2	67
4	3	3	3	76
4	3	3	4	80
5	1	1	1	68
5	1	1	2	79
5	1	1	3	86
5	1	1	4	89
5	1	2	1	49
5	1	2	2	69
5	1	2	3	79
5	1	2	4	84
5	1	3	1	39
5	1	3	2	61
5	1	3	3	74
5	1	3	4	80
5	2	1	1	47
5	2	1	2	67
5	2	1	3	81
5	2	1	4	88
5	2	2	1	25
5	2	2	2	59
5	2	2	3	75
5	2	2	4	83
5	2	3	1	6
5	2	3	2	35
5	2	3	3	70
5	2	3	4	79
6	1	3	1	30
6	1	3	1	58
6	1	3	1	71
6	1	3	1	78
7	1	1	1	45
7	1	1	2	66
7	1	1	3	77
7	1	1	4	83
7	1	2	1	36
7	1	2	2	60
7	1	2	3	73
7	1	2	4	79
7	1	3	1	25
7	1	3	2	55
7	1	3	3	70
7	1	3	4	77
8	1	1	1	59
8	1	1	2	74
8	1	1	3	82
8	1	1	4	86
9	1	1	1	72
9	1	1	2	82
9	1	1	3	87
9	1	1	4	89
10	1	1	1	77
10	1	1	2	84
10	1	1	3	90
10	1	1	4	92
11	1	1	1	57
11	1	1	2	73
11	1	1	3	82
11	1	1	4	86
11	1	2	1	43
11	1	2	2	65
11	1	2	3	76
11	1	2	4	82
11	1	3	1	32
11	1	3	2	58
11	1	3	3	72
11	1	3	4	79

8. Other Data File:

70 90 110 125 58 100 50 80 17 130 200 46 250 28 120 20 130 90 110 60 80 65 46 100 43 30 52 10
65
10
300
301
0.1
3
0.70
125
360
0.006
72
0.04

9. Economics Data File:

35
700
73
150
20
30
0.12
0.05
6

1	1	12000
2	2	12000
3	3	12000
4	4	12000
5	5	12000
6	6	12000

10. Groundwater Calibration Data File (Year: 1996-1997):

6 52 301.05 299.74 0.1

			302.50	301.05	301.07	306.36	306.41	303.83
3	6	1996	302.50	301.05	301.07	306.36	306.41	303.83
10	6	1996	301.25	300.85	300.92	306.26	306.31	303.73
17	6	1996	300.65	300.80	300.82	306.16	306.21	303.73
24	6	1996	300.55	300.80	300.82	306.16	306.21	303.73
1	7	1996	300.55	300.80	300.82	306.16	306.21	303.73
8	7	1996	300.55	300.80	300.82	306.16	306.21	303.73
15	7	1996	300.55	300.80	300.82	306.16	306.21	303.73
22	7	1996	300.55	300.80	300.87	306.21	306.31	303.78
29	7	1996	300.65	300.80	300.87	306.21	306.31	303.78
5	8	1996	300.65	300.80	300.92	306.26	306.31	303.83
12	8	1996	300.70	300.85	300.92	306.26	306.36	303.83
19	8	1996	300.75	300.90	301.12	306.31	306.36	303.88
26	8	1996	301.35	301.60	301.82	307.41	307.51	304.03
2	9	1996	304.55	301.65	301.87	307.41	307.51	304.13
9	9	1996	304.75	305.00	305.92	307.86	308.86	306.83
16	9	1996	305.85	305.60	306.02	308.11	308.91	308.73
23	9	1996	305.95	305.75	306.07	308.46	309.31	308.83
30	9	1996	305.75	305.50	305.62	308.66	309.51	308.63
7	10	1996	305.95	305.55	305.62	308.76	309.91	308.53
14	10	1996	306.05	305.50	305.32	308.46	309.91	308.53
21	10	1996	305.65	305.50	305.32	308.36	309.91	308.43
28	10	1996	306.05	305.95	305.67	309.56	311.16	309.13
4	11	1996	306.05	305.95	305.72	309.51	311.11	309.13
11	11	1996	305.95	305.60	305.52	309.46	311.06	309.03
18	11	1996	305.80	305.50	305.32	309.36	311.01	308.98
25	11	1996	305.75	305.45	305.32	309.36	310.91	308.93
2	12	1996	305.55	305.25	305.02	309.06	310.31	308.73
9	12	1996	305.35	305.05	304.82	308.96	310.01	308.63
16	12	1996	305.05	304.95	304.62	308.86	309.86	308.03
23	12	1996	305.05	304.90	304.57	308.86	309.86	307.83
30	12	1996	304.90	304.65	304.52	308.76	309.61	307.68
6	1	1997	304.67	304.55	304.42	308.66	309.56	307.63
13	1	1997	304.65	304.45	304.37	308.56	309.51	307.53
20	1	1997	304.55	304.40	304.37	308.46	309.41	307.53
27	1	1997	304.30	304.15	304.32	308.36	309.21	307.43
3	2	1997	304.25	304.05	304.07	308.31	309.11	307.43
10	2	1997	304.15	303.95	304.02	308.16	309.01	307.33
17	2	1997	304.05	303.90	303.97	308.06	308.96	307.28
24	2	1997	304.00	303.85	303.92	308.01	308.91	307.28
3	3	1997	303.90	303.80	303.92	308.01	308.86	307.23
10	3	1997	303.85	303.75	303.87	307.96	308.81	307.23
17	3	1997	303.80	303.65	303.82	307.91	308.81	307.18
24	3	1997	303.75	303.55	303.82	307.86	308.81	307.13
31	3	1997	303.75	303.55	303.72	307.86	308.81	307.13
7	4	1997	303.70	303.55	303.67	307.96	308.76	307.13
14	4	1997	303.60	303.45	303.47	308.06	308.36	306.78
21	4	1997	303.40	303.30	303.47	308.11	308.21	306.58
28	4	1997	303.00	303.05	302.82	308.16	308.06	306.23
5	5	1997	302.75	302.90	302.57	308.16	307.86	305.78
12	5	1997	302.55	302.75	301.37	308.26	307.51	305.38
19	5	1997	301.45	302.65	301.02	308.26	307.31	305.03

11. Groundwater Calibration Data File (Year: 1997-1998):

6 52 301.05 299.74 0.1

			300.95	302.1	301.17	308.21	307.01	304.68
2	6	1997	300.95	302.1	301.17	308.21	307.01	304.68
9	6	1997	300.8	302.1	300.87	308.61	306.91	305.33
16	6	1997	301.55	303.65	301.82	308.61	308.01	306.33
23	6	1997	303.75	304.15	303.42	308.56	308.91	307.28
30	6	1997	303.7	304.35	303.82	308.61	308.76	307.43
7	7	1997	304.4	304.4	304.02	308.66	308.81	307.53
14	7	1997	304.45	304.45	304.74	308.61	308.91	307.63
21	7	1997	304.45	304.45	304.32	308.56	308.91	307.63
28	7	1997	304.65	304.55	304.42	308.51	309.06	307.78
4	8	1997	304.6	304.55	304.42	308.46	309.06	307.78
11	8	1997	304.55	304.5	304.37	308.46	309.06	307.73
18	8	1997	304.55	304.5	304.37	308.41	309.01	307.68

25	8	1997	305.35	305.25	304.87	308.36	309.71	308.38
1	9	1997	305.4	305.3	304.87	308.31	309.81	308.43
8	9	1997	305.35	305.25	304.82	309.11	309.71	308.33
15	9	1997	305.4	305.3	304.87	309.31	309.76	308.37
22	9	1997	305.3	305.25	304.77	309.26	309.76	308.38
29	9	1997	305.25	305.2	304.67	309.26	309.71	308.33
6	10	1997	305.15	305.15	304.62	309.26	309.61	308.28
13	10	1997	305.1	305.05	304.52	309.21	309.51	308.23
20	10	1997	305.05	305	304.47	309.16	309.51	308.23
27	10	1997	305.05	304.95	304.42	309.11	309.46	308.18
3	11	1997	305	304.95	304.37	309.01	309.41	308.13
10	11	1997	304.95	304.9	304.37	308.96	309.36	308.08
17	11	1997	304.9	304.85	304.32	308.91	309.31	308.08
24	11	1997	305.45	305.45	304.77	308.86	309.91	308.58
1	12	1997	305.6	305.55	304.97	308.76	310.11	308.93
8	12	1997	305.55	305.6	304.92	308.64	310.11	308.88
15	12	1997	305.5	305.55	304.92	308.51	310.11	308.83
22	12	1997	305.5	305.5	304.87	308.39	310.06	308.83
29	12	1997	305.45	305.45	304.87	308.3	310.06	308.78
5	1	1998	305.45	305.4	304.87	308.17	310.06	308.73
12	1	1998	305.43	305.35	304.77	308.08	310.06	308.68
19	1	1998	305.38	305.28	304.72	308.07	310.01	308.63
26	1	1998	305.35	305.2	304.67	308.06	309.96	308.58
2	2	1998	305.28	305.13	304.62	308.05	309.91	308.48
9	2	1998	305.2	305.05	304.57	308.04	309.76	308.43
16	2	1998	305.1	304.95	304.47	308.03	309.66	308.38
23	2	1998	304.98	304.83	304.35	308.02	309.56	308.28
2	3	1998	304.93	304.71	304.22	308.01	309.43	308.16
9	3	1998	304.78	304.59	304.1	308	309.31	308.03
16	3	1998	304.65	304.49	304	307.99	309.21	307.93
23	3	1998	303.5	304.39	303.87	307.98	309.11	307.81
30	3	1998	303.43	304.29	303.02	307.97	309.01	307.73
6	4	1998	303.34	304.2	302.77	307.98	308.86	307.63
13	4	1998	303.25	304.11	302.67	307.87	308.71	307.48
20	4	1998	303.14	304.01	302.52	307.76	308.56	307.33
27	4	1998	303.03	303.9	302.38	307.67	308.41	307.18
4	5	1998	302.9	303.78	302.23	307.66	308.21	306.98
11	5	1998	302.74	303.68	302.08	307.48	308.01	306.78
18	5	1998	302.58	303.45	301.93	307.36	307.84	306.53

12. Groundwater Calibration Data File (Year: 1998-1999):

6	53	301.05	299.74	0.1				
			302.35	303.08	301.59	307.01	307.51	306.03
1	6	1998	302.35	303.08	301.59	307.01	307.51	306.03
8	6	1998	302.08	302.93	301.46	306.88	307.31	305.78
15	6	1998	302.01	302.78	301.36	306.68	307.13	305.73
22	6	1998	303.15	303.2	302.45	307.06	307.86	306.48
29	6	1998	303.25	303.3	302.55	307.11	307.96	306.63
6	7	1998	303.35	303.35	302.64	307.16	308.01	306.73
13	7	1998	303.15	303.4	302.72	307.11	307.96	306.68
20	7	1998	303	303.35	302.67	306.96	307.91	306.63
27	7	1998	303.35	303.6	302.87	307.26	308.01	306.93
3	8	1998	304.1	304.25	303.62	307.56	308.46	307.08
10	8	1998	304.3	304.35	303.82	307.71	308.96	307.73
17	8	1998	304.85	304.85	304.12	308.06	309.36	307.98
24	8	1998	304.95	304.75	303.92	308.51	309.51	308.13
31	8	1998	305.05	304.95	304.42	308.71	309.63	308.13
7	9	1998	305.13	304.95	304.47	308.76	309.71	308.28
14	9	1998	305.55	305.5	304.92	309.21	310.06	308.53
21	9	1998	307.05	306.55	306.42	310.96	311.91	310.43
28	9	1998	307.35	306.95	306.82	311.16	312.21	310.63
5	10	1998	307.42	307.05	306.74	311.51	312.41	311.03
12	10	1998	306.85	306.6	306.36	310.91	311.76	310.46
19	10	1998	306.8	306.47	306.34	310.76	311.66	310.28
26	10	1998	306.75	306.33	306.3	310.66	311.56	310.18
2	11	1998	306.35	306.1	305.47	310.31	311.46	310.03
9	11	1998	306.25	306.05	305.42	310.11	311.36	309.73
16	11	1998	306.2	305.95	305.37	310.06	311.21	309.68
23	11	1998	306.15	305.91	305.32	310.01	311.11	309.63
30	11	1998	306.1	305.8	305.32	309.96	311.01	309.58
7	12	1998	305.95	305.65	305.27	309.91	310.86	309.53
14	12	1998	305.85	305.6	305.22	309.86	310.76	309.48
21	12	1998	305.75	305.55	305.18	309.76	310.71	309.43

28	12	1998	305.66	305.51	305.16	309.71	310.66	309.28
4	1	1999	305.5	305.45	304.82	309.51	310.61	309.18
11	1	1999	305.45	305.35	304.67	309.46	310.46	309.03
18	1	1999	305.37	305.35	304.57	309.36	310.31	308.98
25	1	1999	305.3	305.25	304.52	309.26	310.26	308.83
1	2	1999	305.2	305.17	304.38	309.26	310.16	308.73
8	2	1999	305.12	305	304.34	309.06	310.06	308.63
15	2	1999	305.05	304.97	304.28	309.06	309.99	308.53
22	2	1999	305	304.94	304.25	309	309.95	308.5
1	3	1999	304.98	304.9	304.22	308.96	309.91	308.45
8	3	1999	304.95	304.85	304.17	308.86	309.81	308.38
15	3	1999	304.92	304.7	304.12	308.81	309.66	308.28
22	3	1999	304.89	304.45	304.02	308.74	309.41	308.23
29	3	1999	304.85	304.4	303.87	308.66	309.26	308.18
6	4	1999	304.77	304.35	303.97	308.61	309.41	308.23
13	4	1999	304.55	304.25	303.72	308.16	309.01	307.98
20	4	1999	304.45	304.15	303.42	308.11	308.91	307.68
27	4	1999	304.3	304.1	303.27	308.06	308.86	307.57
3	5	1999	304.25	304.05	303.17	308.01	308.81	307.58
10	5	1999	304.2	304	303.12	307.96	308.76	307.53
17	5	1999	304.15	304.02	303.04	307.91	308.71	307.48
24	5	1999	304.05	303.85	303.5	307.84	308.66	307.35
31	5	1999	303.95	303.75	302.82	307.66	308.59	307.33

13. Groundwater Calibration Data File (Year: 1999-2000):

6	52	301.05	299.74	0.1				
			303.80	303.67	302.72	307.56	308.51	307.26
7	6	1999	303.80	303.67	302.72	307.56	308.51	307.26
14	6	1999	303.75	303.63	302.67	307.54	308.46	307.23
21	6	1999	303.85	303.67	302.70	307.57	308.49	307.27
28	6	1999	303.87	303.70	302.73	307.60	308.52	307.28
5	7	1999	303.90	303.74	302.82	307.66	308.58	307.33
12	7	1999	304.00	303.85	302.92	307.76	308.72	307.35
19	7	1999	304.03	303.90	302.97	307.81	308.76	307.47
26	7	1999	304.15	303.98	303.06	307.96	308.82	307.53
2	8	1999	305.12	305.05	304.62	308.41	309.31	308.00
9	8	1999	306.90	306.60	306.87	309.41	311.01	310.00
16	8	1999	307.45	307.15	307.27	311.86	312.91	311.25
23	8	1999	307.50	307.20	307.47	312.06	313.11	311.33
30	8	1999	307.45	307.15	306.82	311.81	312.86	311.28
6	9	1999	307.40	307.15	306.67	311.76	312.84	311.23
13	9	1999	307.45	307.17	306.72	311.78	312.94	311.25
20	9	1999	307.43	307.13	306.69	311.74	312.86	311.28
27	9	1999	307.65	307.35	307.22	312.03	313.26	311.83
4	10	1999	308.10	307.70	307.42	312.26	313.56	312.13
11	10	1999	308.15	307.75	307.47	312.46	313.71	312.23
18	10	1999	308.10	307.65	307.37	312.56	313.66	312.13
25	10	1999	308.03	307.60	307.32	312.46	313.56	312.03
1	11	1999	307.55	306.70	306.72	312.16	312.96	311.78
8	11	1999	307.50	306.63	306.67	312.11	312.91	311.68
15	11	1999	307.35	306.45	306.52	311.76	312.61	311.03
22	11	1999	307.10	306.35	306.32	311.46	312.50	310.73
29	11	1999	306.50	306.10	305.77	310.91	312.41	310.41
6	12	1999	306.35	306.00	305.62	310.56	311.91	310.2
13	12	1999	306.25	305.93	305.40	310.39	311.76	310.01
20	12	1999	306.17	305.83	305.24	310.18	311.55	309.83
27	12	1999	306.00	305.65	305.12	310.00	311.35	309.64
3	1	2000	305.92	305.44	304.93	309.77	311.15	309.46
10	1	2000	305.80	305.25	304.77	309.56	311.01	309.38
17	1	2000	305.68	305.15	304.62	309.39	310.91	309.23
24	1	2000	305.54	305.05	304.46	309.21	310.79	309.08
31	1	2000	305.40	304.93	304.32	309.06	310.65	308.88
7	2	2000	305.23	304.80	304.18	308.96	310.53	308.72
14	2	2000	305.07	304.65	304.04	308.81	310.41	308.53
21	2	2000	304.96	304.51	303.92	308.64	310.31	308.38
28	2	2000	304.88	304.44	303.82	308.56	310.19	308.23
6	3	2000	304.78	304.29	303.68	308.44	310.08	308.11
13	3	2000	304.66	304.25	303.53	308.32	309.96	307.98
20	3	2000	304.51	304.01	303.37	308.21	309.81	307.83
27	3	2000	304.36	303.88	303.23	308.11	309.61	307.68
3	4	2000	304.24	303.75	303.09	308.01	309.51	307.58
10	4	2000	304.13	303.62	302.95	307.91	309.41	307.48

17	4	2000	304.01	303.48	302.83	307.80	309.29	307.38
24	4	2000	303.89	303.36	302.70	307.69	309.18	307.28
1	5	2000	303.79	303.23	302.57	307.58	309.05	307.18
8	5	2000	303.67	303.11	302.44	307.46	308.93	307.08
15	5	2000	303.55	302.98	302.32	307.34	308.81	307.00
22	5	2000	303.44	302.86	302.17	307.22	308.71	306.90
29	5	2000	303.34	302.74	302.06	307.1	308.61	306.83

14. Groundwater Calibration Data File (Year: 2000-2001):

6	53	301.05	299.74	0.1				
			303.24	302.64	301.93	306.97	308.51	306.72
5	6	2000	303.24	302.64	301.93	306.97	308.51	306.72
12	6	2000	303.13	302.5	301.78	306.84	308.41	306.61
19	6	2000	303.02	302.35	301.65	306.72	308.31	306.5
26	6	2000	302.91	302.24	301.52	306.58	308.21	306.39
3	7	2000	302.95	302.25	301.72	306.66	308.26	306.43
10	7	2000	303.55	302.55	302.82	307.56	308.41	307.03
17	7	2000	305.35	305	304.27	308.26	309.81	307.48
24	7	2000	306.35	306.15	305.87	309.71	310.91	309.13
31	7	2000	306	305.75	305.82	309.61	310.81	309.03
7	8	2000	305.75	305.5	305.17	309.41	310.56	308.83
14	8	2000	305.65	305.45	305.07	309.26	310.41	308.73
21	8	2000	305.55	305.4	305.02	309.16	310.21	308.63
28	8	2000	306.2	305.45	305.72	309.7	310.71	309.18
4	9	2000	306.65	306.2	305.97	310.41	311.56	310.03
11	9	2000	306.05	305.75	305.52	309.91	311.11	309.53
18	9	2000	306	305.7	305.45	309.86	311.01	309.43
25	9	2000	305.95	305.62	305.37	309.81	310.91	309.38
2	10	2000	305.8	305.45	305.22	309.71	310.81	309.25
9	10	2000	305.7	305.35	305.07	309.51	310.56	309.03
16	10	2000	305.6	305.25	304.87	309.31	310.11	308.63
23	10	2000	305.35	305.05	304.47	309.06	309.71	308.33
30	10	2000	305.2	304.8	304.32	308.91	309.26	308.13
6	11	2000	305.15	304.7	304.22	308.8	309.21	307.98
13	11	2000	305.1	304.6	304.12	308.71	309.11	307.83
20	11	2000	305	304.55	304.02	308.61	309.01	307.74
27	11	2000	304.95	304.5	303.91	308.51	308.91	307.68
4	12	2000	304.85	304.35	303.72	308.41	308.76	307.55
11	12	2000	304.75	304.2	303.57	308.26	308.63	307.42
18	12	2000	304.62	304.05	303.42	308.11	308.49	307.28
25	12	2000	304.44	303.87	303.21	307.96	308.34	307.11
1	1	2001	304.8	304.45	304.02	308.76	308.76	307.63
8	1	2001	304.75	304.35	304.02	308.71	308.71	307.53
15	1	2001	304.58	304.15	303.82	308.51	308.56	307.41
22	1	2001	304.43	304	303.42	308.26	308.41	307.23
29	1	2001	304.25	303.78	303.02	308.06	308.29	307.08
5	2	2001	304.1	303.45	302.82	307.71	308.16	306.98
12	2	2001	303.95	303.25	302.67	307.56	308.11	306.93
19	2	2001	303.83	303.1	302.57	307.41	307.91	306.63
26	2	2001	303.65	302.95	302.47	307.26	307.86	306.43
5	3	2001	303.45	302.85	302.42	307.16	307.81	306.23
12	3	2001	303.2	302.75	302.37	307.11	307.61	306.18
19	3	2001	303.2	302.7	302.27	307.06	307.56	306.13
26	3	2001	303.15	302.55	302.17	306.96	307.51	305.98
2	4	2001	303.05	302.45	302.02	306.86	307.41	305.93
9	4	2001	302.95	302.35	301.92	306.76	307.26	305.83
16	4	2001	302.85	302.2	301.82	306.66	307.11	305.73
23	4	2001	302.75	302.05	301.72	306.56	306.96	305.63
30	4	2001	302.65	301.8	301.62	306.41	306.81	305.43
7	5	2001	302.6	301.65	301.52	306.16	306.66	305.33
14	5	2001	302.35	301.55	301.47	305.91	306.51	305.18
21	5	2001	302.45	301.45	300.72	305.71	306.41	305.13
28	5	2001	302.35	301.3	300.62	305.56	306.29	305.03

15. Groundwater Calibration Data File (Year: 2001-2002):

6	53	301.05	299.74	0.1				
			302.25	301.45	300.02	305.41	306.14	304.98
4	6	2001	302.25	301.45	300.02	305.41	306.14	304.98
11	6	2001	302.35	301.35	301.52	305.66	306.51	304.83

18	6	2001	302.85	302.2	301.42	305.86	306.66	305.23
25	6	2001	302.8	302.15	301.42	305.81	306.41	305.03
2	7	2001	302.75	302.1	301.37	305.76	306.31	304.73
9	7	2001	302.7	302.05	301.32	305.71	306.21	304.53
16	7	2001	302.65	302.05	301.27	305.76	306.31	304.33
23	7	2001	302.7	302.1	301.32	305.81	306.21	304.13
30	7	2001	302.65	302	301.22	305.76	306.11	304.03
6	8	2001	302.75	301.95	301.27	305.81	306.11	303.95
13	8	2001	303.1	302.15	301.42	305.91	306.31	304.83
20	8	2001	303.15	302.35	302.47	307.06	307.51	305.03
27	8	2001	303.2	302.65	302.82	307.26	307.91	305.83
3	9	2001	303.05	302.6	302.72	307.16	307.81	305.78
10	9	2001	302.95	302.55	302.62	307.11	307.71	305.73
17	9	2001	302.85	302.5	302.52	307.06	307.61	305.68
24	9	2001	302.85	302.45	302.42	307.01	307.51	305.63
1	10	2001	302.95	302.45	302.47	307.16	307.81	305.73
8	10	2001	303.55	303.75	303.02	307.96	308.61	307.13
15	10	2001	304.1	304.00	303.52	308.06	309.51	307.73
22	10	2001	304.25	304.05	303.92	308.56	309.71	307.73
29	10	2001	304.1	303.95	303.72	308.51	309.91	307.68
5	11	2001	303.95	303.85	303.62	308.41	309.86	307.63
12	11	2001	303.8	303.6	303.52	308.36	309.81	307.58
19	11	2001	303.65	303.45	303.42	308.31	309.76	307.53
26	11	2001	303.45	303.4	303.32	308.26	309.91	307.48
3	12	2001	303.4	303.35	303.22	308.21	309.71	307.43
10	12	2001	303.35	303.25	303.02	308.16	309.61	307.38
17	12	2001	303.3	303.15	302.82	308.11	309.51	307.33
24	12	2001	303.15	302.95	302.57	308.06	309.41	307.28
31	12	2001	303.1	302.95	302.32	307.96	308.86	307.23
7	1	2002	302.98	302.77	302.07	307.68	308.76	307.13
14	1	2002	302.9	302.61	302.02	307.66	308.66	307.03
21	1	2002	302.8	302.55	301.92	307.56	308.56	306.93
28	1	2002	302.65	302.46	301.85	307.46	308.49	306.82
4	2	2002	302.57	302.34	301.82	307.36	308.41	306.73
11	2	2002	302.55	302.34	301.77	307.26	308.36	306.58
18	2	2002	302.35	302.25	301.72	307.16	308.29	306.33
25	2	2002	302.25	302.17	301.67	307.06	308.21	306.13
4	3	2002	302.15	302.07	301.62	306.96	308.11	305.83
11	3	2002	302	301.93	301.52	306.86	307.96	305.43
18	3	2002	301.95	301.85	301.42	306.76	307.84	304.93
25	3	2002	301.82	301.75	301.32	306.66	307.71	305.16
1	4	2002	302.35	301.65	301.22	306.56	307.61	304.43
8	4	2002	302.25	301.55	301.12	306.46	307.46	304.38
15	4	2002	302.15	301.45	301.01	306.36	307.31	304.33
22	4	2002	302.05	301.34	300.9	306.26	307.18	304.33
29	4	2002	302	301.24	300.77	306.16	307.01	304.28
6	5	2002	301.95	301.13	300.65	306.06	306.61	304.23
13	5	2002	301.85	301	300.53	305.91	306.21	304.18
20	5	2002	301.75	300.86	300.41	305.76	305.91	304.18
27	5	2002	301.7	300.74	300.28	305.61	305.56	304.13

16. Groundwater Calibration Data File (Year: 2002-2003):

6	44	301.05	299.74	0.1				
			301.70	300.61	300.13	305.46	305.26	304.03
3	6	2002	301.70	300.61	300.13	305.46	305.26	304.03
10	6	2002	301.65	300.47	299.99	305.31	304.79	303.95
17	6	2002	301.60	300.35	299.85	305.21	304.06	303.88
24	6	2002	301.50	300.24	299.74	305.11	304.06	303.83
1	7	2002	302.10	300.65	299.82	305.26	304.01	304.03
8	7	2002	302.50	301.55	300.71	305.16	304.91	303.88
15	7	2002	302.55	301.95	300.67	305.06	305.21	303.83
22	7	2002	302.60	301.90	300.62	304.96	307.01	303.78
29	7	2002	302.70	301.85	300.57	304.86	306.96	303.73
5	8	2002	302.80	301.80	300.47	304.81	306.91	303.63
12	8	2002	302.85	301.95	301.22	305.56	307.16	303.08
19	8	2002	302.95	301.85	300.52	305.51	307.01	303.03
26	8	2002	303.05	302.05	300.62	305.36	307.21	305.93
2	9	2002	303.35	303.35	303.52	306.96	308.20	306.88
9	9	2002	306.75	306.45	306.32	309.76	311.31	309.93
16	9	2002	306.45	306.15	306.42	309.46	311.00	309.63
23	9	2002	306.15	305.85	305.92	309.31	310.60	309.33
30	9	2002	305.85	305.55	305.62	309.16	310.30	309.23

7	10	2002	305.50	305.25	305.32	309.06	310.06	308.93
14	10	2002	305.25	305.05	305.12	308.81	309.81	308.73
21	10	2002	304.95	304.80	304.87	308.46	309.51	308.48
28	10	2002	304.75	304.55	304.67	308.21	309.26	308.23
4	11	2002	304.55	304.45	304.22	308.46	309.21	308.13
11	11	2002	304.35	304.15	304.02	308.06	309.06	307.93
18	11	2002	304.15	304.00	303.72	307.86	308.91	307.73
25	11	2002	303.95	303.80	303.52	307.66	309.21	308.03
2	12	2002	303.85	303.70	303.32	307.46	309.11	307.93
9	12	2002	303.75	303.75	303.12	307.36	309.06	307.88
16	12	2002	303.65	303.65	302.92	307.26	308.91	307.73
23	12	2002	303.50	303.35	302.82	307.06	308.71	307.53
30	12	2002	303.40	303.25	302.72	306.96	308.56	307.43
6	1	2003	303.25	303.05	302.62	306.81	308.46	307.33
13	1	2003	303.15	302.95	302.52	306.61	308.31	307.18
20	1	2003	303.00	302.85	302.37	306.51	308.16	307.03
27	1	2003	302.90	302.65	302.37	306.46	308.06	306.93
3	2	2003	302.80	302.55	301.97	306.36	307.96	306.83
10	2	2003	302.70	302.45	301.87	306.26	307.86	306.73
17	2	2003	302.60	302.35	301.77	306.16	307.76	306.63
24	2	2003	302.50	302.25	301.67	306.06	307.66	306.53
3	3	2003	302.35	302.10	301.57	305.96	307.51	306.43
10	3	2003	302.25	302.00	301.47	305.86	307.41	306.28
17	3	2003	302.10	301.80	301.27	305.66	307.20	306.18
24	3	2003	302.05	301.65	301.04	305.51	307.10	305.98
31	3	2003	302.00	301.55	300.97	305.41	307.06	305.88

17. Infiltration Rate Calibration Data File:

3

1
11

1	120
3	90
5	60
10	30.4
20	20.5
30	15
60	12.5
90	11
130	10.3
260	10.1
350	10.1

18. Tank Dimensions Data File:

6

1	3	24.33	24.33	24.33	24.33	20.33	20.33	20.33	20.33	2
2	3	23.39	23.39	23.39	23.39	19.39	19.39	19.39	19.39	2
3	3	17.57	17.57	17.57	17.57	13.57	13.57	13.57	13.57	2
4	3	20.07	20.07	20.07	20.07	16.07	16.07	16.07	16.07	2
5	3	26.32	26.32	26.32	26.32	22.32	22.32	22.32	22.32	2
6	3	18.96	18.96	18.96	18.96	14.96	14.96	14.96	14.96	2

19. Well Data File (Calibration and Evaluation Mode):

6
137
175

1	2	0.15	10	25000
2	4	0.15	10	25000
3	6	0.15	10	25000
4	10	0.15	10	25000
5	17	0.15	10	25000
6	18	0.15	10	25000

20. Well Data File (Simulation and Optimization Mode):

6
137
175

1	5	0.15	10	25000
2	15	0.15	10	25000
3	25	0.15	10	25000
4	30	0.15	10	25000
5	50	0.15	10	25000
6	60	0.15	10	25000

Appendix-7-3

Input Data Files for Pimpalgaon Ujjaini watershed

Please refer to Appendix A7-1 for the format of these tables. The rows in Appendix A7-1 correspond to the columns in this appendix

1. Field Data File:

447										
1	3	2963.21	100.00	695.00	7.95	11	1	2	14	0
2	3	2699.47	128.12	695.00	5.35	11	1	2	14	0
3	3	2571.53	220.94	695.00	2.12	11	1	2	14	0
4	3	3086.16	259.63	695.00	3.64	11	1	2	14	0
5	3	2679.71	358.23	695.00	2.89	11	1	2	14	0
6	3	2700.28	482.20	695.00	1.38	11	1	2	7	0
7	3	2580.29	484.75	695.00	1.61	11	1	2	7	0
8	3	2205.66	528.43	695.00	0.31	11	1	2	3	0
9	3	2077.83	541.43	695.00	0.85	11	1	2	3	0
10	3	2144.80	572.90	695.00	1.29	11	1	2	3	0
11	3	2591.02	648.99	695.00	0.58	11	1	2	7	0
12	3	2007.58	648.59	695.00	1.28	11	1	2	3	0
13	3	2508.73	543.54	695.00	9.38	11	1	2	7	0
14	3	3257.04	490.67	705.00	11.65	11	1	2	14	0
15	3	2436.04	713.79	695.00	0.71	11	1	2	7	0
16	3	2342.12	720.58	695.00	0.69	11	1	2	7	0
17	3	2297.51	477.06	695.00	7.81	11	1	2	3	0
18	3	2742.52	694.36	695.00	4.19	11	1	2	7	0
19	3	2546.13	741.48	695.00	0.76	11	1	2	7	0
20	3	2264.37	769.63	695.00	0.71	11	1	2	7	0
21	3	1865.60	778.00	695.00	2.18	11	1	2	3	0
22	3	1724.15	838.41	695.00	0.36	11	1	2	3	0
23	3	2464.86	779.57	695.00	2.03	11	1	2	7	0
24	3	2333.02	840.05	695.00	1.26	11	1	2	7	0
25	3	1641.27	889.59	695.00	0.72	11	1	2	3	0
26	3	2395.57	883.31	695.00	0.97	11	1	2	7	0
27	2	2975.21	636.13	705.00	21.02	11	1	2	14	0
28	3	2006.50	871.13	695.00	6.41	11	1	2	10	0
29	3	1446.93	990.85	695.00	0.97	2	1	3	3	0
30	3	1835.98	989.01	695.00	1.69	11	1	2	10	0
31	2	2608.29	906.94	705.00	9.70	11	1	2	9	0
32	3	1999.01	1051.19	695.00	3.33	11	1	2	10	0
33	3	1507.34	1015.05	695.00	5.10	11	1	2	3	0
34	2	2861.94	1027.87	705.00	2.34	11	1	2	9	0
35	3	1674.50	1066.81	695.00	3.21	11	1	2	10	0
36	3	2155.65	1129.93	695.00	0.89	11	1	2	10	0
37	3	1942.74	1131.15	695.00	1.82	11	1	2	10	0
38	3	1262.83	1179.42	695.00	4.35	11	1	2	3	0
39	3	953.27	1246.47	695.00	0.29	11	1	2	3	0
40	2	2751.57	1098.68	705.00	4.87	11	1	2	10	0
41	3	2272.99	1023.32	695.00	8.84	11	1	2	10	0
42	3	2004.52	1203.96	695.00	2.70	11	1	2	10	0
43	3	878.50	1289.49	695.00	0.67	11	1	2	3	0
44	3	1767.78	1211.96	695.00	4.13	11	1	2	10	0
45	2	3153.78	1263.38	715.00	0.94	11	1	2	9	0
46	2	2985.42	1134.52	705.00	6.03	11	1	2	9	0
47	2	2045.56	1259.13	705.00	1.77	2	1	3	10	0
48	2	2668.03	1190.34	705.00	2.88	11	1	2	10	0
49	2	3018.27	1253.09	705.00	2.86	11	1	2	9	0
50	2	2045.77	1301.37	705.00	1.55	2	1	3	7	0
51	3	731.30	1344.64	695.00	0.55	1	1	3	10	0
52	3	1747.37	1342.05	695.00	1.63	11	1	2	11	0
53	2	3074.53	1333.01	715.00	0.94	11	1	2	9	0
54	3	629.59	1391.92	695.00	0.67	1	1	3	10	0
55	2	2091.02	1330.00	705.00	1.95	11	1	2	7	0
56	2	3187.58	1348.51	715.00	2.15	11	1	2	9	0
57	2	2616.64	1273.11	705.00	2.91	11	1	2	10	0
58	2	2130.12	1376.01	705.00	1.09	11	1	2	7	0
59	2	2347.64	1357.81	705.00	1.98	11	1	2	7	0
60	3	1225.72	1316.36	695.00	5.26	11	1	2	3	0
61	2	2541.78	1311.38	705.00	3.07	11	1	2	10	0

62	3	672.11	1443.62	695.00	0.62	2	1	3	10	0
63	3	1507.55	1308.04	695.00	8.48	11	1	2	11	0
64	2	2480.65	1340.40	705.00	1.55	11	1	2	10	0
65	3	573.46	1454.12	695.00	0.89	1	1	3	10	0
66	3	467.73	1465.49	695.00	0.83	1	1	3	10	0
67	2	2439.53	1361.29	705.00	1.38	11	1	2	10	0
68	2	2447.89	1470.36	705.00	0.50	11	1	2	10	0
69	2	3487.98	1445.03	715.00	1.52	11	1	2	2	0
70	2	2414.89	1474.45	705.00	0.30	11	1	2	10	0
71	2	3391.42	1443.46	715.00	1.94	11	1	2	2	0
72	2	2365.02	1498.35	705.00	0.97	11	1	2	7	0
73	2	1770.16	1450.88	705.00	2.44	1	1	3	11	0
74	2	2868.13	1437.87	715.00	6.30	11	1	2	9	0
75	2	2026.99	1544.55	705.00	0.84	11	1	2	11	0
76	2	3311.98	1557.53	715.00	0.48	11	1	2	2	0
77	2	2161.44	1471.23	705.00	6.43	11	1	2	7	0
78	3	807.25	1437.10	695.00	7.97	1	1	3	12	0
79	2	1771.07	1577.94	705.00	0.56	2	1	3	11	0
80	2	2703.27	1528.34	715.00	0.84	11	1	2	10	0
81	3	435.05	1558.72	695.00	2.61	1	1	3	10	0
82	2	2506.78	1556.33	705.00	3.15	11	1	2	10	0
83	2	3046.42	1524.75	715.00	3.53	11	1	2	9	0
84	2	2047.02	1618.92	705.00	0.79	11	1	2	11	0
85	3	1145.43	1511.67	695.00	10.25	2	1	3	11	0
86	2	1898.20	1534.30	705.00	2.90	11	1	2	11	0
87	2	2503.97	1629.23	705.00	1.30	11	1	2	11	0
88	3	833.04	1588.28	695.00	3.07	2	1	3	12	0
89	2	1836.89	1635.28	705.00	1.13	2	1	3	11	0
90	3	1219.68	1643.42	695.00	2.62	1	1	3	11	0
91	2	2185.16	1649.90	705.00	1.53	11	1	2	11	0
92	2	3233.52	1479.03	715.00	6.58	11	1	2	9	0
93	2	1837.44	1685.60	705.00	0.35	2	1	3	11	0
94	2	2300.36	1650.09	705.00	1.57	11	1	2	11	0
95	2	2509.87	1664.67	705.00	1.09	11	1	2	11	0
96	2	1957.78	1655.63	705.00	0.87	2	1	3	11	0
97	3	1155.71	1712.29	695.00	2.56	2	1	3	11	0
98	2	3441.98	1596.13	715.00	4.28	11	1	2	2	0
99	3	185.38	1686.47	695.00	2.64	2	1	3	12	0
100	2	1866.11	1734.31	705.00	0.38	2	1	3	11	0
101	3	854.04	1713.46	695.00	0.70	2	1	3	12	0
102	3	319.56	1656.68	695.00	3.41	2	1	3	12	0
103	3	554.79	1672.29	695.00	3.35	1	1	3	12	0
104	3	805.71	1720.48	695.00	0.46	2	1	3	12	0
105	2	3553.35	1658.10	715.00	2.01	11	1	2	2	0
106	2	2529.05	1773.62	715.00	0.28	2	1	3	11	0
107	2	1920.72	1765.93	705.00	1.06	2	1	3	11	0
108	2	3671.77	1743.36	715.00	1.00	11	1	2	2	0
109	2	1649.28	1619.06	705.00	6.35	2	1	3	11	0
110	2	2751.83	1700.52	715.00	1.88	12	1	1	11	0
111	2	3734.66	1262.61	715.00	71.87	11	1	2	14	0
112	2	2067.57	1726.00	705.00	1.68	1	1	3	11	0
113	2	1540.13	1656.57	705.00	2.14	1	1	3	11	0
114	3	894.67	1809.30	695.00	0.51	2	1	3	12	0
115	2	3573.84	1752.87	715.00	1.56	11	1	2	2	0
116	2	3054.63	1736.71	715.00	1.84	11	1	2	2	0
117	3	848.53	1815.98	695.00	0.26	2	1	3	12	0
118	3	816.88	1817.26	695.00	0.26	1	1	3	12	0
119	3	771.45	1776.02	695.00	0.81	2	1	3	12	0
120	2	2537.24	1732.11	715.00	3.83	2	1	3	11	0
121	2	3416.88	1785.24	715.00	2.15	11	1	2	2	0
122	2	2930.48	1702.51	715.00	3.54	11	1	2	10	0
123	2	2004.85	1824.55	705.00	1.06	2	1	3	11	0
124	3	575.92	1764.60	695.00	3.33	2	1	3	12	0
125	2	3277.81	1721.60	715.00	2.57	11	1	2	2	0
126	2	1482.52	1679.63	705.00	2.88	2	1	3	11	0
127	2	2457.18	1868.78	715.00	0.33	2	1	3	11	0
128	2	2823.45	1857.57	715.00	0.63	2	1	3	11	0
129	2	2866.55	1767.29	715.00	2.77	1	1	3	11	0
130	3	707.39	1830.18	695.00	1.73	2	1	3	12	0
131	2	1222.40	1835.49	705.00	0.42	2	1	3	11	0
132	2	1262.41	1840.16	705.00	1.06	1	1	3	11	0
133	2	3486.13	1881.79	715.00	0.51	11	1	2	2	0
134	2	1305.64	1832.43	705.00	0.55	1	1	3	11	0
135	2	1478.46	1853.73	705.00	1.30	2	1	3	11	0
136	2	2569.38	1873.07	715.00	0.40	2	1	3	11	0

137	2	3222.65	1799.45	715.00	1.76	11	1	2	2	0
138	2	1198.20	1831.49	705.00	0.46	2	1	3	11	0
139	3	658.24	1914.81	695.00	0.40	2	1	3	12	0
140	3	580.46	1879.50	695.00	1.31	2	1	3	12	0
141	2	1392.18	1793.73	705.00	2.76	1	1	3	11	0
142	2	2749.27	1898.01	715.00	0.33	2	1	3	11	0
143	2	2855.47	1926.28	715.00	0.28	2	1	3	11	0
144	2	2303.97	1932.50	715.00	0.51	2	1	3	7	0
145	2	1146.87	1847.68	705.00	1.70	2	1	3	11	0
146	2	1506.69	1951.84	705.00	0.97	2	1	3	11	0
147	2	2657.67	1861.36	715.00	0.46	2	1	3	11	0
148	2	1927.60	1945.60	705.00	0.37	2	1	3	7	0
149	2	2597.60	1907.08	715.00	0.77	2	1	3	11	0
150	2	2713.59	1836.23	715.00	2.48	2	1	3	11	0
151	2	2541.55	1906.99	715.00	0.47	2	1	3	11	0
152	2	2312.79	1982.49	715.00	0.35	1	1	3	7	0
153	2	1082.27	1872.38	705.00	1.46	2	1	3	11	0
154	3	988.78	1845.29	695.00	2.99	2	1	3	12	0
155	2	2520.60	1936.45	715.00	0.36	2	1	3	11	0
156	2	2191.59	1858.09	705.00	8.10	2	1	3	11	0
157	2	2389.23	1916.80	715.00	1.01	2	1	3	11	0
158	2	2638.91	1890.12	715.00	0.82	2	1	3	11	0
159	2	1766.96	1859.93	705.00	5.64	2	1	3	11	0
160	2	2056.37	1993.32	705.00	0.27	2	1	3	7	0
161	2	3400.12	1927.01	715.00	1.55	11	1	2	11	0
162	2	1980.89	1994.23	705.00	0.62	2	1	3	7	0
163	2	3170.87	1887.00	715.00	2.81	11	1	2	11	0
164	2	1600.05	2000.65	705.00	0.42	1	1	3	11	0
165	2	2889.82	1989.88	715.00	0.79	2	1	3	11	0
166	2	3750.61	1877.64	715.00	12.33	11	1	2	2	0
167	2	3341.35	1980.22	715.00	0.67	1	1	3	11	0
168	2	3275.05	2010.63	715.00	1.21	2	1	3	11	0
169	3	633.04	2000.04	695.00	0.72	2	1	3	11	0
170	2	2490.61	1984.21	715.00	1.85	2	1	3	5	0
171	3	818.39	1955.68	695.00	4.69	2	1	3	11	0
172	3	228.25	1893.62	695.00	7.50	2	1	3	12	0
173	2	1799.07	1993.18	705.00	2.98	2	1	3	11	0
174	2	3077.76	1955.49	715.00	2.15	2	1	3	11	0
175	2	2636.16	2024.39	715.00	0.55	2	1	3	5	0
176	3	122.99	2059.40	695.00	0.30	11	1	2	10	0
177	2	2720.65	2034.10	715.00	1.09	2	1	3	5	0
178	2	1260.70	1979.80	705.00	3.50	1	1	3	11	0
179	2	1432.61	2035.71	705.00	2.54	2	1	3	11	0
180	2	2933.77	2061.08	715.00	0.56	2	1	3	11	0
181	3	565.34	2016.14	695.00	1.00	2	1	3	12	0
182	2	1172.08	2083.00	705.00	0.34	1	1	3	11	0
183	2	1114.86	2066.99	705.00	0.52	1	1	3	11	0
184	3	1064.80	2064.89	695.00	0.56	1	1	3	11	0
185	3	1013.51	2059.64	695.00	0.65	1	1	3	11	0
186	3	973.83	2071.30	695.00	0.34	1	1	3	11	0
187	2	3000.29	2005.95	715.00	2.07	2	1	3	11	0
188	2	3141.99	2087.81	715.00	0.75	1	1	3	11	0
189	2	3201.65	2090.30	715.00	0.40	1	1	3	11	0
190	3	542.17	2132.31	695.00	0.38	2	1	3	12	0
191	3	1107.75	2138.47	695.00	0.96	1	1	3	11	0
192	2	1571.59	2089.44	705.00	1.57	2	1	3	11	0
193	2	1403.54	2133.87	705.00	1.46	2	1	3	11	0
194	2	2983.43	2135.96	715.00	0.31	2	1	3	11	0
195	2	4039.67	2013.86	715.00	4.57	11	1	2	2	0
196	3	792.89	2108.95	695.00	1.23	2	1	3	11	0
197	3	406.18	2032.07	695.00	7.02	2	1	3	12	0
198	2	2853.22	2067.12	715.00	2.57	2	1	3	11	0
199	3	522.16	2181.79	695.00	0.50	2	1	3	7	0
200	2	3295.39	2120.39	715.00	0.71	2	1	3	11	0
201	2	3316.48	2144.76	715.00	0.69	2	1	3	11	0
202	1	1585.20	2176.71	715.00	0.73	2	1	3	11	0
203	3	907.13	2106.89	695.00	2.75	1	1	3	11	0
204	2	3084.94	2178.25	715.00	0.31	2	1	3	11	0
205	1	1467.27	2197.84	715.00	0.45	2	1	3	11	0
206	1	1404.66	2205.11	715.00	0.43	2	1	3	11	0
207	3	208.55	2145.64	695.00	1.72	1	1	3	10	0
208	3	1270.35	2156.21	695.00	1.12	2	1	3	11	0
209	2	3115.88	2183.36	715.00	0.40	2	1	3	11	0
210	2	1801.26	2133.18	705.00	4.96	2	1	3	11	0
211	2	4037.20	2148.64	715.00	3.22	11	1	2	2	0

212	2	3032.33	2181.91	715.00	1.14	2	1	3	2	0
213	3	1198.76	2225.34	695.00	2.03	2	1	3	12	0
214	2	3191.87	2176.27	715.00	1.80	2	1	3	11	0
215	2	3214.06	2245.36	715.00	0.32	2	1	3	11	0
216	3	558.49	2229.88	695.00	0.51	2	1	3	7	0
217	2	2151.15	2118.89	705.00	7.20	14	1	1	7	0
218	1	1807.68	2281.87	715.00	0.29	2	1	3	11	0
219	1	1686.61	2215.86	715.00	1.54	2	1	3	11	0
220	1	1594.78	2257.62	715.00	0.63	2	1	3	11	0
221	3	367.37	2230.35	695.00	2.15	11	1	2	7	0
222	3	499.83	2251.18	695.00	0.80	2	1	3	7	0
223	3	663.27	2180.29	695.00	3.72	2	1	3	12	0
224	2	3927.97	2267.25	735.00	0.37	11	1	2	2	0
225	3	766.89	2240.45	695.00	0.76	2	1	3	12	0
226	1	1829.37	2311.15	715.00	0.41	2	1	3	11	0
227	3	656.52	2319.79	695.00	0.57	11	1	2	7	0
228	2	3747.04	2304.84	735.00	0.50	11	1	2	2	0
229	1	1704.98	2294.08	715.00	0.44	2	1	3	11	0
230	3	824.01	2264.05	695.00	1.16	2	1	3	12	0
231	3	544.45	2323.54	695.00	0.46	11	1	2	7	0
232	2	3840.63	2250.28	735.00	1.89	11	1	2	2	0
233	1	1848.27	2343.78	715.00	0.52	2	1	3	11	0
234	3	994.33	2246.85	695.00	3.21	2	1	3	12	0
235	2	2330.76	2275.78	705.00	1.30	11	1	2	5	0
236	3	665.08	2355.76	695.00	0.55	11	1	2	7	0
237	2	4370.47	2322.02	735.00	0.84	11	1	2	14	0
238	1	1865.41	2375.73	715.00	0.54	2	1	3	11	0
239	3	1128.71	2320.87	695.00	3.63	2	1	3	12	0
240	1	1948.61	2312.52	715.00	1.60	4	1	3	11	0
241	3	528.27	2381.61	695.00	0.61	11	1	2	7	0
242	3	655.96	2397.17	695.00	0.81	11	1	2	7	0
243	2	4337.79	2376.03	735.00	1.05	11	1	2	14	0
244	3	350.22	2332.12	695.00	3.50	11	1	2	7	0
245	2	2676.02	2230.33	715.00	21.03	11	1	2	5	0
246	3	1053.28	2402.10	695.00	0.95	2	1	3	7	0
247	3	1153.39	2415.75	695.00	0.56	2	1	3	12	0
248	3	300.24	2391.45	695.00	0.55	11	1	2	7	0
249	2	3339.27	2241.38	715.00	9.70	2	1	3	2	0
250	1	1237.41	2435.60	715.00	0.67	2	1	3	7	0
251	1	1582.90	2429.83	715.00	0.48	2	1	3	12	0
252	1	1889.78	2426.20	715.00	1.32	2	1	3	11	0
253	1	1705.58	2383.06	715.00	2.82	2	1	3	11	0
254	2	3734.45	2414.88	735.00	0.73	11	1	2	2	0
255	2	3498.48	2232.10	735.00	4.47	11	1	2	2	0
256	1	1249.73	2480.17	715.00	0.43	2	1	3	7	0
257	1	1405.50	2349.70	715.00	5.87	2	1	3	12	0
258	1	1476.57	2462.22	715.00	0.56	2	1	3	12	0
259	1	1553.18	2389.96	715.00	1.54	2	1	3	12	0
260	2	3577.79	2244.74	735.00	5.14	11	1	2	2	0
261	1	1739.30	2501.20	715.00	0.88	2	1	3	12	0
262	3	1067.40	2490.42	695.00	1.16	2	1	3	7	0
263	1	2145.59	2335.60	715.00	8.19	11	1	2	7	0
264	1	1865.36	2501.58	715.00	0.93	2	1	3	11	0
265	1	1610.66	2504.05	715.00	0.89	2	1	3	12	0
266	1	2003.42	2472.46	715.00	0.69	2	1	3	11	0
267	3	745.84	2432.67	695.00	2.93	11	1	2	7	0
268	2	3977.87	2364.40	735.00	4.47	11	1	2	2	0
269	2	4152.39	2531.36	735.00	0.79	11	1	2	2	0
270	3	1172.00	2511.60	695.00	0.67	11	1	2	7	0
271	3	1088.29	2565.74	695.00	0.77	11	1	2	7	0
272	1	2331.26	2490.21	715.00	2.84	11	1	2	7	0
273	2	3667.83	2281.63	735.00	8.89	11	1	2	2	0
274	2	4068.16	2542.06	735.00	0.78	11	1	2	2	0
275	3	846.65	2497.15	695.00	2.29	11	1	2	7	0
276	1	1728.52	2570.67	715.00	1.13	2	1	3	12	0
277	1	1839.75	2577.84	715.00	0.57	2	1	3	12	0
278	2	4279.05	2501.06	735.00	2.61	11	1	2	2	0
279	2	3627.50	2503.37	735.00	2.81	11	1	2	2	0
280	1	2201.73	2595.51	715.00	0.55	11	1	2	7	0
281	1	1928.59	2534.67	715.00	0.96	2	1	3	11	0
282	2	3785.98	2451.61	735.00	2.65	11	1	2	2	0
283	2	3767.28	2518.06	735.00	1.52	11	1	2	2	0
284	3	962.25	2540.67	695.00	2.69	11	1	2	7	0
285	1	2375.66	2570.01	715.00	1.93	11	1	2	7	0
286	1	1993.08	2554.34	715.00	1.76	2	1	3	11	0

287	2	4077.00	2439.68	735.00	8.29	11	1	2	2	0
288	2	3764.69	2639.67	735.00	1.90	11	1	2	2	0
289	1	2017.90	2594.56	715.00	0.73	2	1	3	7	0
290	1	1624.81	2635.31	715.00	0.35	2	1	3	12	0
291	1	2254.89	2666.42	715.00	0.67	11	1	2	7	0
292	1	1751.45	2657.42	715.00	1.42	2	1	3	12	0
293	1	1838.17	2662.51	715.00	0.26	2	1	3	12	0
294	2	4059.20	2637.97	735.00	1.23	11	1	2	2	0
295	2	3205.91	2552.82	715.00	7.78	11	1	2	14	0
296	1	1226.00	2633.08	715.00	1.29	11	1	2	7	0
297	1	1765.91	2711.65	715.00	0.38	2	1	3	12	0
298	1	1328.00	2599.25	715.00	1.62	11	1	2	7	0
299	1	1603.45	2658.80	715.00	0.62	2	1	3	12	0
300	1	1652.83	2655.85	715.00	0.40	2	1	3	12	0
301	1	2149.25	2686.92	715.00	1.50	11	1	2	7	0
302	1	1278.07	2618.20	715.00	1.05	11	1	2	7	0
303	3	900.12	2678.11	695.00	1.39	11	1	2	4	0
304	2	4123.49	2658.71	735.00	0.66	11	1	2	2	0
305	1	1762.17	2735.09	715.00	0.65	2	1	3	12	0
306	1	1492.88	2632.67	715.00	1.26	2	1	3	12	0
307	1	2710.31	2646.80	735.00	3.62	11	1	2	1	0
308	2	4019.29	2711.80	735.00	1.05	11	1	2	2	0
309	1	1932.66	2732.18	715.00	1.51	11	1	2	7	0
310	1	2077.05	2617.76	715.00	2.64	2	1	3	7	0
311	1	2144.71	2772.59	735.00	0.49	13	1	1	7	0
312	2	4427.61	2681.94	735.00	2.68	11	1	2	2	0
313	2	4586.56	2639.94	735.00	5.83	11	1	2	2	0
314	1	2326.37	2746.78	735.00	0.70	11	1	2	7	0
315	2	4356.80	2598.47	735.00	6.33	11	1	2	2	0
316	2	4174.88	2711.07	735.00	2.00	11	1	2	2	0
317	1	1753.89	2777.29	715.00	1.43	1	1	3	12	0
318	1	1958.99	2812.73	715.00	0.74	11	1	2	7	0
319	1	1604.21	2787.76	715.00	0.44	2	1	3	12	0
320	1	2228.62	2778.87	735.00	0.76	13	1	1	7	0
321	1	2283.34	2780.58	735.00	0.57	11	1	2	10	0
322	1	1553.05	2661.65	715.00	2.00	2	1	3	12	0
323	1	2485.15	2684.31	735.00	6.11	11	1	2	7	0
324	1	2615.58	2773.16	735.00	1.36	11	1	2	7	0
325	1	2174.80	2826.29	735.00	0.49	13	1	1	7	0
326	1	3139.05	2774.60	735.00	1.31	11	1	2	2	0
327	2	3154.08	2729.51	715.00	3.05	11	1	2	14	0
328	2	3128.96	2683.72	715.00	3.63	11	1	2	14	0
329	1	2114.32	2833.23	735.00	0.31	13	1	1	7	0
330	2	4526.07	2826.10	735.00	1.08	11	1	2	2	0
331	2	3461.77	2742.35	735.00	2.92	11	1	2	14	0
332	1	1967.96	2862.93	715.00	0.85	11	1	2	7	0
333	3	992.00	2766.54	695.00	2.06	11	1	2	4	0
334	1	2697.67	2818.02	735.00	2.64	11	1	2	1	0
335	1	1751.63	2860.21	715.00	2.87	2	1	3	12	0
336	1	1549.18	2874.46	715.00	0.61	2	1	3	12	0
337	2	3553.56	2797.36	735.00	2.81	11	1	2	14	0
338	1	2278.24	2885.21	735.00	0.38	13	1	1	7	0
339	1	3182.17	2844.09	735.00	0.87	11	1	2	2	0
340	1	1967.88	2916.13	735.00	0.72	11	1	2	7	0
341	2	4713.81	2817.76	735.00	4.83	11	1	2	2	0
342	1	1545.43	2918.57	715.00	0.55	2	1	3	12	0
343	1	3214.68	2866.70	735.00	0.61	11	1	2	2	0
344	1	2386.33	2860.59	735.00	1.85	11	1	2	10	0
345	1	3280.97	2922.86	735.00	0.42	11	1	2	2	0
346	1	1768.51	2945.73	715.00	1.78	2	1	3	12	0
347	1	2332.59	2917.47	735.00	0.37	13	1	1	10	0
348	1	3261.65	2966.73	735.00	1.00	11	1	2	14	0
349	1	2328.89	2965.06	735.00	0.27	13	1	1	7	0
350	1	1429.57	2935.39	715.00	1.20	11	1	2	7	0
351	3	735.84	2691.00	695.00	12.71	11	1	2	4	0
352	3	1096.64	2779.29	695.00	5.35	11	1	2	7	0
353	1	1195.68	2806.72	715.00	1.53	11	1	2	7	0
354	1	1184.19	2881.05	715.00	0.69	11	1	2	4	0
355	1	2232.97	2928.49	735.00	1.72	13	1	1	7	0
356	2	3754.19	2852.61	735.00	8.43	11	1	2	14	0
357	2	4761.16	2958.17	735.00	1.26	11	1	2	14	0
358	1	1685.94	3030.54	715.00	0.30	2	1	3	7	0
359	1	1764.60	3008.61	715.00	1.50	2	1	3	7	0
360	2	4764.32	2328.86	735.00	78.15	11	1	2	14	0
361	1	3086.49	2982.12	735.00	1.35	11	1	2	14	0

362	2	4024.83	2888.04	735.00	8.54	11	1	2	14	0
363	1	2453.22	2940.80	735.00	1.81	11	1	2	7	0
364	1	1501.30	3021.72	715.00	0.73	11	1	2	7	0
365	1	2543.22	3021.76	735.00	0.48	11	1	2	7	0
366	3	734.81	2869.78	695.00	4.85	11	1	2	7	0
367	1	2589.38	3055.23	735.00	0.26	11	1	2	10	0
368	1	3322.53	3081.08	735.00	2.74	11	1	2	14	0
369	1	2856.18	3044.14	735.00	2.12	11	1	2	1	0
370	1	2456.33	3021.93	735.00	1.75	11	1	2	7	0
371	1	2801.60	2625.48	735.00	15.41	11	1	2	6	0
372	1	2496.98	3090.32	735.00	1.22	11	1	2	7	0
373	1	2552.68	3120.29	735.00	0.87	11	1	2	7	0
374	1	1956.50	3065.19	735.00	3.81	11	1	2	7	0
375	1	2157.95	3029.18	735.00	7.80	13	1	1	7	0
376	1	2880.92	3134.84	735.00	1.74	11	1	2	7	0
377	1	2611.49	3139.89	735.00	1.05	11	1	2	7	0
378	1	1694.60	3119.47	715.00	1.52	11	1	2	7	0
379	1	2739.10	2970.72	735.00	6.81	11	1	2	7	0
380	2	4340.64	3011.07	735.00	11.19	11	1	2	14	0
381	1	1730.92	3220.21	715.00	0.30	11	1	2	4	0
382	2	4587.53	3050.55	735.00	7.20	11	1	2	14	0
383	1	1329.55	2921.20	715.00	14.19	11	1	2	4	0
384	1	2727.20	3196.22	735.00	0.78	11	1	2	10	0
385	1	1566.12	3205.31	715.00	0.78	11	1	2	4	0
386	2	4876.41	3085.56	735.00	11.12	11	1	2	14	0
387	1	1456.88	3157.27	715.00	3.50	11	1	2	4	0
388	2	3644.76	3052.54	735.00	7.15	11	1	2	2	0
389	2	3909.18	3093.52	735.00	10.32	11	1	2	14	0
390	1	2074.04	3226.51	735.00	0.59	11	1	2	7	0
391	1	3441.55	3295.59	735.00	0.29	11	1	2	1	0
392	1	2143.00	3248.32	735.00	1.58	11	1	2	7	0
393	1	1780.10	3172.21	715.00	2.29	11	1	2	7	0
394	1	2207.76	3257.92	735.00	0.94	11	1	2	7	0
395	1	2800.23	3305.17	735.00	1.04	11	1	2	7	0
396	1	2257.69	3291.66	735.00	2.05	11	1	2	7	0
397	1	2838.27	3326.15	735.00	0.59	11	1	2	7	0
398	1	1625.58	3162.80	715.00	4.23	11	1	2	4	0
399	1	2332.21	3275.18	735.00	1.32	11	1	2	7	0
400	1	3044.41	3300.30	735.00	3.33	11	1	2	7	0
401	1	2862.04	3348.77	735.00	0.63	11	1	2	7	0
402	1	2733.21	3406.44	735.00	0.44	11	1	2	7	0
403	1	2868.71	3278.06	735.00	3.28	11	1	2	7	0
404	1	3333.03	3348.46	735.00	1.56	11	1	2	1	0
405	1	3393.50	3399.12	735.00	1.48	11	1	2	7	0
406	1	3690.47	3378.83	735.00	6.43	11	1	2	14	0
407	1	3470.56	3401.38	735.00	1.39	11	1	2	7	0
408	1	1490.63	3358.79	715.00	1.91	11	1	2	4	0
409	1	2986.77	3446.58	735.00	1.83	11	1	2	7	0
410	1	2637.09	3425.93	735.00	1.93	11	1	2	7	0
411	1	1602.48	3394.49	715.00	1.81	11	1	2	4	0
412	1	1109.88	3307.20	715.00	17.75	11	1	2	4	0
413	1	1463.15	3462.80	715.00	4.88	11	1	2	4	0
414	1	3035.56	3574.98	735.00	2.08	11	1	2	7	0
415	1	2835.40	3527.35	735.00	4.00	11	1	2	7	0
416	1	2498.64	3396.81	735.00	12.23	11	1	2	7	0
417	1	1303.60	3567.76	715.00	3.51	11	1	2	4	0
418	1	3315.48	3309.85	735.00	18.32	11	1	2	1	0
419	1	2806.08	3635.67	735.00	0.78	11	1	2	7	0
420	1	1537.85	3653.59	715.00	2.45	11	1	2	4	0
421	1	1721.42	3557.91	715.00	6.03	11	1	2	4	0
422	1	3708.50	3576.29	735.00	11.19	11	1	2	14	0
423	1	3683.30	3253.54	735.00	8.69	11	1	2	14	0
424	1	3541.05	3786.35	735.00	0.66	11	1	2	14	0
425	1	3339.89	3710.27	735.00	1.96	11	1	2	7	0
426	1	2589.31	3729.17	735.00	10.00	11	1	2	4	0
427	1	3323.65	3853.40	735.00	0.74	11	1	2	4	0
428	1	3121.40	3809.63	735.00	1.44	11	1	2	4	0
429	1	3167.60	3749.66	735.00	4.68	11	1	2	7	0
430	1	2033.78	3438.55	735.00	15.35	11	1	2	4	0
431	1	3302.30	3957.45	735.00	0.94	11	1	2	4	0
432	1	3587.49	3794.18	735.00	14.02	11	1	2	14	0
433	1	1994.84	3722.81	735.00	11.45	11	1	2	4	0
434	1	2305.66	3808.46	735.00	14.19	11	1	2	4	0
435	1	2935.70	3871.88	735.00	7.93	11	1	2	4	0
436	1	3400.64	3998.63	735.00	2.94	11	1	2	4	0

437	1	3231.19	4020.57	735.00	2.20	11	1	2	4	0
438	1	3335.73	4144.29	735.00	1.62	11	1	2	4	0
439	1	3504.52	4087.92	735.00	2.21	11	1	2	4	0
440	1	2526.78	4087.37	735.00	5.18	11	1	2	4	0
441	1	3429.36	4220.97	735.00	0.71	11	1	2	4	0
442	1	2927.41	4203.07	735.00	2.50	11	1	2	4	0
443	1	2728.41	4043.13	735.00	13.53	11	1	2	4	0
444	1	3046.31	4073.83	735.00	3.82	11	1	2	4	0
445	1	3338.38	4246.37	735.00	1.44	11	1	2	4	0
446	1	3144.97	4139.19	735.00	4.60	11	1	2	4	0
447	1	3222.56	4297.77	735.00	1.39	11	1	2	4	0

2. Stream Data File:

3								
6								
1	100.00	1879.50	690.00	3	3	2	2	4
2	1274.82	2338.61	710.00	3	1	1	3	
3	2083.15	2795.13	730.00	3	1	0		
4	1075.49	1962.76	700.00	3	2	1	5	
5	2264.83	1974.06	710.00	3	2	1	6	
6	3318.38	2353.11	730.00	3	2	0		
1								

3. Field-Crop Data File:

1	6		
2	6		
3	6		
4	6		
5	6		
6	6		
7	6		
8	6		
9	6		
10	6		
11	6		
12	6		
13	6		
14	6		
15	6		
16	6		
17	6		
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4. Soil Data File:

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1   24.00   12.00   1.35   25.00   1.00    208.80   0.46   31.00
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2
1   32.00   15.00   1.35   25.00   1.00    208.80   0.46   31.00
3
3
1   18.00   10.00   1.50   25.00   10.90   110.10   0.45   41.00
2
4
1   18.00   10.00   1.50   25.00   10.90   110.10   0.45   41.00
2
5
1   20.00   10.00   1.35   25.00   1.50    218.50   0.40   33.00
2
6
1   32.00   15.00   1.35   25.00   1.00    208.80   0.46   31.00
2
7
1   20.00   10.00   1.35   25.00   1.50    218.50   0.40   33.00
2
8
1   24.00   12.00   1.35   25.00   1.00    208.80   0.46   31.00
3
9
1   18.00   10.00   1.50   25.00   10.90   110.10   0.45   41.00
3
10
1   32.00   15.00   1.35   25.00   1.00    208.80   0.46   31.00
4
11
1   32.00   15.00   1.35   25.00   1.00    208.80   0.46   31.00
4
12
1   32.00   15.00   1.35   25.00   1.00    208.80   0.46   31.00
4
13
1   32.00   15.00   1.35   25.00   1.00    208.80   0.46   31.00
4
14
1   32.00   15.00   1.35   25.00   1.00    208.80   0.46   31.00
2
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5. **Groundwater Calibration Data File (Year: 2001-2002):**

9	13	696.73	692.35	0.1							
			681.95	685.4	685.11	689.14	684.26	723.31	680.88	734.13	706.38
01	06	2001	681.95	685.4	685.11	689.14	684.26	723.31	680.88	734.13	706.38
01	07	2001	683.44	690	686.2	688.65	686.88	722.79	679.82	735.36	706.32
01	08	2001	686.62	694.2	690.51	695.08	692.95	727.19	682.36	739.5	708.52
01	09	2001	692.89	696.98	696.78	701.38	700.22	732.44	685.09	742.67	711.98
01	10	2001	695.38	699.75	698.91	702.71	703	735.19	689.46	743.44	714.54
01	11	2001	695.08	699.31	698.74	702.22	701.14	734.7	689.69	742.6	712.41
01	12	2001	694.96	699.24	697.81	700.62	699.48	734.49	688.92	743.6	713.93
01	01	2002	694.1	698.25	696.24	699.37	697.95	733.55	688.56	742.64	713.29
01	02	2002	691.31	695.18	692.69	695.24	694.24	730.38	686.2	742.21	710.14
01	03	2002	687.12	692.02	687.9	692.33	690.86	726.64	682.65	741.63	708.52
01	04	2002	682.92	687.37	683.98	688.48	687.49	724.6	682.06	733.3	704.89
01	05	2002	682.45	686.01	683.3	686.45	682.95	722.98	680.75	732.66	704.74
31	05	2002	681.2	684.9	682.2	686.3	682.6	722.4	679.8	731.48	704.28

6. **Groundwater Calibration Data File (Year: 2002-2003):**

9	12	696.73	692.35	0.1							
			681.2	684.9	682.2	686.3	682.6	722.4	679.8	731.48	704.28
01	06	2002	681.2	684.9	682.2	686.3	682.6	722.4	679.8	731.48	704.28
01	07	2002	681.02	684.74	682.65	687.5	685.5	723.28	680.69	733.34	705.02
01	08	2002	688.42	693.6	694.46	700.86	699.82	728.41	685.18	740.59	710.89
01	09	2002	693.27	697.47	696.65	701.08	700.13	732.97	686.32	741.48	711.2
01	10	2002	693.86	697.72	696.72	700.73	699.62	733.14	686.45	742.18	707.04
01	11	2002	689.7	693.9	692	698.15	695.25	729.1	685	739.52	704.9
01	12	2002	686.52	690.45	687.44	692.88	693	725.32	681.39	736.6	704.7
01	01	2003	684.99	688.55	686.25	689.96	689.46	725.11	680.85	734.59	704.85
01	02	2003	681.42	686.33	683.08	687.08	685.9	723.66	679.82	730.23	704.74
01	03	2003	679.32	685.45	681.6	686.26	683.78	723.62	679.32	730.08	704.48
01	05	2003	678.73	684.18	681.08	685.44	682.24	722.9	678.9	729.98	704.12
31	05	2003	679	684.14	680.77	685.44	681.69	723.28	678.1	729.56	703.56

7. **Tank Dimensions Data File:**

2										
1	3	780.0	780.0	780.0	780.0	595.0	595.0	595.0	595.0	1.48
2	3	540.0	540.0	540.0	540.0	400.0	400.0	400.0	400.0	1.00

8. **Well Data File (Calibration mode)**

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430				
175				
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2	85	5	10	25000
3	205	5	10	25000
4	359	5	10	25000
5	346	5	10	25000
6	413	5	10	25000
7	239	5	10	25000
8	98	5	10	25000
9	142	5	10	25000