Appendix A

Contaminant Seepage Examples

This appendix provides an example of contaminant seepage from different pollution sources. These pollution sources are: lined canal/ditch, unlined canal/drain and surface foul water bodies. Figures A.1 and A.2 show water distribution pipes that lie below a canal/drain (lined/unlined) and a surface foul water body respectively. For each of these pollution sources (lined canal/ditch, unlined canal/drain, and surface foul water body), the required input data are presented (Tables A.1, A.3 and A.5 for lined canal/drain, unlined canal/drain and surface foul water body respectively), along with output of relative contaminant concentration (Table A.2 and Figure A.3 for lined canal/ditch, Table A.4 and Figure A.4 for unlined canal/ditch and Table A.6 and Figure A.5 for surface foul water body). The outputs of relative contaminant concentration are obtained by using the procedure described in Chapter 2 of this book.
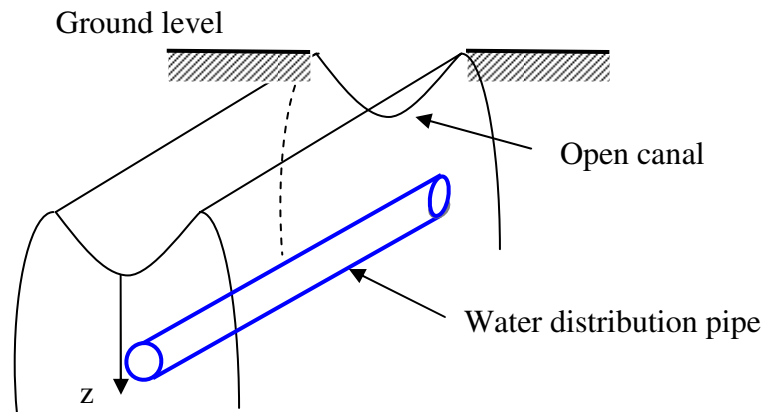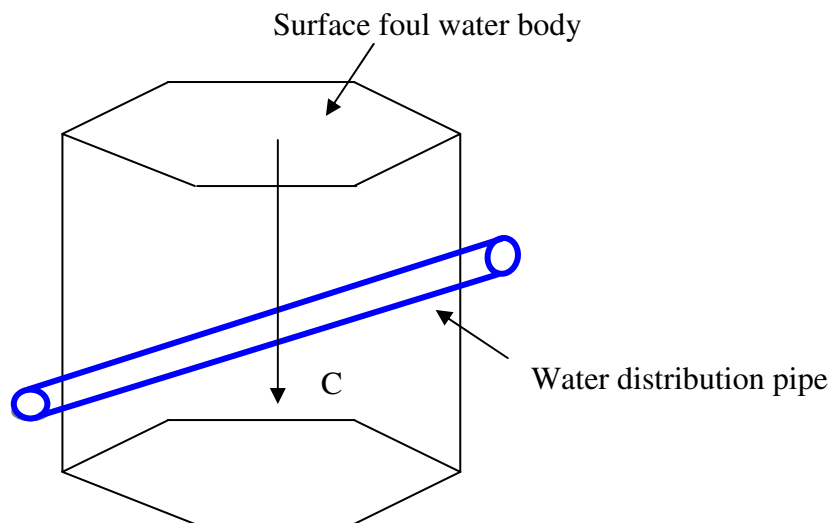

Figure A.1. Contaminant seepage from open canal

Figure A.2. Contaminant seepage from surface foul water body

Table A.1. Example to demonstrate the estimation of contaminant concentration at water distribution pipe due to lined canal/ditch

Known parameters

Sewer pipe

Property	Symbol	Value	Units
Material	Brick		
Seepage rate	r	0.05	*m/day*
Depth of water	h_s	10	*cm*

Soil

Saturated volumetric content	θ_s	0.43	cm^3/cm^3
Initial volumetric water content	θ_0	0.0776	cm^3/cm^3
Saturated hydraulic conductivity	K_s	1.05	*cm/hour*
Soil characteristic curve coefficient	b	3.07	-
Soil porosity	n	0.43	cm^3/cm^3
Air entry head	ψ_b	-38.9	*cm*
Pore size index	λ_b	0.56	-
Bulk density	ρ_b	1.4	*g/cc*
Sorption constant	K_d	7.3 x 10^{-2}	*cc/g*

Contaminant

Liquid phase decay	λ	2.22 x 10^{-4}	*/hour*
Diffusion coefficient	D_p	0.72	cm^2/day

Procedure used

See Sections 2.3.1.2 and 2.4.1

Results

See Table A.2 and Figure A.3 for profile of relative contaminant concentration

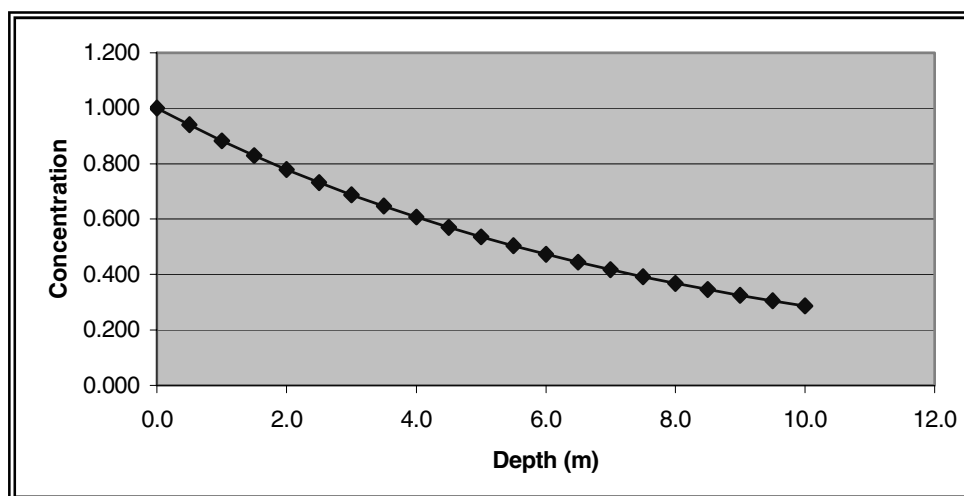| Table A.2. Relative contaminant concentration in soil due to lined canal/ditch (for data presented in Table A.1)	
Depth z (m)	**Relative concentration C/C_0**
0.0	1.000
0.5	0.940
1.0	0.883
1.5	0.829
2.0	0.779
2.5	0.732
3.0	0.688
3.5	0.646
4.0	0.607
4.5	0.570
5.0	0.536
5.5	0.504
6.0	0.473
6.5	0.445
7.0	0.418
7.5	0.392
8.0	0.369
8.5	0.346
9.0	0.325
9.5	0.306
10.0	0.287

Figure A.3. Relative contaminant concentration in soil due to lined canal/ditch (for data presented in Table A.1)

Table A.3. Example to demonstrate the estimation of contaminant concentration at water distribution pipe due to unlined canal/drain

Known parameters

Sewer pipe

Property	Symbol	Value	Units
Soil type	Silty clay		
Water depth	H	5	*cm*
Width	B	10	*cm*

Soil

Saturated volumetric content	θ_s	0.36	cm^3/cm^3
Saturated hydraulic conductivity	K_s	0.0079	*cm/hour*
Soil porosity	n	0.36	cm^3/cm^3

Contaminant

Liquid phase decay	λ	2.22×10^{-4}	*/hour*
Diffusion coefficient	D_p	0.0006	$cm^2/day.$

Procedure used

See Sections 2.3.1.1 and 2.4.2

Results

See Table A.4 and Figure A.4 for profile of relative contaminant concentration

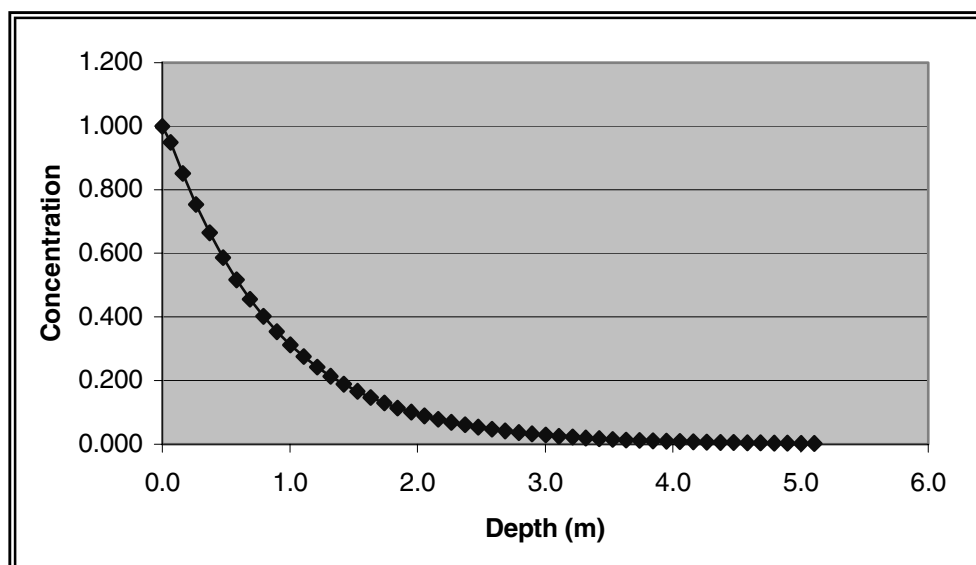| Table A.4. Relative contaminant concentration in soil due to unlined canal/drain (for data presented in Table A.3)	
Depth z (m)	Relative concentration C/C_0
0.0	1.000
0.5	0.586
1.0	0.312
1.5	0.166
2.0	0.100
2.5	0.053
3.0	0.028
3.5	0.015
4.0	0.009
4.5	0.005
5.0	0.003

Figure A.4. Relative contaminant concentration in soil due to unlined canal/drain (for data presented in Table A.3)

Table A.5. Example to demonstrate the estimation of contaminant concentration at water distribution pipe due to surface foul water body

Known parameters

Sewer pipe

Property	Symbol	Value	Units
Soil type	Loam		
Water depth	h_s	10	*cm*

Soil

Saturated volumetric content	θ_s	0.43	cm^3/cm^3
Initial volumetric water content	θ_0	0.0776	cm^3/cm^3
Saturated hydraulic conductivity	K_s	1.05	*cm/hour*
Soil characteristic curve coefficient	b	3.07	-
Soil porosity	n	0.43	cm^3/cm^3
Air entry head	ψ_b	-38.9	*cm*
Pore size index	λ_b	0.56	-
Bulk density	ρ_b	1.4	*g/cc*
Sorption constant	K_d	7.3×10^{-2}	*cc/g*

Contaminant

Liquid phase decay	λ	2.22×10^{-4}	*/hour*
Diffusion coefficient	D_p	0.72	cm^2/day

Procedure used

See Sections 2.3.1.3 and 2.4.2

Results

See Table A.6 and FigureA.5 for profile of relative contaminant concentration

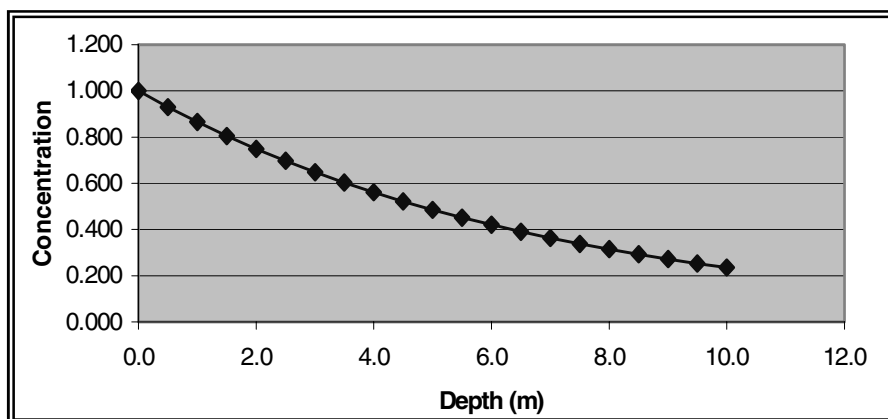| Table A.6. Relative contaminant concentration in soil due to surface foul water body (for data presented in Table A.5)	
Depth z (m)	Relative concentration C/C_0
0.0	1.000
0.5	0.930
1.0	0.865
1.5	0.805
2.0	0.749
2.5	0.697
3.0	0.648
3.5	0.603
4.0	0.561
4.5	0.522
5.0	0.486
5.5	0.452
6.0	0.420
6.5	0.391
7.0	0.364
7.5	0.338
8.0	0.315
8.5	0.293
9.0	0.272
9.5	0.253
10.0	0.236

Figure A.5. Relative contaminant concentration in soil due to surface foul water body (for data presented in Table A.5)

Appendix B

Analytical Hierarchy Process

In the Pipe Condition Assessment (PCA) and Risk Assessment (RA) models, it is extremely important to evaluate the possible alternatives carefully. For example, in the PCA model it is necessary to know the relative influence of each of the factors of Group 1 at Level 1 (material decay, diameter, length, internal protection and external protection) on the pipe indicators, which eventually influences the physical indicators. Similarly it is necessary to know the relative influence of corrosion indicators and load/strength indicators of Group 2 at Level 2 on environmental indicators which eventually influences the pipe condition. In the Risk Assessment model, the relative influence of the factors such as hazard (contaminant concentration and section of pipe in contaminant zone) and vulnerability (pipe condition) on the risk needs to be known. This makes decision-making difficult and thus there is a need for an approach which allows the decision-maker to break the evaluation process down into a series of assessments of the different factors involved. The Analytical Hierarchy Process (AHP), which is a mathematical technique for multi-criteria decision-making (Saaty 1977; Saaty 1980; Saaty 1994), allows the policy analyst to do this by structuring the problem hierarchically and guiding him/her through a sequence of pair-wise comparison judgements.

AHP is conducted using the following steps:
1. Set up the hierarchy (goal, factors and alternatives)
2. Perform pair-wise comparisons for factors
3. Prepare a matrix (judgement matrix) for factors
4. Compute the priority vector for factors
5. Comparison of alternatives
6. Compute the priority vector for alternatives
7. Assess consistency of pair-wise judgements
8. Compute the relative weights/ranks.

In both PCA and RA models, the relative influence of different factors (for example, the relative influence of material decay, diameter, length, internal protection and external protection) on only one alternative (pipe indicators) is required to be assessed, and hence Steps 5 and 6 are skipped. The procedure used in obtaining the relative weights for each factor is described below and shown in the flowchart of Figure B.1.
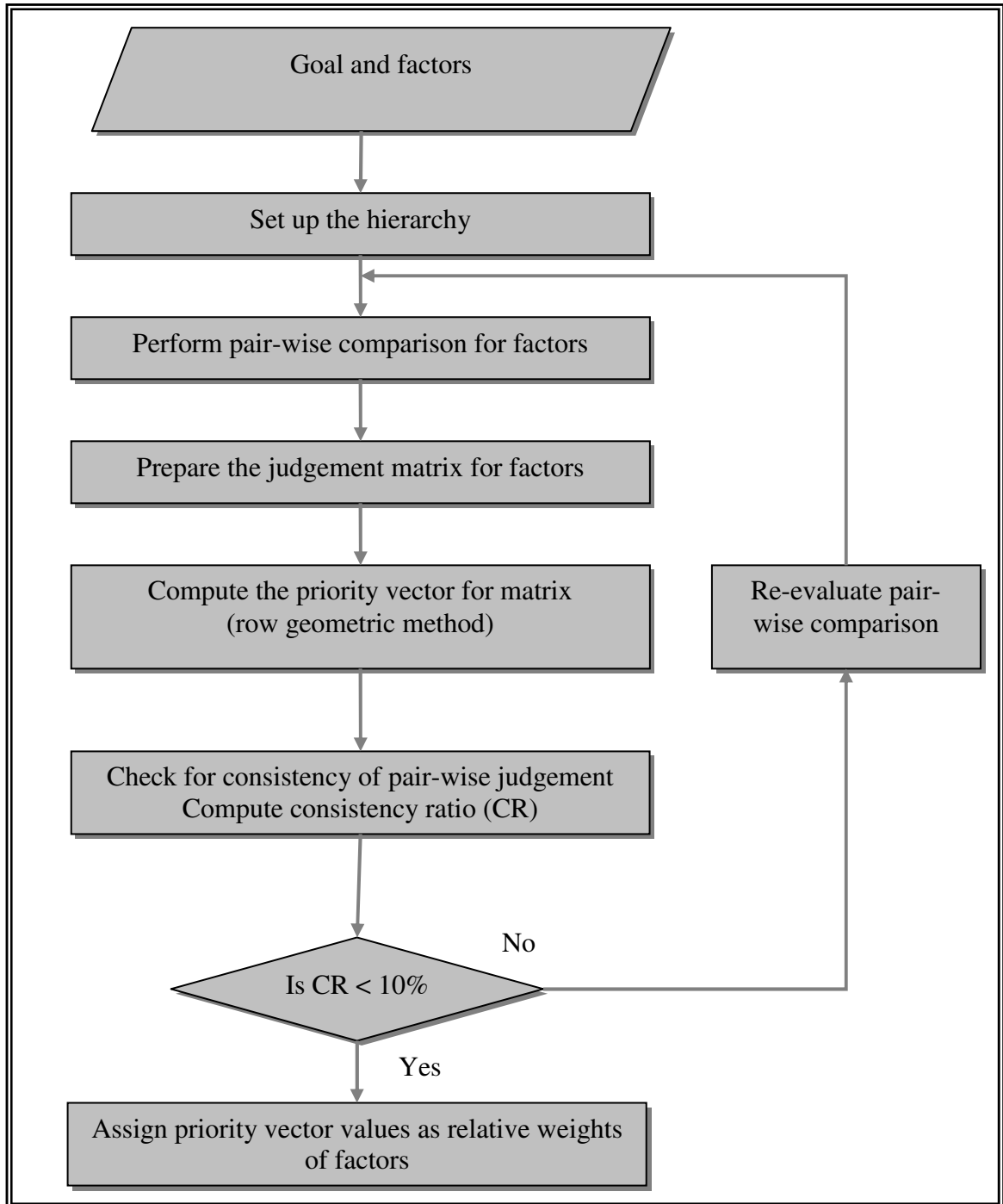
Figure B1. The procedure for obtaining the relative weights for each factor

1. Setting up the hierarchy

The problem needs to be structured into a hierarchy (see Figure B.2). The first level denotes the overall goal of the decision-maker. For example, this is to find out the best estimate of the pipe indicator. The second level consists of several different factors that contribute to this goal. The number of factors involved can vary from case to case, for example in Group 1 of Level 1 there are five, whereas in Group 2 of Level 2 there are two.
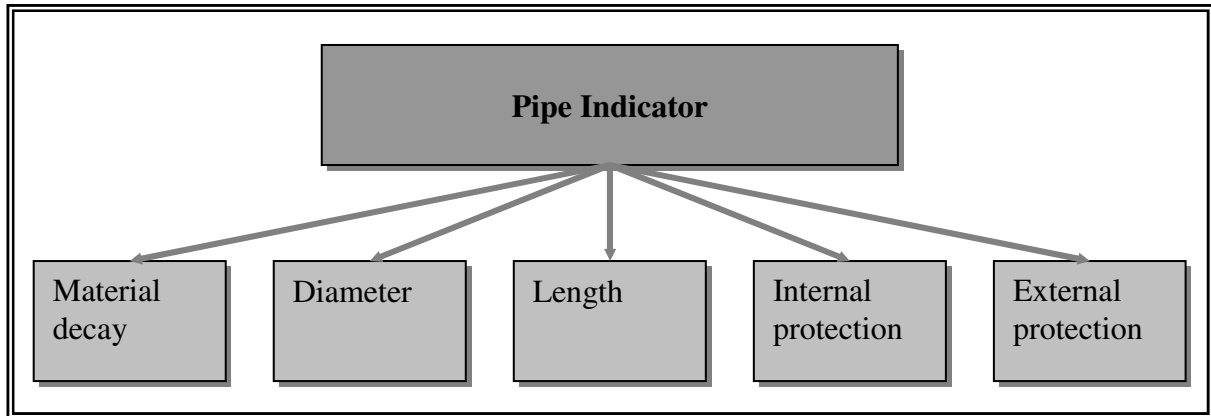
Figure B.2. Establishing the hierarchy of the problem in PCA/RA models

2. Pair-wise comparisons

The Analytic Hierarchy Process (AHP) method does not require decision-makers to quantify precisely the level of importance, but they are required to carry out pair-wise comparisons among factors to give the relative importance of each pair according to established nine-point intensity scale systems shown in Table B.1. Thus, in this step, the factors are compared with each other to determine the relative importance of each factor in the accomplishing the overall goal. The structure of the questionnaire to aid decision-makers to determine the relative importance of each factor over another according to scale system (modified to a 5-point scale) is presented in Appendix D for some cases.

Table B.1. Scales for pair-wise comparisons		
Comparative importance	**Definition**	**Explanation**
1	Equally important	Two decision elements (e.g. indicators) equally influence the parent decision element
3	Moderately more important	One decision element is moderately more influential than the other
5	Strongly more important	One decision element has a stronger influence than the other
7	Very strongly more important	One decision element has significantly more influence than the other
9	Extremely more important	The difference between influences of the two decision elements is extremely significant
2, 4, 6, 8	Intermediate judgement values	Judgment values between equally, moderately, strongly, very strongly, and extremely
Reciprocals		If v is the judgement value when i is compared to j, then 1/v is the judgement value when j is compared to i.

3. Matrix for factors

A matrix is prepared with the factors (in our example material decay, diameter, length, internal protection and external protection) listed at the top and on the left. Based on individually surveyed information and the resulting informed judgement of the decision-maker (Step 2), the matrix is then filled in with numerical values denoting the importance of the factor on the left relative to the importance of the factor on the top. A high value means that the factor on the left is relatively more important than the factor at the top. In Table B.2, for example, material decay is considered to be three times as important as diameter, whereas length is only one third as important as the internal protection. When a factor is compared with itself the ratio of importance is obviously one, resulting in a diagonal line across the matrix. The resulting matrix is known as the judgement matrix.

Table B.2. The judgement matrix for the factors					
	Material Decay	**Diameter**	**Length**	**Internal Protection**	**External Protection**
Material Decay	1	3	4	2	2
Diameter	1/3	1	2	2	2
Length	1/4	1/2	1	1/3	1/3
Internal Protection	1/2	1/2	3	1	1
External Protection	1/2	1/2	3	1	1

In this example the priorities are clear. Material decay is considered to be the factor which influences the pipe indicator most (the pipe indicator in turn influences the pipe condition), followed by internal and external protection. Diameter is considered more important than length.

4. Priority vector for factors

In this step the decision-maker uses the matrix (Table B.2) to get an overall priority value for each factor. AHP computes an overall priority value or weight for each decision element based on the pair-wise comparisons using mathematical techniques such as

- Eigenvalue
- Mean Transformation and
- Row Geometric Mean

In the present study (Pipe Condition Assessment model and Risk Assessment model) the 'Row Geometric Mean' technique for computing the weights under AHP has been employed.

Row Geometric Mean: In this method, the geometric mean of each row is calculated (i.e. the elements in each row are multiplied with each other and then the nth root is taken, where n is the number of elements in the row). This forms the vector of geometric mean. The elements of this vector are then normalized by dividing them with the sum. The resulting normalized vector is an approximated maximum eigenvector, herein named as the priority vector. The calculations for the example are presented below:

The vector of geometric mean

Material Decay	$: (1*3*4*2*2)^{1/5}$	$= 2.17$
Diameter	$: (0.333*1*2*282)^{1/5}$	$= 1.21$
Length	$: (0.25*0.50*1*0.333*0.333)^{1/5}$	$= 0.42$
Internal Protection	$: (0.50*0.50*3.0*181)^{1/5}$	$= 0.94$
External Protection	$(0.50*0.50*3.0*1*1)^{1/5}$	$= 0.94$
Total		$= 5.70$

The Priority vector

Material Decay	: 2.17/5.70	$= 0.38$
Diameter	: 1.21/5.70	$= 0.21$
Length	: 0.42/5.70	$= 0.07$
Internal Protection	: 0.94/5.70	$= 0.17$
External Protection	: 0.94/5.70	$= 0.17$
Total		$= 1.00$

5. Consistency of pair-wise judgements

One of the most practical issues in AHP is the non-consistency in pair-wise comparisons. If all the comparisons are perfectly consistent, then the following expression should hold true for any combination of comparisons of the judgement matrix.

$$a_{ij} = a_{ik} \times a_{kj} \tag{B.1}$$

where
a_{ij} - relative importance factor (tabulated values in Table B2) of decision criteria i to j.

Table B.2 is reproduced below with values of i and j (Table B.3).

Table B.3. The judgement matrix for the factors							
			Material Decay	Diameter	Length	Internal Protection	External Protection
	i	j	1	2	3	4	5
Material Decay	1		1 a_{11}	3 a_{12}	4 a_{13}	2 a_{14}	2 a_{15}
Diameter	2		1/3 a_{21}	1 a_{22}	2 a_{23}	2 a_{24}	2 a_{25}
Length	3		¼ a_{31}	½ a_{32}	1 a_{33}	1/3 a_{34}	1/3 a_{35}
Internal Protection	4		½ a_{41}	½ a_{41}	3 a_{41}	1 a_{41}	1 a_{41}
External Protection	5		½ a_{51}	½ a_{51}	3 a_{51}	1 a_{51}	1 a_{51}

If   i=1; j=2; k=3

$a_{12} = 3$

$a_{13} = 4$

$a_{32} = ½$

According to equation (B.1), a_{12} should be equal to a_{13} x a_{32}

However, perfect consistency rarely occurs in practice. Consistency ratio (CR) is commonly used to reflect the degree of consistency of the judgement matrix. The CR is calculated as follow:

$$CI = \frac{\lambda_{max} - n}{(n-1)} \tag{B.2}$$

$$CR = \frac{CI}{RCI} \tag{B.3}$$

where
CI - consistency index
λ_{max} - maximum eigenvalue of judgement matrix
RCI - Random consistency index as given in Table B.4
n - the number of factors

Table B.4. RCI values for different values of *n*									
n	1	2	3	4	5	6	7	8	9
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Maximum eigenvalue (λ_{max}) is obtained by adding the columns in the judgement matrix and multiplying the resulting vector by the vector of priorities (i.e. the approximated eigenvector) obtained earlier. The procedure is explained below.

Adding the columns in the judgement matrix

Material Decay	Diameter	Length	Internal Protection	External Protection
2.58	5.50	13.00	6.33	6.33

Vector of priorities

Material Decay	0.38
Diameter	0.21
Length	0.07
Internal Protection	0.17
External Protection	0.17

Multiplication and addition

Material Decay	2.58 x 0.38	0.98
Diameter	5.50 x 0.21	1.15
Length	13.0 x 0.07	0.91
Internal Protection	6.33 x 0.17	1.07
External Protection	6.33 x 0.17	1.07
Total	λ_{max}	5.18

$$CI = \frac{5.18 - 5}{(4 - 1)} = 0.045$$

$$CR = \frac{0.045}{1.12} = 0.04$$

The pair-wise comparisons in a judgement matrix in AHP are considered to be adequately consistent if the CR is less than 10 per cent (Saaty 1980). If CR is greater than 10 per cent, there is a need for further evaluation of the pair-wise comparison in

the judgement matrix. In the example above, CR is 4 per cent, indicating that the pair-wise comparison is consistent.

6. Computing the relative weights

If the CR of the judgement matrix is satisfactory (less than 10 per cent, for example), the priority vector values will be assigned as relative weights of factors. Thus, in this example, the relative weights for each factor are:

Material Decay	0.38
Diameter	0.21
Length	0.07
Internal Protection	0.17
External Protection	0.17

Appendix C

Pipe Condition Assessment Indicators

The different pipe condition assessment indicators are presented in Chapter 3 of this book. This Appendix provides the details of how these indicators influence the pipe condition.

1. Pipe Indicators

These indicators are related to physical properties of pipe. Pipes deteriorate in different ways due to their physical properties.

Material decay: This indicator is used to manifest the effect of the current condition of different pipe materials on pipe failure. Pipes made from different materials and of different age fail in different ways. The Hazen-William coefficient of friction (C), which varies according to the pipe material and age, is considered to characterize this influence. The 'C' values proposed for different pipe materials of different ages are presented in Table C.1.

Table C.1. Typical values of the Hazen-William coefficient of friction (C) for different types of pipe material									
Pipe Material	**Age in years**								
	New	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
DI	140	130	130	120	120	120	110	100	-
PVC	150	140	140	140	140	140	130	-	-
HDPE	140	130	130	130	130	130	120		
AC	150	130	130	120	120	120	100	-	-
PE	130	120	120	120	120	120	110		
PC/RCC	130	120	110	95	70	70	70	-	-
Steel/GI	150	130	130	100	100	100	60	60	60
CI	150	110	100	90	80	70	70	60	-

(Stephenson 1979; Wallingford Software 2004; King and Crocker 1967; Bonds 1989).

Diameter:

Research into the relationship between pipe diameter and pipe failure reveals that larger diameter pipes (i.e. trunk mains greater than 300 mm) are less prone to failure than smaller diameter pipes. These is due to following three reasons:

- *Pipe wall thickness* increases with pipe diameter. Larger pipes are therefore less susceptible to failure than smaller diameter pipes (Cooper et al. 2000).

- *Ground movement* Larger pipes are less susceptible to ground movement from traffic than smaller pipes as they have a greater cementing surface area (Cooper et al. 2000).
- *Chlorine decay* Studies of chlorine decay in pipes note that chlorine decay profiles are most pronounced in small diameter pipes. This is due to increased absorption of chlorine through contact with biomass. Kiene et al (1998) estimates that this is most pronounced in pipes with a diameter of less than 75 mm.

Typical minimum and maximum diameters for different types of pipe material are presented in Table C.2.

Table C.2. Typical minimum and maximum diameters for different types of pipe material		
Pipe material	**Diameter in mm**	
	Minimum	**Maximum**
DI	75	1600
PVC	100	1200
HDPE	100	1600
AC	50	2500
PE	63	1000
PC/RCC	400	1200
Steel/GI	60	2235
CI	75	2000

Pipe length: The vulnerability of a pipe is directly related to its length. Larger length pipes are more prone to failure than smaller length pipes.

Studies reveal two principal reasons for this:

- *Pipe stress* Over-stressing of pipes is more likely in longer segments of pipe resulting in potential longitudinal breaks (e.g. hoop stress – longitudinal breaks caused by transverse stresses). Studies of vulnerability of varied pipe lengths to failure from earthquake hazards have further reinforced the theory that pipe failures increased with pipe length (Ballantyne and Moore 1995).
- *Pipe jointing* The number of pipe joints increases with pipe length. Studies of pipe jointing have identified it as a high risk point for potential contaminant ingress. The materials used to join the water pipes, e.g. seal threaded pipe, should also be considered as possible sites for microbial colonization (Geldreich 1996). The latter would be of concern as this promotes biofilm formation and consequent chlorine consumption.

Internal protection: The pipes with internal protection by lining and/or coating are less susceptible to corrosion. Modern metallic pipes are mostly manufactured with

internal linings to prevent internal corrosion from soft or aggressive waters. However, older metallic pipes may be unlined and would therefore be susceptible to internal corrosion. The AWWA Research Foundation has published two manuals that provide a detailed description of internal corrosion processes and control (AWWARF 1989; AWWARF/DVGW 1986). Internal corrosion can manifest itself in different ways. They are commonly grouped as follows:

- Pipe degradation (e.g. pitting), which can result in leakage or vulnerability to mechanical failure;
- Tuberculation and scale formation can reduce hydraulic capacity and impair water quality; and
- Corrosion by-product release (e.g. rusty or red water), which can impair water quality.

External protection: The pipes with external protection by lining and/or coating are less susceptible to deterioration. Several types of external corrosion can occur in water mains, including galvanic, electrolytic, pitting, crevice, uniform, localized and microbiologically induced. Galvanic and electrolytic corrosion are the most common types of external corrosion in water distribution systems.

2. Installation indicators

These indicators are related to the pipe and other conditions at the time of installation of pipe. Improper installation conditions will fail the pipe structurally.

Bedding condition: All pipes require proper bedding so as to have adequate structural support. Proper bedding also facilitates the laying of pipes to the required line and level. Improper bedding may result in premature pipe failure.

Workmanship: Workmanship deals with the human factor of quality control of construction work. In many developing countries, pipework does not follow standard codes of construction. This may be because the codes do not exist, are not enforced or logistically/financially are simply not feasible. As a result, poor workmanship may deteriorate the pipes and cause more risk regardless of pipe age and other factors.

Joint method: The main functions of the joints (Davies et al. 2001a) are:

- To be watertight
- To be durable
- To be resistant to root intrusion.

It was reported that improper selection of joint type was the major cause of joint-related structural defects and hence pipe deterioration. Some types of joints experience premature failure (e.g. leadite joints).

Number of joints: Studies of pipe jointing have revealed that pipes at joints are more susceptible to failure. Hence the greater the number of joints a pipe has, the greater the risk of it getting structurally worse.

3. Corrosion indicators

The pipes deteriorate due to corrosion and these indicators are related to the different causes of corrosion.

Year of installation: The year of installation reflects the age of the pipe. More structural defects have been reported in older pipe than in newer pipes. Thus the effects of pipe degradation become more apparent over time.

Soil corrosivity: Generally, buried pipelines suffer from soil corrosion due to (Cunat 2001):

- High moisture content
- A pH value less than 4.5
- A resistivity less than 1000 ohm-cm
- Presence of chlorides, sulphides and bacteria
- Presence of stray currents.

Some soils are corrosive; sandy soils are high up on the resistivity scale and therefore considered the least corrosive while clayey soils are more corrosive. Underground pipes deteriorate due to soil corrosivity. Pipes deteriorate quicker in more corrosive soil and the degree of deterioration depends on the pipe material. The corrosion performance of stainless steel pipes in soil is generally poorer than PVC pipes.

The soil corrosivity of different soils and the range of soil resistivity for different degrees of soil corrosivity are presented in Tables C3 (a) and C3 (b) respectively.

Surface permeability: Surface permeability reflects the ground condition. A more permeable surface allows more moisture to percolate to the pipe. The surface salts will be carried to the pipe with the moisture. The soils around the pipe are also subjected to wetting and drying. This will deteriorate the pipe.

Table C.3 (a). Soil corrosivity for different types of soils	
Soil type	**Corrosivity**
Sand	Essentially non-corrosive
Loamy sand	Mildly corrosive
Sandy loam	Mildly corrosive
Sandy clay loam	Mildly corrosive
Loam	Moderately corrosive
Silt loam	Corrosive
Silt	Highly corrosive
Clay loam	Highly corrosive
Silty clay loam	Highly corrosive
Sandy clay	Corrosive
Silty clay	Extremely corrosive
Clay	Extremely corrosive

Table C.3 (b). Typical range of soil resistivity for different degree of soil corrosivity	
Soil resistivity Ohm-m	**Degree of soil corrosivity**
>20,000	Essentially non-corrosive
10,000 to 20,000	Mildly corrosive
5,000 to 10,000	Moderately corrosive
3,000 to 5,000	Corrosive
1,000 to 3,000	Highly corrosive
<1,000	Extremely corrosive

(Roberge 2000)

Groundwater condition: The following three types of situation exist for water pipes laid underground in relation to the groundwater table.

- Water pipes permanently above the groundwater table
- Water pipes permanently below the groundwater table
- Water pipes intermittently above and below the groundwater table.

Water pipes are deteriorated by the groundwater table through the following effects:

- Water with minerals may corrode pipes. Some groundwater is aggressive toward certain pipe materials.

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- Water flowing through the bedding material may cause ground loss and a subsequent lack of support around the water pipes.
- Intermittent wetting and drying will make the bedding material unstable.

4. Load/strength indicators

The pipes deteriorate as a result of the load/pressure exerted on them. These indicators relate to the different types of loads.

Buried depth: The buried depth has an influence on the structural failure of the pipe. It is widely reported that there is steady decreasing defect rate up to a certain depth and after this depth the defect rate increases (Davies et al. 2001b). The first occurrence probably reflects road traffic and second occurrence reflects the effect of backfill soil, frost load, overburden pressure and soil moisture with buried depth. In this study the effect of traffic load on the pipe failure has been considered separately. Hence the pipes buried at higher depth have more possibility of failure than those buried at shallower depths.

Traffic load: The traffic load influences the pipe conditions. Pipes situated below roads are subjected to the traffic load. Pipe failure rate increases with traffic loads. However, the traffic load depends on the location of pipe. The traffic load is normally more on the principal roads. At the same time these roads are stronger and greater care is taken in the design and construction of these roads and hence the effect of traffic load on the failure of pipes laid below these roads may be minimum.

Hydraulic pressure: Changes to internal water pressure will change stresses acting on the pipe. If the internal pressure is more than the rated pressure, the chances of pipe failure are more.

5. Intermittency indicators

Water supply systems in developing countries have inherent problems due to their intermittent operation (Vairavamoorthy 1994), which cause the pipes to deteriorate. These indicators are related to pipe deterioration due to intermittency in operation.

Number of valves: Different types of valves are necessary for discharge and pressure control. However, it is considered that the pipes installed with valves deteriorate faster than the pipes without valves, mainly due to poor quality, improper installation and frequent operation of valves. Thus the greater the number of valves, the greater the deterioration of the pipe.

Number of water supply periods per day: Water supply systems in developing countries are normally operated intermittently. The frequency of water delivery in the pipe may vary (for example, from twice a day to once in two days). The intermittent water supply deteriorates the pipe due to existence of zero or no pressure and contaminant ingress during the periods of no pressure and variation of pressure from maximum to zero. Hence it is considered that the greater the number of water supply periods, the more the pipes will deteriorate.

Duration of water supply/day: When water supply systems operate intermittently, the duration for which water is present in the system varies. The chances of a pipe deteriorating are more when there is no water in the pipe. Hence the longer the duration of water supply, the smaller the chances of pipe failure.

6. Failure indicators

These indicators relate to disruptions to the system such as breakage, leakage, water quality etc. At this stage only one failure indicator, i.e. breakage history, is considered. Current leakage data indicates the actual condition of the pipe and hence is considered at the next level. No water quality indicator is considered directly, but the contaminant ingress model simulates the contaminant concentration at the pipe and is included in risk assessment.

Breakage history: This is the important indicator in assessing pipe condition. If the pipe breaks frequently at a particular location, then it has the combined effect of all the parameters explained above and the chances of pipe failing again are also more.

Appendix D

Questionnaires for Pipe Condition Assessment

Instructions

The purpose of questionnaires of this kind is to generate the weights for factors of each group at each level by using the analytical hierchy process (AHP). This method requires the degree of preference of one factor over another factor. Therefore there is a need to carry out comparisons for two factors at one time.

Generation of weights for different factors are necessary at the following two stages. These are:
1. Pipe condition assessment (PCA) model
2. Risk assessment (RA) model

The PCA model requires weights for factors of each six groups at level 1; three groups at level 2 and one group at level 3. The pipe condition indicators are the factors in this case. Thus the weights are to be generated for 10 groups. In this Appendix, we take only one group as an example for each hierarchical level (as shown in Figure B.1). Other groups shall follow the same procedure.

The RA model requires the weight to be generated for the two factors at one level.

The questionnaire consists of two columns for each comparison. The respondent is required to tick the preference in **column 1** and tick the degree of preference in **column 2** of each comparison.

For example, in the case of Questionnaire 1, to compare the two indicators of *diameter* and *length* in the *pipe* indicators group, if a respondent feels diameter is a greater contributory factor for deterioration than length, the respondent should tick 'diameter' in **column 1** of the table and then go to column 2. If the respondent thinks that 'diameter' is 'strongly contributory' over the 'length' for pipe deterioration, then 'strongly preferred' should be ticked in **column 2** of the table. In this way the respondent is required to complete all the pair-wise comparisons for each group. At the beginning of the Questionnaire there might be notes describing how each factor contributes to the final output.

Pipe Condition Assessment

Interviewee:

....

Organization:

....

Address:

....

....

....

Profession:

....

Position

....

Experience

.... (years)

Date: .... ╱ .... ╱ ....

Time: ....

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Level 1 - Pipe Indicators Group

> **Notes**
>
> *Material decay:* **This indicator is used for manifesting the effect of the current condition of different pipe materials on pipe failure. Pipes made from different materials and of different age fail in different ways.**
>
> *Pipe diameter:* **Research into the relationship between pipe diameter and pipe failure reveals that larger diameter pipes (i.e. trunk mains greater than 300 mm) are less prone to failure than smaller diameter pipes.**
>
> *Pipe length:* **The vulnerability of a pipe is directly related to its length. Larger length pipes are more prone to failure than smaller length pipes.**
>
> *Internal protection:* **Pipes with internal protection by lining and/or coating are less susceptible to corrosion.**
>
> *External protection:* **Pipes with external protection by lining and/or coating are less susceptible to deterioration.**
>
> **For details refer to Appendix C**

1. Material decay – Diameter

Column 1	Column 2	
❑ Material decay ❑ Diameter	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

2. Material decay – Length

Column 1	Column 2	
❑ Material decay ❑ Length	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

3. Material decay – Internal protection

Column 1	Column 2	
❏ Material decay ❏ Internal protection	❏ Equally preferred ❏ Moderately preferred ❏ Strongly preferred	❏ Very strongly preferred ❏ Extremely preferred
Reasons for preference if any		

4. Material decay – External protection

Column 1	Column 2	
❏ Material decay ❏ External protection	❏ Equally preferred ❏ Moderately preferred ❏ Strongly preferred	❏ Very strongly preferred ❏ Extremely preferred
Reasons for preference if any		

5. Diameter – Length

Column 1	Column 2	
❏ Diameter ❏ Length	❏ Equally preferred ❏ Moderately preferred ❏ Strongly preferred	❏ Very strongly preferred ❏ Extremely preferred
Reasons for preference if any		

6. Diameter – Internal protection

Column 1	Column 2	
❏ Diameter ❏ Internal protection	❏ Equally preferred ❏ Moderately preferred ❏ Strongly preferred	❏ Very strongly preferred ❏ Extremely preferred
Reasons for preference if any		

7. Diameter – External protection

Column 1	Column 2	
❑ Diameter ❑ External protection	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

8. Length – Internal protection

Column 1	Column 2	
❑ Length ❑ Internal protection	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

9. Length – External protection

Column 1	Column 2	
❑ Length ❑ External protection	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

10. Internal protection – External protection

Column 1	Column 2	
❑ Internal protection ❑ External protection	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

Level 2 – Physical Indicators Group

> **Notes**
>
> **Pipe indicators: The pipe indicators consist of the combined influence of the indicators such as Material decay, Diameter, Length, Internal protection and External protection on pipe condition.**
>
> **Installation indicator: the installation indicator is the combined influence of indicators such as Bedding condition, Workmanship, Joint method and Number of joints on pipe condition.**
>
> **For details refer to Appendix C**

1. **Pipe indicators – Installation indicators**

Column 1	Column 2	
❏ Pipe indicators ❏ Installation indicators	❏ Equally preferred ❏ Moderately preferred ❏ Strongly preferred	❏ Very strongly preferred ❏ Extremely preferred
Reasons for preference if any		

Level 3 – Pipe Condition Group

> **Notes**
>
> **Physical indicators: Pipe indicators and Installation indicators**
>
> **Environmental indicators: Environmental indicators are the combined effect of Corrosion indicators and Load/strength indicators on pipe condition.**
>
> **Operational indicators: Operational indicators are the combined effect of Intermittency indicators and Failure indicators on pipe condition.**
>
> **For details refer to Appendix C**

1. **Physical indicators – Environmental indicators**

Column 1	Column 2	
❑ Physical indicators ❑ Environmental indicators	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

2. **Physical indicators – Operational indicators**

Column 1	Column 2	
❑ Physical indicators ❑ Operational indicators	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

3. **Environmental indicators – Operational indicators**

| Column 1	Column 2	
❑ Environmental indicators ❑ Operational indicators	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

Appendix E

Questionnaires for Risk Assessment

Problem

Water distribution pipes can be subject to contamination for several reasons, such as seepage from sewer pipes, open drains or surface foul water bodies. The contaminant load is obtained by combining the contaminant concentration and the length of contamination along water distribution pipe. These pipes are therefore subject to risk because of the level of contaminant load (hazard) and condition of water distribution pipes (vulnerability). The risk may vary depending on the contaminant load and condition of deteriorated pipe subjected to the contaminants. Thus there are the following two risk factors:

1. Contaminant load (hazard)
2. Water pipe condition (vulnerability).

These factors are shown below schematically:
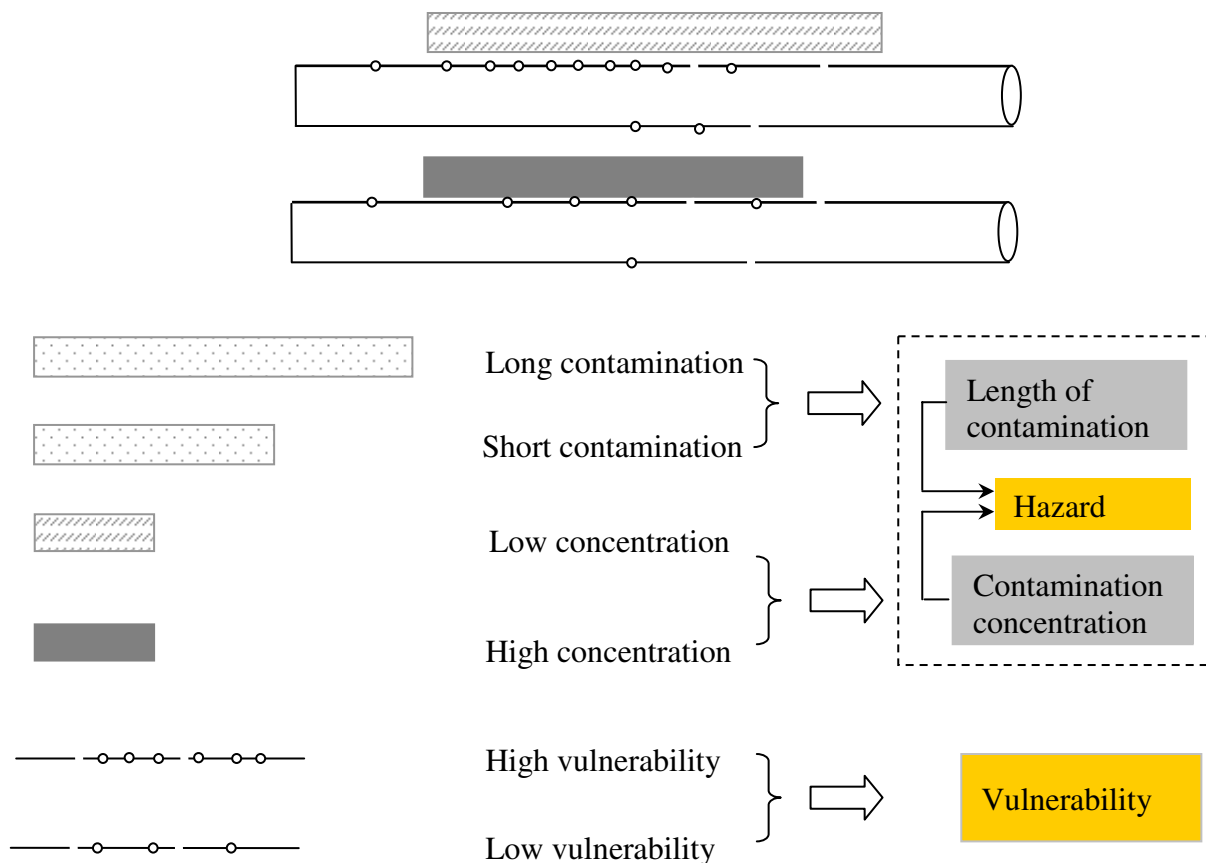
Questionnaire 2

Risk Assessment for Contaminant Intrusion

Interviewee: ....

Organization: ....

Address: ....

....

....

Profession: ....

Position ....

Experience .... (years)

Date: .... / .... / ....

Time: ....

Objectives

The objective of this questionnaire is to assess the risk according to the relative contribution of two factors: hazard and vulnerability. Your assessment regarding the relative importance of each of these factors will be helpful for the risk assessment.

Pair-wise comparisons

> Pair-wise comparisons are given below. You are requested to tick the preference in the left column and tick your degree of preference in the right column.
>
> *__Just for example__*, if you feel 'vulnerability' is a greater contributory factor than 'hazard', you should tick 'vulnerability' in **column 1** of the table and then go to column 2. If you think that 'vulnerability' is 'Strongly preferred' over the 'Hazard' for risk, then tick 'Strongly preferred' in **column 2** of the table. In this way, please complete these pair-wise comparisons.

Vulnerability (pipe condition) vs Hazard (contaminant load)

Column 1	Column 2		
❏ Vulnerability ❏ Hazard	❏ Equally preferred ❏ Moderately preferred ❏ Strongly preferred	❏ Very strongly preferred ❏ Extremely preferred	
Reasons for preference if any			

Appendix F

Water Quality Model

Introduction

Safe drinking water is essential to sustain life, and a reliable and adequate supply is to be ensured by governments. The water supply system has a close association with the health of the people in urban societies, as it is the major source of water for them. The rising population has exerted a very large demand on the public water supply system. The quantity of water supplied depends upon the availability of water at the sources. To have some control over the quantity of water being supplied, most of the cities and towns in developing countries with less available water have adopted an intermittent water supply system. The quality of water supplied is the issue of top priority as contaminated water is a potential hazard to public health. Most water supply networks have water treatment plants for purifying water before it is supplied, but there exists no means of purification if water is contaminated in transit. Intermittent water supply systems are highly prone to contamination while in transit. Hence, assessment of the risk involved in water distribution networks is essential.

The quality of water supplied is an issue inherent with water supply networks or schemes. Water quality may deteriorate either at the source or in the pipelines. Quality deterioration at the source can be averted to a great extent by appropriate and ample treatment processes. However, quality relapse in transit needs to be addressed properly.

Intermittent systems of water supply fulfil to a great extent the water demands of the public, especially when the available water is inadequate. Even though the water supplied may be less than the demand, it ensures a sustainable supply of water. But this solution is not free from flaws. Intermittent supplies are prone to contamination in distribution pipes that are often under no or negative pressure. The situation is serious in cities with unsanitary excreta disposal where sewage flows in open ditches close to distribution pipes. In Delhi, an intermittent supply and the proximity of water and sewage pipelines were the prime suspects of a paratyphoid fever outbreak in 1996 (Guillermo et al. 2001). The bacteriological quality of an intermittent water supply is substantially lower than that of a continuous service. In four districts in Indian towns between 27 per cent and 76 per cent of samples under intermittent water supply tested positive for fecal coli-forms, whereas the figure was only 10 per cent for the samples under continuous water supply. In-house storage tanks to cope with an intermittent supply also risk bacteriological deterioration of water.

Water quality deterioration in the pipelines can occur for many reasons, the major one being contamination due to seepage from drainage networks and foul water bodies. In many places, sewer pipelines are normally positioned above the water pipelines. This is quite common in the development process. Initially the water pipelines are laid, and later sewer pipes are laid. Most of the water supply systems in the country are designed with an assumption of continuous supply, whereas the systems actually operate intermittently. This means that there are many occasions when the pressure in the pipeline is zero or negative. A low pressure inside the water supply pipeline favours the entry of sewage into the pipeline. When the water supply resumes, the contaminants get mixed with water, resulting in the deterioration of the quality of water supplied. Thus leakages in the drinking water pipelines and close proximity

of sewer lines, foul water bodies and garbage disposal areas to pipelines pose a serious risk of contamination of the drinking water and hence the health of the people.

Once a potentially hazardous situation has been recognized, however, the risk to health, the availability of alternative sources, and the availability of suitable remedial measures must be considered so that a decision can be made about the acceptability of the supply. Failure to provide adequate protection and effective treatment will expose the community to the risk of outbreaks of diseases. Those at greatest risk of waterborne disease are infants and young children, people who are debilitated or living under unsanitary conditions, the sick, and the elderly.

The quality of water supplied is of utmost importance in all water distribution systems. However, the system cannot be made 100 per cent foolproof, avoiding all possible quality deterioration. Constant watch on the system and routine maintenance works are required for the proper functioning of the system. In developing countries, the funds available for maintenance or renovation works will often be too little. Thus it becomes essential to have a trade-off between the works to be undertaken. The assessment of risk involved in water supply systems is essential for the adoption of better management policies for averting hazards. The fault that is likely to affect the maximum number of population and also those that have serious impacts on the health of the general public are to be attended to with immediate priority. This decision-making is crucial in protecting the health of the public and the management of available funds. Such decision support systems require handling a large amount of data, for which geographic information systems (GIS) will be the best tool. GIS technology is applied in a variety of problems in water distribution networks. GIS gives a visual model of the field conditions and hence can be used with ease, even by a layman. A Water Quality model can be integrated with the GIS tool to simulate the hydraulic and water quality analysis at various points in the pipe networks. Then, using the GIS tool, the area and number of families affected by deterioration in water quality can be determined. A decision support system with GIS interface will be an effective tool in the proper management of the water supply system.

The aim is to assess the risk involved in intermittent water supply systems and to determine the area affected and decide alternative routes for water supply using GIS tools. Risk is defined as the product of probability of occurrence of an event and the loss associated with it. In case of water supply networks the event of concern is the occurrence of a leakage in the pipeline and water getting contaminated due to the presence of sewer lines or other sources of contamination nearby. The failure probability analysis can be done using a fault tree analysis. Then, using the data obtained by spatial analysis, the loss involved in the particular event can be determined. Thus the risk of contamination in pipe networks can be determined.

Integration of water supply network analysis models and GIS can be a feasible and affordable tool for many municipalities and engineering firms for analysing the system as well as for assessment of risk and adopting suitable alternatives. It can serve as an efficient tool in water distribution system management. The applicability of the developed models has been demonstrated with a case study of the Guntur water supply system.

Methodology

The procedure adopted for development of an integrated water quality risk assessment model consists of three phases. The first phase consists of integrating the pipe network analysis model with GIS. A network analysis model is used to simulate the propagation of contaminant through the network and locating the affected sections of the network. The integrated model is then applied to the water supply network of zone VIII in Guntur city. Assessment of risk is done in the second phase. This includes quantification of risk involved in various components of the network and health risk to the customers. Third phase consists of formulating the decision support system. The various phases of the methodology are shown in the block diagram (Figure F.1).
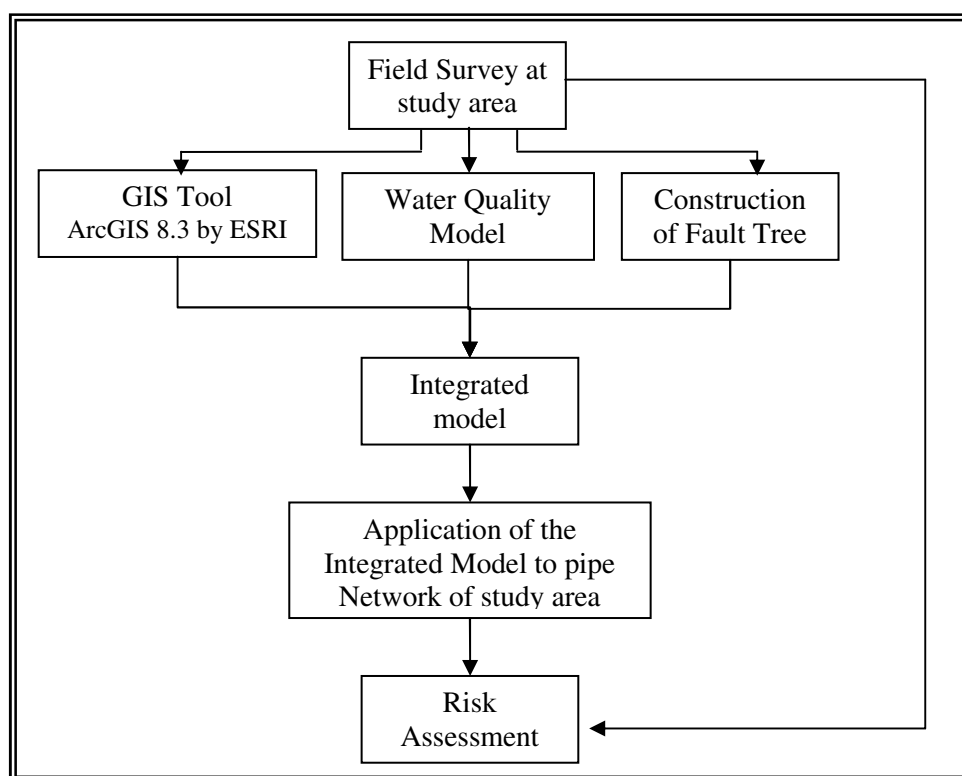
Figure F.1. Various Phases of Methodology

ArcGIS Desktop 8.3 software package by ESRI (Environmental Systems Research Institute, Inc.) was used to map the network and other geographic features of zone VIII. The water supply network analysis model was integrated to ArcGIS using the macro editor provided for visual basic application. This retrieves required data from the attribute tables of features of the map and creates the input for the network analysis model. After successful simulation of the model, it loads the results to the attribute table of appropriate features in the map. Then using the spatial analysis tool provided in ArcGIS, the contamination prone areas are identified. The results are displayed in the GIS interface.

A field survey was done for gathering information on the frequency of failure of network components, frequency of contamination events, number of people affected by a particular event of contamination etc. From this data, the probability of failure of network components was determined. Information on the routine maintenance works and replacements, and the

expected expenditure on medical treatments on occurrence of contamination was also collected. A risk table was created, to facilitate comparison of risk involved in various network components and to identify the locations that require immediate attention.

Creating Thematic Maps

Thematic maps were created for different features of the study area. In GIS all thematic maps are associated with an attribute table, which contains the properties of every element of the feature class (thematic maps). Each field in the attribute table represents a particular property. GIS will automatically create the attribute table and adds certain default fields to it. Many more fields are required to fully describe the network as required by EPANET. These fields can be added to the table by a procedure similar to that in other database management tools.

Features are represented in GIS by means of points, lines and polygons. In the case of a water supply network, the nodes are mapped as points and links as lines. The ward map, soil-types map etc. are created using polygons. The fields required in the attribute table for the nodes and links are given in Tables F1 and F2 respectively. There are certain fields that are essentially required for the simulation of network analysis model. These fields are to be populated for the creation of the proper input file. Certain fields are required for loading the results. The units of the values entered in the fields depend upon the unit system chosen for the analysis. There are two main types of units for EPANET, viz. US customary units and SI Metric units. The unit of parameters based on the unit type selected is given in Table F.3. There is an option to choose the unit system while creating the input file, which sets the unit for all the parameters. Details on the input file format and other information for running the simulation are available at the help section in the EPANET 2.0 software package.

Table F.1. Fields to be added in the GIS Attribute table for Network Analysis using EPANET (for the feature class for Nodes)		
Field	**Field Type**	**Remarks**
Object ID	Number	Added automatically by GIS
Shape	Text	Added automatically by GIS
* Node ID	Text	ID of the node
* Node type	Text	Type of node (Junction, Tank or Reservoir)
* Elevation	Number	For tank, it is the bottom level of the tank and for reservoir it is the total head available
Initial quality	Number	Initial concentration of chemicals at the nodes
Demand	Number	Demand at the nodes. No demand for tank and reservoir nodes Demand may be zero for head dependent flow analysis
Pattern	Text	ID of the time pattern for the node
Source type	Text	Type of source (detailed in EPANET Help)
Source strength	Number	Concentration at the source
Source pattern	Text	ID of the time pattern for source concentration
* Flow coefficient	Number	Flow coefficient value, in case of head dependent flow
+ Actual demand	Number (single)	Demand or outflow calculated during the run
+ Hydraulic head	Number (single)	Total hydraulic head at the node
+ Pressure	Number (single)	Pressure at the node
+ Actual quality	Number (single)	Concentration of chemical species at the node
+ Mass flow rate of chemical source	Number (single)	Flow rate of chemical at the node
# No. of house connections	Number (integer)	No. of house connections from the node
# No. of standpipes	Number (integer)	No. of standpipes connected to the node
* Essential fields for pipe network analysis + Essential fields for loading results # Essential fields determining no. of outlets affected by contamination.		

Table F.2. Fields to be added in the GIS Attribute table for Network Analysis using EPANET(for the feature class for Links)		
Field	**Field Type**	**Remarks**
ObjectID	Number	Added automatically by GIS
Shape	Text	Added automatically by GIS
* Link ID	Text	ID of the link
* Link type	Text	Type of link (Pipe, Valve or Pump)
* Start node	Text	ID of Start node for the link
* End node	Text	ID of end node for the link
* Length	Number	Length of the link (only for pipes)
* Diameter	Number	Diameter of link
* Roughness coefficient	Number	Roughness coefficient for the pipe material (only for pipes)
Minor loss coefficient	Number	Minor loss coefficient for links
Valve type	Text	Type of valve, as defined by EPANET
Valve setting	Number	Pressure/flow settings for valves
Reaction type	Text	Reaction type in the link (Bulk/Wall)
Reaction coefficient	Number	Reaction coefficient for the link
* Link status	Text	'Open' or 'Closed'
[+] Flow rate	Number (single)	Flow rate in the link
[+] Velocity	Number (single)	Velocity of flow in the link
[+] Head loss	Number (single)	Total head loss during flow in the link
[+] Status	Text (Open/Closed)	Status of the link during simulation
[+] Settings	Number (single)	Pipe roughness/ valve setting during simulation
* Essential fields for pipe network analysis [+] Essential fields for loading results		

Table F.3. Unit System used in EPANET 2.0		
Parameter	**US customary units**	**SI Metric units**
Concentration	mg/L or ug/L	Mg/L or ug/L
Demand	(same as Flow)	(same as Flow)
Diameter (Pipes)	inches	mm
Diameter (Tanks)	feet	m
Efficiency	*%*	*%*
Elevation	Feet	m
Flow coefficient	Flow units / /psi	Flow units / /meter
Flow	CFS(Cubic feet/sec) GPM (gallons/min) MGD (million gallons/day) IMGD (Imperial MGD) AFD (acre-feet/day)	LPS(litres/sec) LPM (litres/min) MLD (mega litres/day) CMH (cubic-metres/hr) CMD (cubic-metres/day)
Roughness coefficient	Unitless (Millifeet for Darcy Weisbach equation)	Unitless (Millimetres for Darcy Weisbach equation)
Hydraulic head	feet	m
Length	feet	m
Minor loss coefficient	Unitless	Unitless
Pressure	Pounds per square inch	m
Reaction coefficient (Bulk)	1/days (1st order)	1/days (1st order)
Reaction coefficient (Wall)	Mass/L/day (0 order) Feet/day (1st order)	Mass/L/day (0 order) Metres/day (1st order)
Source mass injection	Mass/minute	Mass/minute
Velocity	Feet per second	m/s
Volume	Cubic feet	Cubic metres
Water age	hours	hours

Integrating Network Analysis Model (EPANET) with GIS

The software package used for GIS application was ArcGIS Desktop 8.3, which is composed of three modules called ArcMap, ArcCatalog and ArcToolbox. ArcGIS provides for changing or creating toolbars and menus in the work environment. Custom commands can be created with VBA (Visual Basic Application) in ArcMap using the extensive object library. New objects are created and codes are attached to them to accomplish a particular set of actions. Custom-made toolbars and menus can be saved to a template (*.mxt in ArcMap). All maps

made in a particular template will have all the custom-made commands saved to the template and will be available every time the map is opened.

A template (Pipe_Network_Analysis.mxt) was created to save the new toolbars and menus for integrating the water supply network analysis tool. All the maps created for analysis of water supply networks were made in this template. The template consisted of the menus and commands as explained below.

The menu for water quality analysis is depicted in Figure F.2. It consists of four commands, namely, '*Create Input File*', '*View Input File*', '*Run Model*' and '*Load Output*'. The command, '*Create Input File*', will create a text file in the format for input to the network analysis model, EPANET 2.0. Clicking on to the command will open up a dialog for retrieving specific data from the themes (Figure F.3). The data required are derived from the related shape files (representing the themes or layers in ArcMap) from appropriate fields in the attribute tables. The fields contained in the attribute tables of the selected theme are listed in the combo box next to each parameter. The field, which contains the value corresponding to the parameter required, is to be selected for each combo box in the dialog. There are two options for hydraulic analysis viz. Pressurized flow analysis and the Head dependent flow analysis (Figure F.4). For head dependent flow analysis, the flow coefficient values are to be added to the attribute tables as required by EPANET.

After choosing the necessary options, clicking to the '*ADD Network Components*' button starts adding the network parameters to the default input file. After adding the network components, another dialog as shown in Figure F.5 opens up automatically for choosing the analysis options. This is similar to the normal EPANET interface. For each tab in the dialog, short notes are given at the bottom of the dialog. Clicking the '*Create Input File*' button completes the input file and a message box is displayed (Figure F.6).
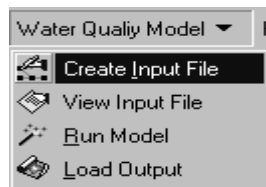

Figure F.2. Menu for simulating water quality model (network analysis model EPANET 2.0)

Figure F.3. Dialog for retrieving data from appropriate fields of selected themes

Figure F.4. Dialog box for choosing the type of analysis

Figure F.5. Dialog for choosing the analysis options

Figure F.6. Message box, on successfully creating the input

The input file created can be viewed using the '*View Input File*' command from the *Water Quality Analysis* menu (Figure F.7). The default input file can also be saved in a different filename.

Once the input file is created, the network can be simulated using the '*Run Model*' command from the menu. An input file other than the default input file can be chosen in the dialog that appears. A different name may be given for the report file. The simulation is triggered by the '*RUN*' button in the dialog. It generates a message, whether the run was successful or not. If the run was unsuccessful, the report file can be viewed for error checking in the input file. The errors should be corrected before any further simulation or loading of results.
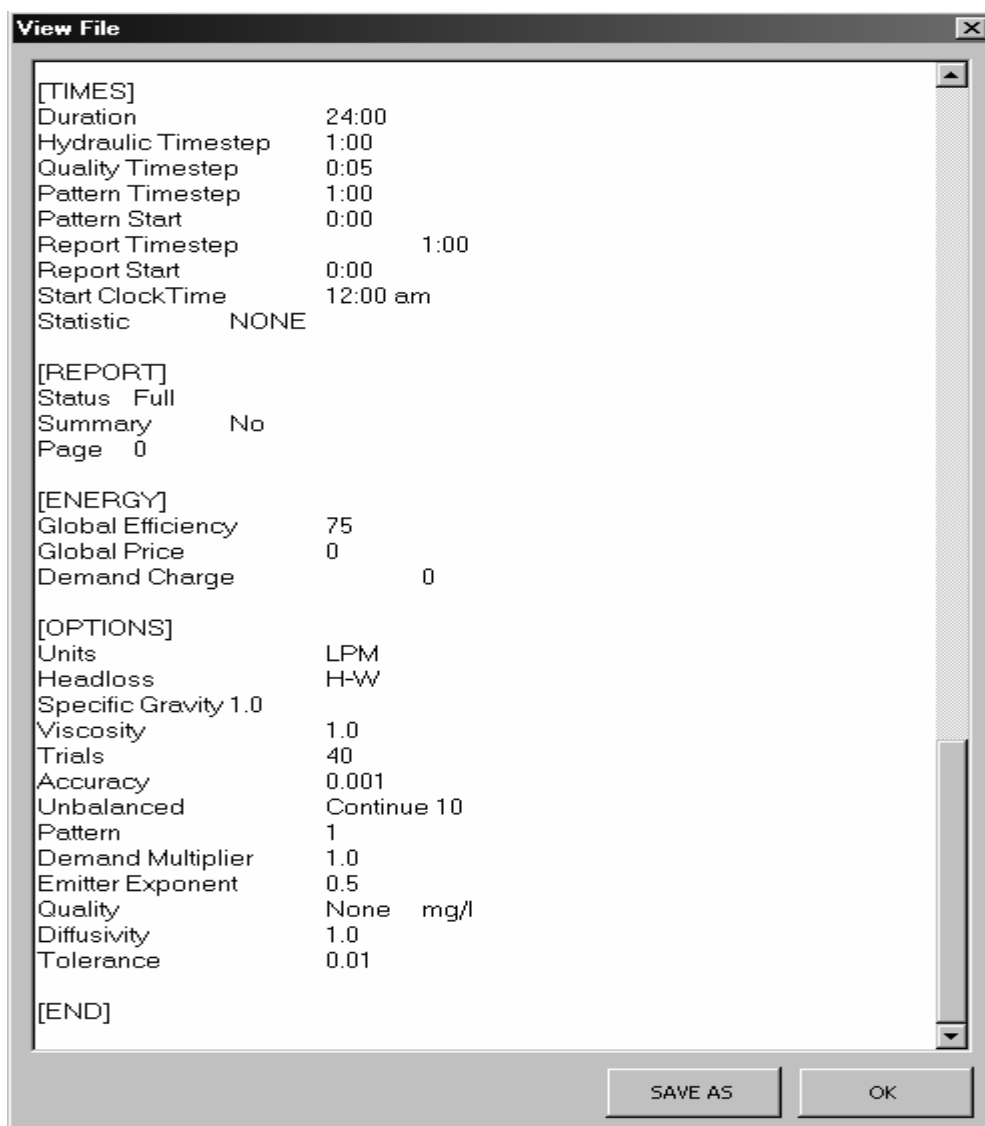
```
View File                                                    [×]

[TIMES]
Duration                24:00
Hydraulic Timestep      1:00
Quality Timestep        0:05
Pattern Timestep        1:00
Pattern Start           0:00
Report Timestep                     1:00
Report Start            0:00
Start ClockTime         12:00 am
Statistic       NONE

[REPORT]
Status   Full
Summary         No
Page    0

[ENERGY]
Global Efficiency       75
Global Price            0
Demand Charge                       0

[OPTIONS]
Units                   LPM
Headloss                H-W
Specific Gravity 1.0
Viscosity               1.0
Trials                  40
Accuracy                0.001
Unbalanced              Continue 10
Pattern                 1
Demand Multiplier       1.0
Emitter Exponent        0.5
Quality                 None    mg/l
Diffusivity             1.0
Tolerance               0.01

[END]

                            SAVE AS        OK
```

Figure F.7. Dialog box for viewing the input file created

Once the input file is successfully run, the outputs can be loaded to the attribute tables. The output tables should have fields for loading the results as described in Appendices 1 and 2. The results can be loaded to the attribute table of the thematic maps in the current map document in ArcMap. This implies that the maps should be added as layers to the current map document. Activating the '*Load Output*' command from the menu brings up the dialog for choosing the fields to which the results are to be loaded.

The dialog lists the themes already loaded into the map. The combo boxes list the fields available in the tables. Respective fields may be chosen for both node and link results. The time period for which the results are to be loaded should also be chosen from the lowermost combo box in the dialog. After loading the results, the symbology of the layer is changed to show the variation in chemical concentration.

Water Quality Simulation

The water supply network of the study area was simulated so that the water quality condition for four cases could be analysed. The menus and commands developed as explained above were used for the analysis. The four cases are:

        Case 1: Contamination at a single node – Instantaneous intrusion
        Case 2: Contamination at a single node – Continuous intrusion
        Case 3: Contamination at multiple nodes – Instantaneous intrusion
        Case 4: Contamination at multiple nodes – Continuous intrusion.

Node no. 534 was chosen as the contaminated node for cases 1 and 2. This is one of the nodes at which the sewer line crosses pipelines. The scenario in case 1 is that a particular amount of contaminant has entered into the pipeline through a leak at this point. This is assumed to result in a contaminant concentration of 100mg/l in water at this node for the first five minutes after resuming water supply. The contaminant intrusion will be absent once water supply resumes because of higher pressure within the pipeline.

For case 2, the node 534 is assumed to have continuous intrusion into the pipeline, resulting in the contaminant concentration of 100mg/l in water for the first five minutes after resuming water supply and 10mg/l for the rest of the time for which water is supplied. This is the case when the pressure inside the water pipeline is not sufficient to push the contaminant outside the pipe. But since the pipe is not empty, the intrusion rate will not be as high as when there was no water in the pipe. Thus it was taken as about 10 per cent of the initial intrusion rate.

Cases 3 and 4 consider similar situations, but with the contaminant intrusion occurring at two different nodes. Node no. 589, which is close to a foul water body, and node no. 487, which is crossed by a sewer line, were chosen for these two cases. The resulting contaminant concentration in water and the pattern of variation in the intrusion rate was considered the same as that of the previous cases.

Assessment of Risk due to Contamination

A field survey was conducted in zone VIII of Guntur City, for gathering information on failures of water supply and drainage network components and occurrence of contamination events. The aim was to meet the technical people as well as the general public and collect data on failure frequencies, time taken to repair, maintenance/replacement expenses, frequency of occurrence of epidemics due to contaminated water and the population affected. A questionnaire was prepared for the survey (Table F.4). The survey yielded valuable information on the major causes of failures in the water supply system as well as the drainage network, the frequency and severity of such failures and the cost of repair or replacement. Information was obtained on the impact of a contamination event on the general public and GMC (Guntur Municipal Corporation). The expenditure on medical treatment in the case of an intake of contaminated water was also obtained from the public. The fault tree approach was used to assess the overall probability of failure due to contamination. Information obtained from the survey was compiled to develop a fault tree for determining the probability of occurrence of contamination in the water supply network. The probability of occurrence of each of the base events in the fault tree was calculated from the data obtained from the field survey. The data on expenses incurred in each failure or contamination event were used to evaluate the risk involved in the system.

Table F.4. Questionnaire for field survey of Study area – zone VIII of Guntur City

Risk Assessment of Water Supply Pipe Networks in Guntur

General

Date: ……… February 2004   Interviewer: _____
LOCATION:

Respondent Details

Respondent Name:	
Age:	
Duration of stay in the region: [Years]	
Address:	
Number of members in Family:	Adult Children
Educational qualification:	
Source of water:	Pipe Connection Street Pipe Others [specify]:
Water consumption per day: [Approximate]	

Vulnerable Locations

Area:				Number of locations:		
Location/Land mark	**Sewer**			**Water Pipe**		
	Type [Open/Closed]	Diameter [cm]	Burial Depth [m]	Type [Major/ Distributory/Domestic]	Diameter [cm]	Burial Depth [m]
1.						

Failure of Water Supply Pipes

Number of failures [Leakage/Break]:				
Location	Failure point [Valve/Joint/Pipe]	Type of failure [Major/Minor]	Causes of failure [E.g.: age, heavy traffic, corrosion, material defect…]	Time taken to restore water supply or for maintenance [Days/Hours]
1.				

Failure of Sewer Lines

Number of failures [Leakage/Break]:		Time span [Years]:	
Location of failure	**Type of failure [Lining failure/ Pipe-Break/Unlined]**	**Causes of failure [E.g.: age, heavy traffic, corrosion, material defect…]**	**Time taken to restore or for maintenance work [Days/Hours]**
1.			

Consequences*

Work location [pipe/joint/valve/sewer]	Work type	Cost per unit work [Rs]	Other expenses
1.		Pre: Res:	
Pre: Maintenance before failure, Res: Restoration work after failure.			

* To be obtained from Authorities

Additional information

In case of water supply failure, what are the alternative sources available	
Lorry load	Cost: Rs……… per………. Quantity: ……………………………
Stand pipe	Quantity: ……………………………
…………….	Cost: Rs……… per………. Quantity: ……………………………

Other expenditure due to failure	

Whether contamination has occurred at any time	☐ **Yes** ☐ **No**

If YES,
     How many times contamination has occurred:
                 Disease:
           Duration of persist:
    Number of members of family affected:	

Survey done by

Signature……………………………

Name………………………………..

Risk is defined as the product of probability of occurrence of an event and its consequences. One additional menu – *Risk Assessment* – was added in the template (Pipe_Network_ Analysis.mxt) for fault tree analysis and to retrieve data from attribute tables about the number of house connections and standpipes affected by contamination (Figure F.8). The dialog for fault tree analysis contains a fault tree as shown in Figure F.9 and was developed based on the information gathered from the field survey. The probabilities for failure of various components are to be entered in the corresponding enabled text boxes, and the probability of contamination is automatically calculated. The text box for probabilities that are automatically calculated, are disabled.
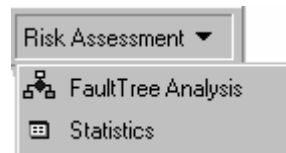
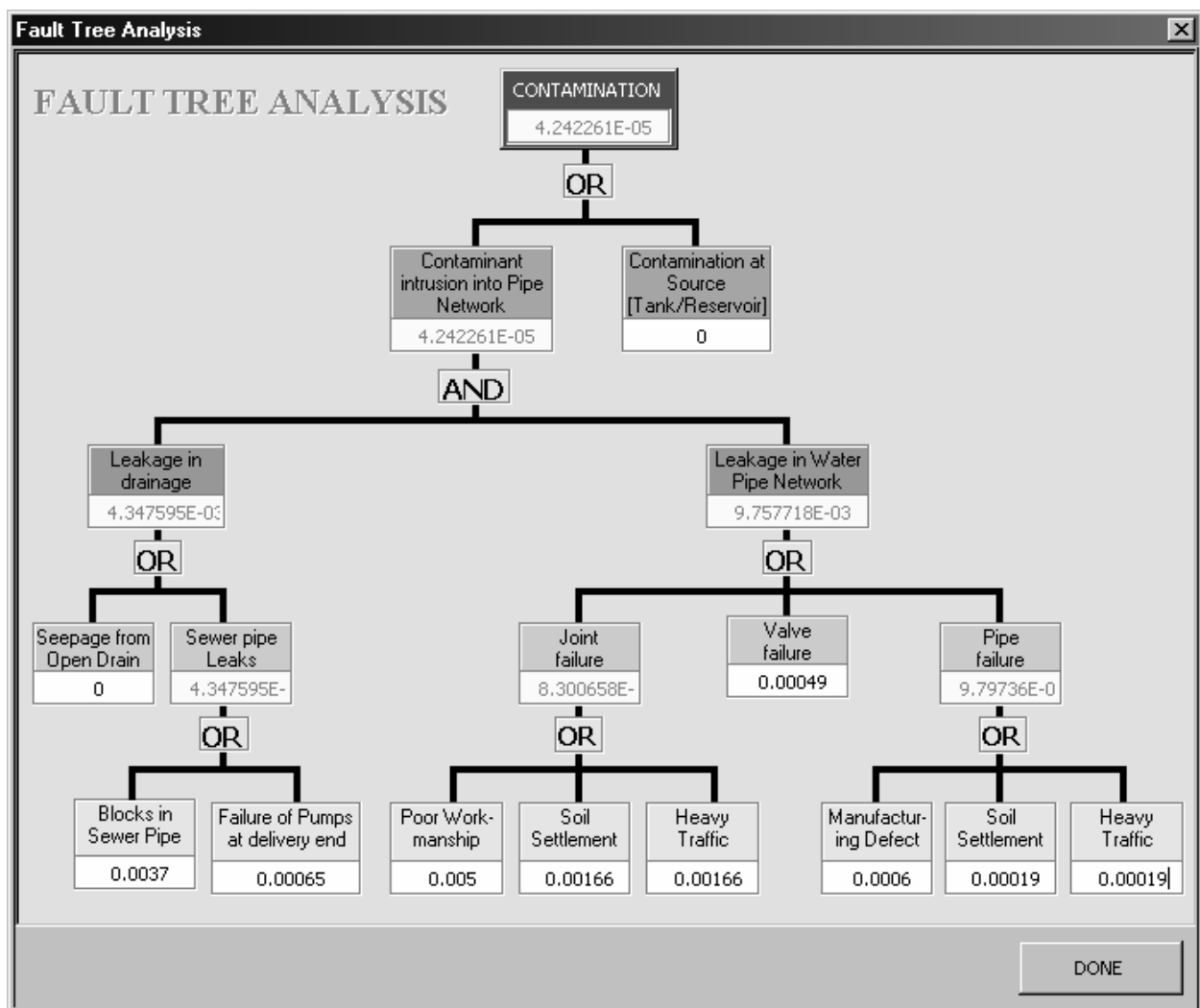**Figure F.8. Menu for Risk Assessment**

Figure F.9. Dialog for fault tree analysis

The '*Statistics*' command in the menu activates the statistics dialog shown in Figure F.10. The purpose of this is to retrieve the data from the attribute tables, the number of house connections and standpipes in the network affected by contamination. Similar to earlier cases, the appropriate feature class and corresponding fields are to be selected from the lists given in the dialog window. Probability of contamination can be either typed in or obtained from the fault tree. On clicking the '*CALCULATE*' button, the total number of house connections and standpipes at which the chemical concentration is greater than zero is calculated and displayed in the space below.

Figure F.10. Dialog for risk statistics

Various options are available in GIS for spatial analysis of the results. ArcMap provides the '*Spatial Analyst*' tool for different types of spatial analysis. The inverse distance weighted method was used to create a buffer region surrounding the nodes affected by contamination. This is according to the assumption that people living within a certain distance from the node will use the water from a particular node. The area covered by the buffer can be measured to understand the extent of contamination. From the population density map, the approximate

population at risk of being affected by a particular event of contamination could be found out. The probability of occurrence of the event of contamination is determined from the fault tree analysis. The consequence is evaluated in monetary terms. Contamination essentially occurs with a failure in the water supply network and drainage network as depicted in the fault tree. This implies that one of the consequences is the cost of repair or replacement of the failed network component. A repair or replacement activity requires 1 to 5 days to complete, depending on the type of failure. During this time period, alternative arrangements are to be made for water supply. The expense incurred in this provision adds to the consequences of the failure event. These are the consequences affecting the authorities responsible for water supply or drainage networks. There are also consequences which affect the consumers. Contaminated water is hazardous to health and in most cases it requires that medical treatments are to be sought. This is yet another consequence of contamination. Thus the total consequence is the sum of costs incurred by the authorities in restoration of water supply and temporary alternative arrangements, and to consumers who are in the affected area.

The product of contamination probability and consequences gives the risk involved in a particular failure event. A risk table was created to evaluate the total consequence of various failure events and risk engrossed in that. The risk table helps to compare the risk in various components and to make decisions about the maintenance or replacement work that requires immediate attention. The expenses entailed with various consequences are obtained from the field survey of technical people who attend the failures in zone VIII and also from the Engineers-in-charge at GMC (Guntur Municipal Corporation).

The sensitivity of risk to various measures adopted for improving the system was also analysed with the risk table. For example, the risk was determined after reducing the probability of occurrence of failure of joints due to a particular cause, say improper maintenance. This gave the percentage reduction in risk produced by adoption of better maintenance methods. Similarly, the reduction in risk was determined for other measures. The percentage reduction in risk in each case was compared to determine the most sensitive measure. This helps to discard the measures which do not yield significant reduction in risk.

Since only limited funds are available for routine maintenance works, an intelligent fund allocation is required to use resources efficiently. Risk assessment gives handy information on activities to be undertaken immediately. The risk table gives both the event that requires immediate attention and the event that reduces risk significantly. A judicious combination of these two creates an excellent tool in decision-making processes.

Application of Model to Study Area

The development and application of a GIS-based risk assessment model following the procedure explained in the previous section are detailed below.

Field survey

The salient features of the water supply network of zone VIII of Guntur, as revealed from the field survey, are as follows.

- There are frequent occurrences of leaks in water supply network as well as the sewer networks. The failure frequency is about eight cases per day for water pipelines and two to three cases per day for sewer pipelines.

- The time taken for maintenance work ranges from one day to one week in certain cases. On average the leaks remain unattended for about three days.
- The majority of leaks in the water supply network occur at the joints. This is attributed to poor workmanship and the absence of soil bedding for the pipeline. A few cases of leakages were due to cracks in pipelines and wear and tear in valves.
- Leaks in the sewer line also occur at joints, but the main cause of leaks is the frequent blocks in the sewer lines. Sometimes it happens as a result of failure of the pumps at the delivery end of the sewer lines.
- Contamination of water supply has occurred many times. This lasts for some time after water supply resumes and also when people try to pump water from the pipes after the supply has stopped. The contamination was identified by changes in the colour and taste of water and the odour. This confirms the movement of sewage from the leaks in the sewer lines and its entry to the water pipeline through the leaks in it.
- The water is not used if contamination is identified by colour, odour or taste, but there were cases when the contamination could not be identified by these means. This resulted in consumption of polluted water, leading to severe health hazards.
- Outbreaks of disease due to consumption of contaminated water were reported to affect about 500 people per year.
- In the event of contamination or leaks in pipelines, GMC (Guntur Municipal Corporation) supplied drinking water to the people of affected area by tanker lorry.
- The expense involved in a leakage event includes the cost of components, replacement/maintenance charge, the cost of alternative arrangements for water supply and the cost of medical treatment for health probems caused by contamination. This information was collected from the general public and also from the technical people from GMC and Deputy Engineer in charge of water supply networks.

Thematic maps of the study area

Thematic maps of the study area were prepared in ArcGIS Desktop 8.3 and the attribute tables were modified by adding the fields required, as mentioned in Appendices 1 and 2. The maps concerning pipe network (Figure 6.2), sewer network (Figure 6.3), open drain network (Figure 6.4) along with foul water bodies (Figure 6.5), land cover (Figure 6.7) and population density (Figure F.11) were prepared and used for further analysis.

Integration of EPANET model with ArcGIS 8.3

The water supply network analysis model, EPANET 2.0, was integrated to the GIS environment using Visual Basic scripts as explained in the methodology. The input file for EPANET was successfully created from the interactive and user-friendly menus and commands developed. Also the model was simulated with the created input file. The results of water quality analysis for the different cases and various time intervals were loaded to the attribute table of the corresponding thematic maps. After loading to the attribute tables the results were displayed in a map using suitable colour ramp showing the variation of contaminant concentration at the affected nodes. This was achieved using the symbology property of the maps as given by ArcGIS.
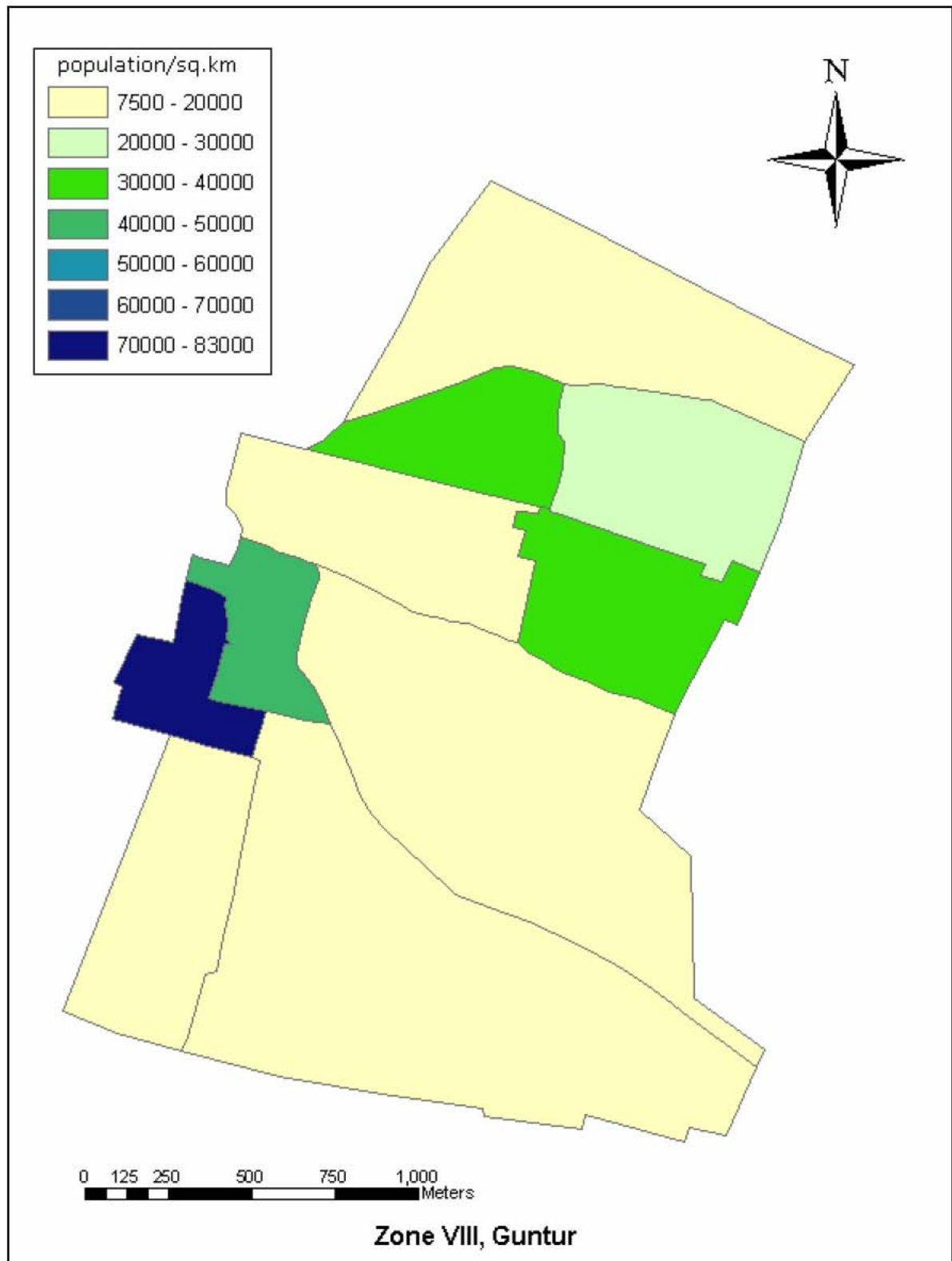
Figure F.11. Population density map for zone VIII of Guntur (ward-based)

Water Quality Simulation for Pipe Network

Water quality simulation for the water supply network of zone VIII of Guntur was done with the following parameters.

- Analysis was done for head dependent flow at outlets (nodes). The flow coefficient value for the outlets was assumed on average to be 40, where the flow unit is LPM and head in metres. (Flow coefficient value of 40 corresponds to the orifice constant 0.82 and opening diameter of 15 mm.)
- The nodes assumed to be affected by contamination (node numbers 534, 589 and 487 in different cases as described in the methodology) is set to be contaminated by a non-reactive contaminant with resultant initial concentration of 100 mg/l. The node was set as a 'set-point' source with the contaminant being present at the node in the initial five minutes for plug flow cases (cases 1 and 3). For continuous intrusion cases (cases 2 and 4) the contaminant concentration was 100 mg/l for the initial five minutes and 10 mg/l for the rest of the time period.
- Extended period simulation was done for a time period of one hour with a time interval of 10 minutes.
- The results of water quality analysis for the last time interval (after one hour) for case 1 and case 2 are displayed in the GIS interface as shown in Figure F.12. Results of case 3 and case 4 are shown in Figure F.13.
- A buffer was created for the contaminated nodes for a distance of 100 m around the node. This is under the assumption that people within this distance from the node use water from those nodes. This was done using the spatial analyst tool in ArcGIS, with the Inverse Distance Weighted (IDW) method of interpolation. This gives the area surrounding a node that is likely to be affected by the contamination, as given in Figure F.14 and Figure F.15.
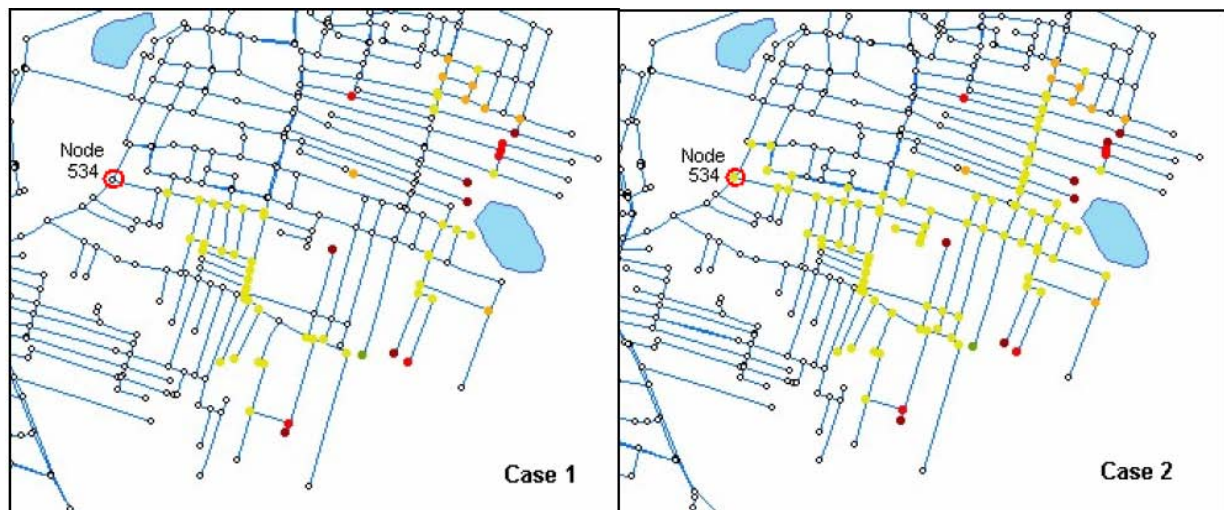

Figure F.12. Results of water quality simulations after one hour for node 534

Case 1: Single node – Plug flow intrusion
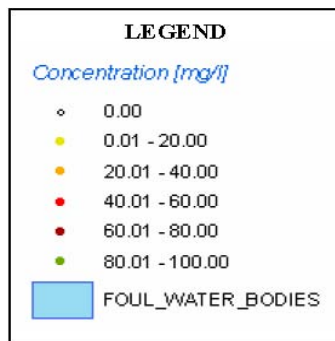Case 2: Single node – Continuous intrusion

Figure F.13. Results of water quality simulations after one hour for nodes 589 and 487

Case 3: Multiple nodes – Plug flow intrusion
Case 4: Multiple nodes – Continuous intrusion

Contaminant Concentration [mg/l]

- 0 - 20
- 20 - 30
- 30 - 40
- 40 - 50
- 50 - 60
- 60 - 70
- 70 - 80
- 80 - 100

Case 1: Single node – Plug flow intrusion
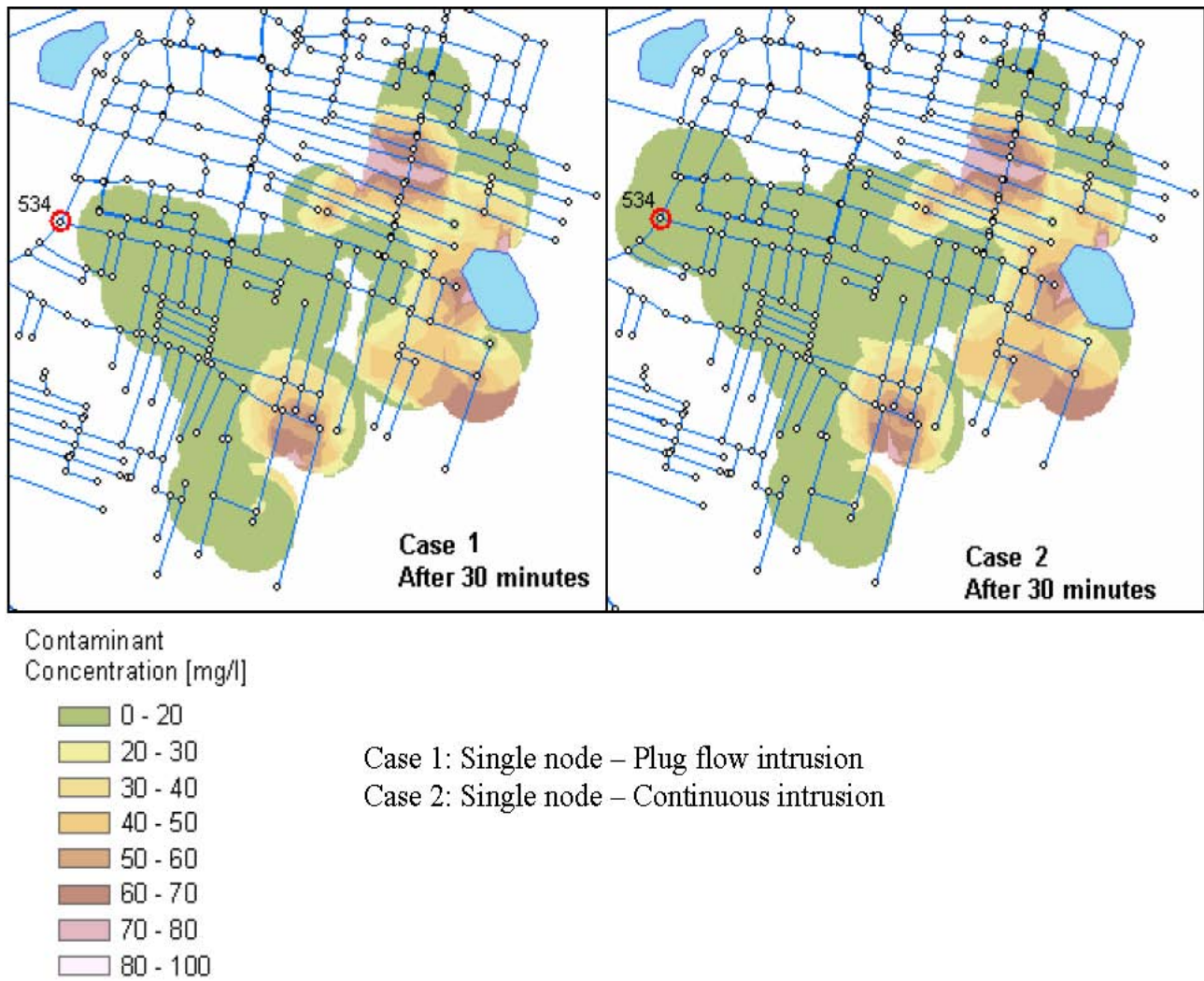Case 2: Single node – Continuous intrusion

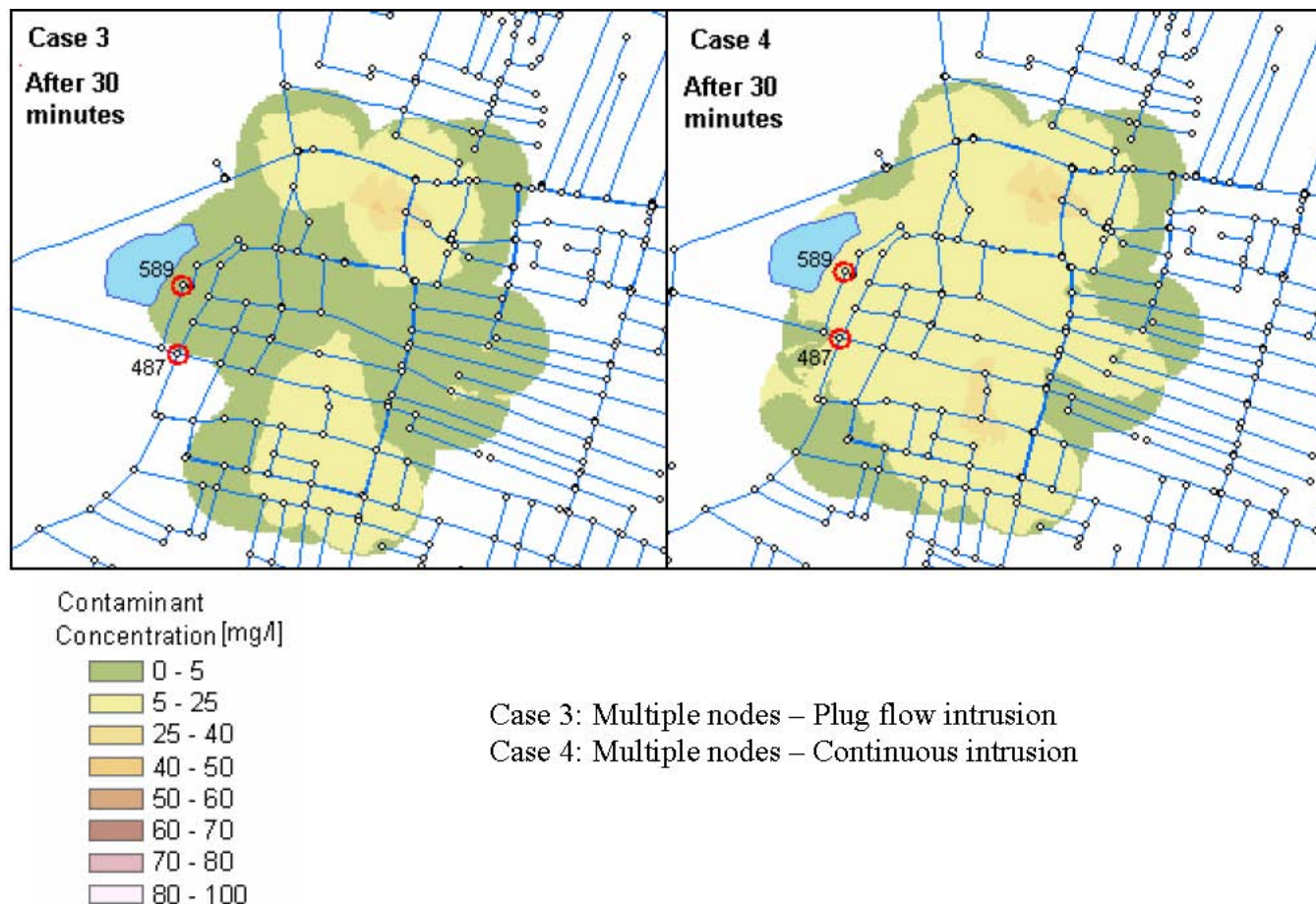**Figure F.14. Affected areas due to contamination at node 534**

Figure F.15. Affected areas at due to contamination at nodes 589 and 487

Retrieving Statistics for Contaminated Nodes

After loading the results from the water quality simulation, the information on affected population could be obtained. The total number of household connections and standpipes to the nodes affected by contamination was retrieved from the GIS database. This includes all the connections from the nodes with contaminant concentration greater than zero.

The number of affected connections at different time intervals was obtained and is shown in Figure F.16, which gives the statistics for nodes affected by contamination during the one-hour simulation. From the figure it can be seen that continuous intrusion has affected a greater number of nodes compared with plug flow intrusion at any time interval. Also the location of the contaminated node has significant effect on the number of affected nodes. For example, in case 1, node no. 534, which supplied water to a large number of downstream nodes, was contaminated, resulting in more affected nodes than in case 3, where multiple nodes were affected. The results obtained for plug flow intrusions (cases 1 and 3) are to be closely analysed. The results displayed show affected nodes at each time intervals. In these cases the nodes affected earlier in the time period may not be considered as affected nodes

later, as intrusion is stopped and fresh water starts flowing through those nodes after some time. But there are chances of health hazards during the time when the nodes were affected. Thus the actual number of affected nodes will be between the number of nodes affected in case of plug flow intrusion and continuous intrusion. Maps generated showing the area affected due to contamination also give insight to the extent of contamination. The maps are created by assuming that people within a radius of 100 m from a node have access to water from that node and interpolated using the Inverse Distance Weighted method of spatial analysis in ArcGIS. These results are important in the final decision-making. After determining the rankings based on risk analysis the final decision on management policy is to be made by considering the number of nodes, and hence the number of people affected by different events of contamination.
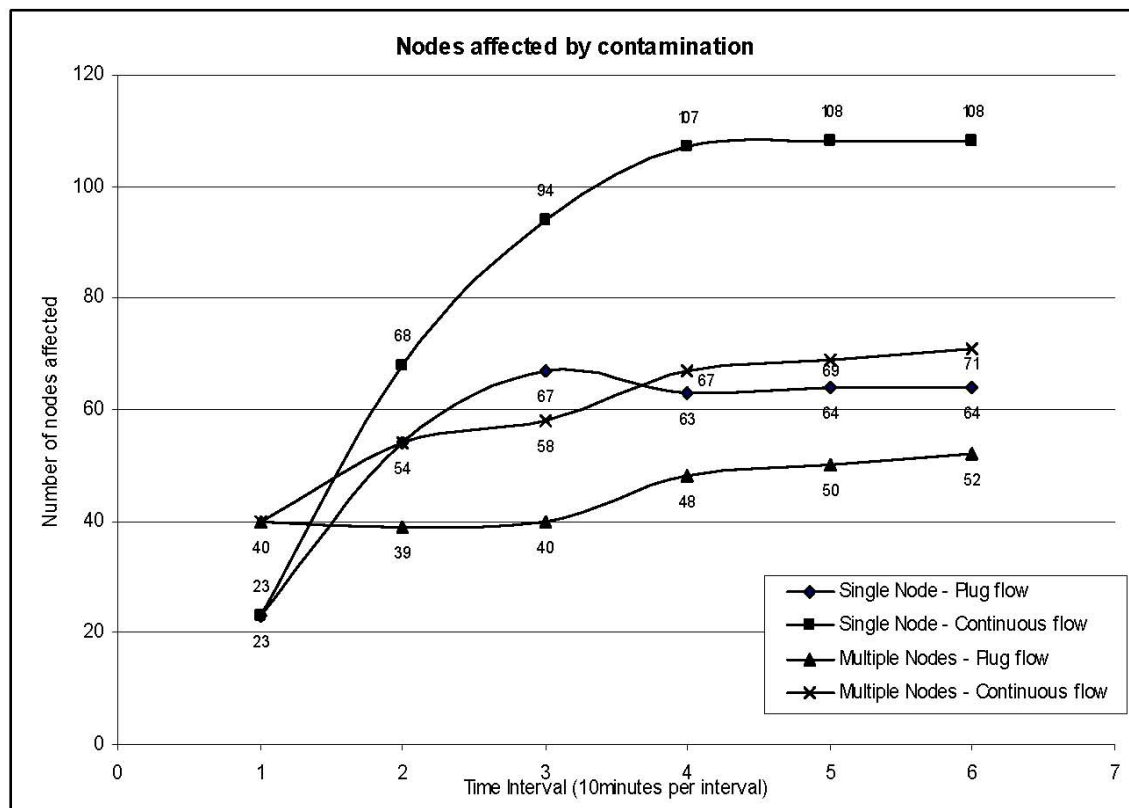

Figure F.16. Retrieving statistics for contaminated nodes

Determination of Alternative Connectivity for the Affected Nodes

Using the network analysis tool in ArcGIS, the connectivity to various nodes from the tank, in case of blocking of a part of the network, was traced out. Blocking of part of the water supply network is done to repair the leakage or eliminating the contamination occurred. It was checked whether there is an alternative route to supply water to the downstream nodes, in case a particular node was contaminated due to failure of the network component. This is essentially required if the maintenance work to be undertaken is of large volume and it takes more time to complete. Thus it may affect large number of people for longer time. Re-routing the water saves money spent on tankers and other alternative means of water supply.

Figure F.17. Contaminant intruded node and affected nodes after one hour of water flow
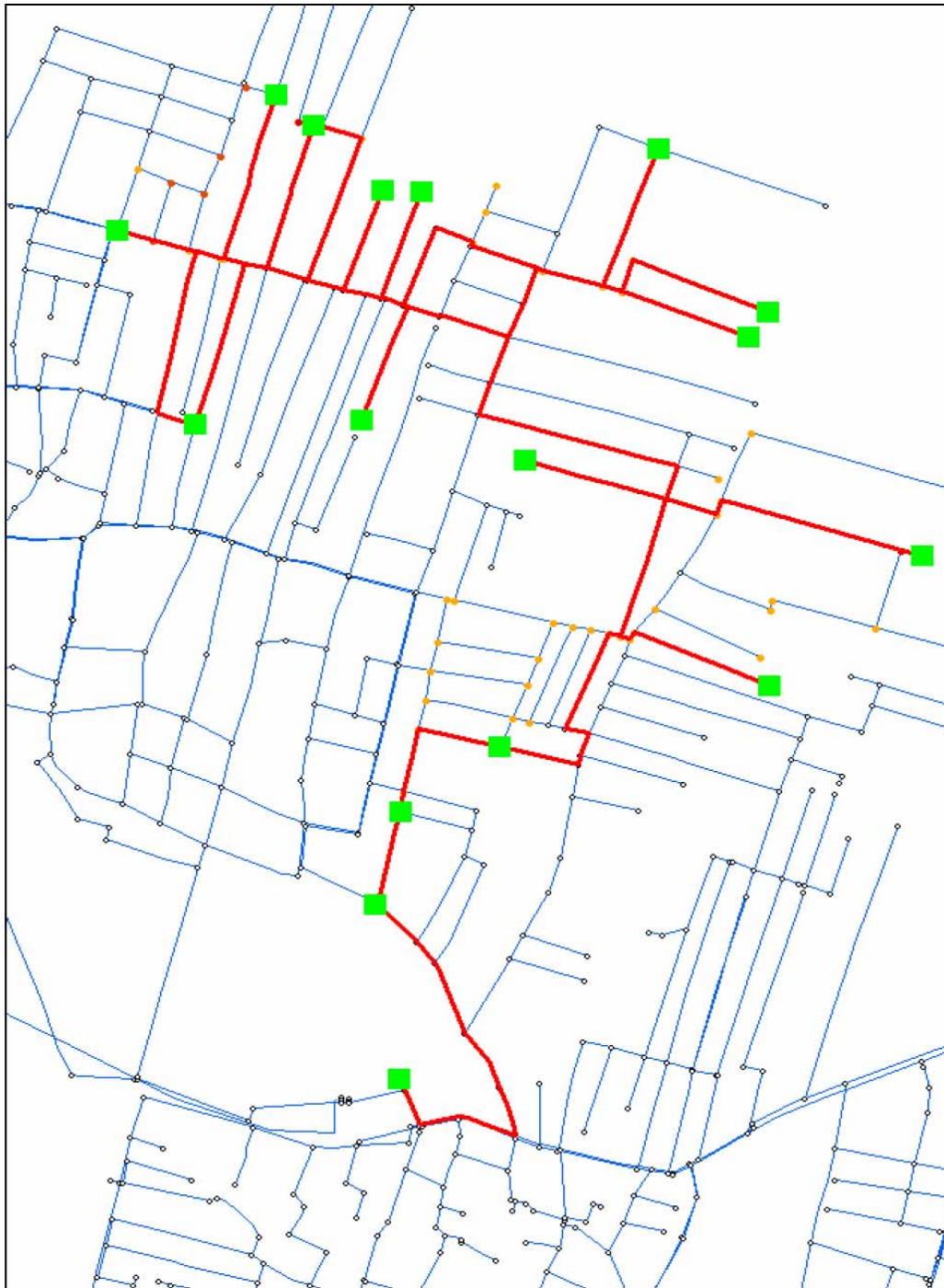
225

Figure F.18. A possible path of water from the tank to various nodes through the contaminant affected node
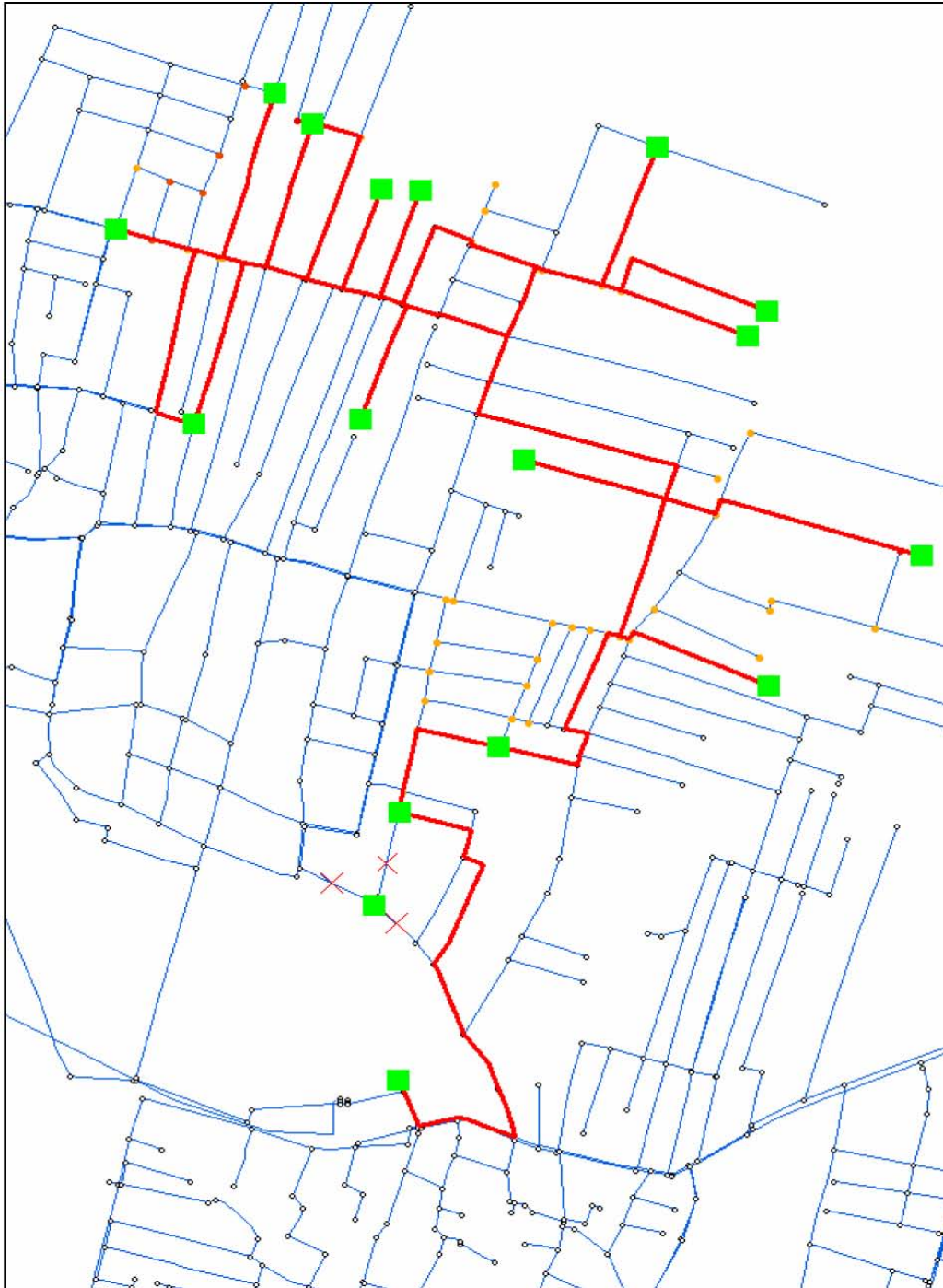
Figure F.19. Alternative path for water flow to various nodes, bypassing the contaminant affected node

In the trial simulation, node no. 534 was assumed to be having a leakage and contaminant intruded into the water supply pipes. Figure F.17 shows the spread of the contaminant within the water supply network after one hour of water flow as simulated by EPANET 2.0. Figure F.18 shows a possible pathway of water from the tank, through node no. 534, to various nodes. Node 534 has to be isolated to prevent contamination as well as to repair the leakage occurred. Thus three pipes that are connected to node 534 were blocked. Then again the network analysis tool was used to see whether the downstream nodes are connected to the

tank through an alternative route. Figure F.19 depicts the results of this analysis.

These results are required to determine the cost of alternative arrangements in case of maintenance activity. The cost of alternative arrangement also adds to the total risk involved in the water supply network. Suitable planning before undertaking the maintenance work saves time and money. Determining the alternative routes for water supply and re-routing the water supply avoids the need for transport of water by tankers, and hence reduces the risk.

Fault Tree for Risk Analysis

The fault tree developed is shown in Figure F.20. The probabilities for the events shown in circles (basic events) are calculated from the field data and the probability of contamination is determined using the logical gates as shown in the fault tree.
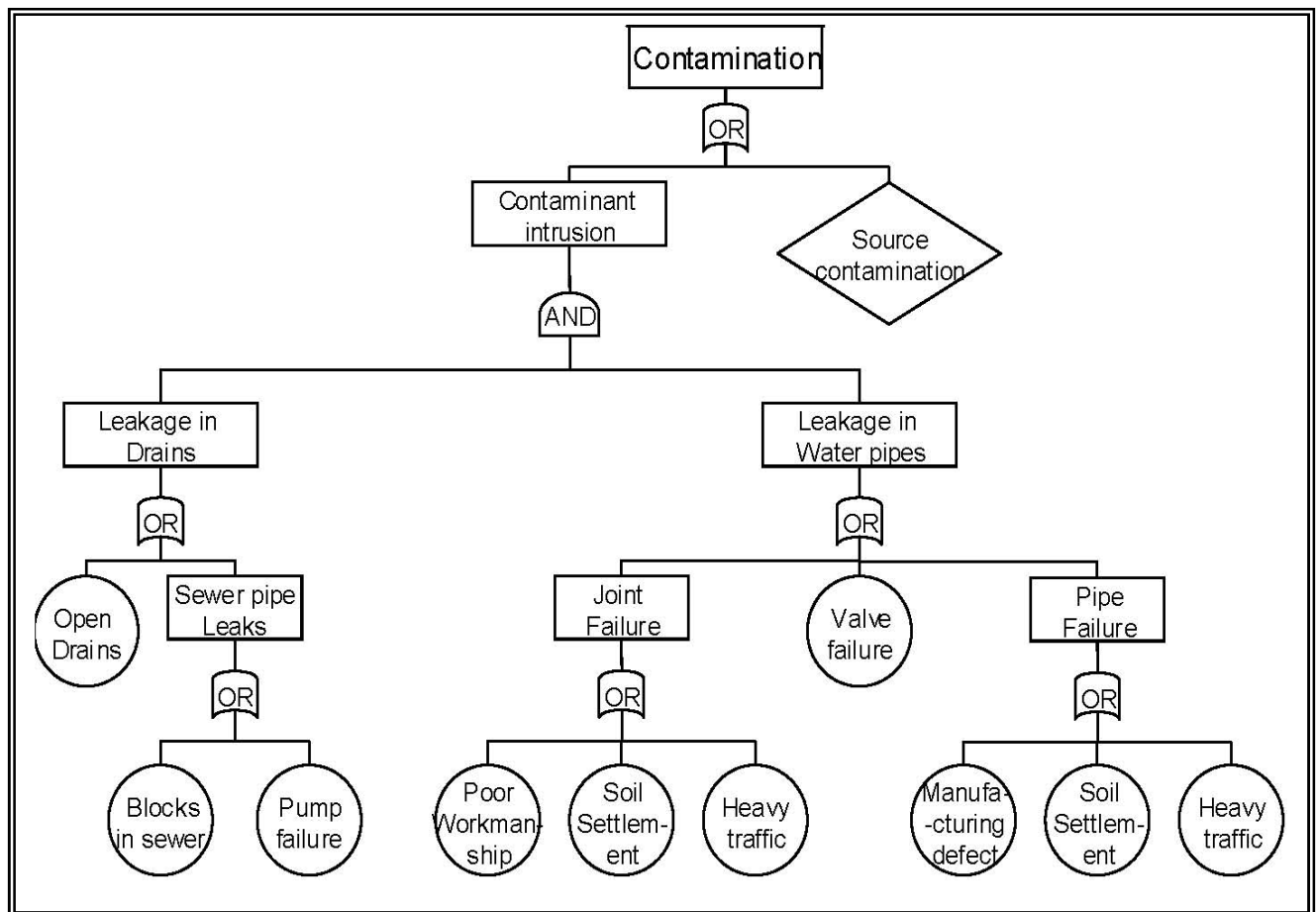
Figure F.20. Fault tree for contamination in water distribution system

Probability is determined as the ratio of the number of occurrences of failure of a component to the total number of the components in the network. For example, there are 821 pipes in the water supply network of zone VIII. The field survey revealed that an average of eight pipe leakages occur per day in the zone. Therefore there are 8 x 365 = 2920 cases of leakages per year. Of these 85 per cent of leakages are due to failure at joints; i.e. about 2503 cases. Also 60 per cent of the 2503 cases are due to poor workmanship. Thus the probability of occurrence of leakage in the network due by joint failure due to poor workmanship is

$$(2503 \times 0.60) \div (365 \times 821) = 0.00501$$

Other probabilities were also determined and are given in Table F.5.

Table F.5. Probabilities of base events		
Item	**Event**	**Probability**
Leaks from open drains		0.4000
Leak in sewer pipe	Block in sewer pipe	0.00278
	Pump failure at delivery end	0.10411
Joint failure in water distribution network	Poor workmanship	0.00501
	Soil settlement	0.00167
	Heavy traffic	0.00167
Pipe failure in water distribution network	Manufacturing defect	0.00059
	Soil settlement	0.00020
	Heavy traffic	0.00020
Valve failure in water distribution network		0.01007

Since the water is undergoing treatment at a water treatment plant before being supplied, the probability of contamination at the source is taken as zero. The probability of contamination calculated using the above values is 0.008949. From GIS, 512 locations were identified, where the water supply pipes cross (intersect) or are close to sewer lines or open drains. Thus from the fault tree results it is inferred that contamination is likely to occur four to five times per day (512 x 0.008949) at or near the intersections. This conforms to the results obtained from field survey, i.e. at least four events of contamination are reported in zone VIII of Guntur per day. Most of these events do not turn out to be a debacle, because the contamination is identified by the change in colour, odour and taste of water and so the water is abandoned.

Risk is defined as the product of probability and consequences. The consequences were evaluated in fiscal terms. The failures in zone VIII of Guntur remain unattended for about three days on average according to the information obtained from the field survey. Thus the probabilities of occurrence of failures in water supply networks and sewers increase to three times the actual value (Andrews and Moss 2002). This also increases the probability of contamination. Applying this concept in fault tree analysis, the resultant probability of contamination was obtained as 3.42×10^{-2}

Repair or maintenance activities necessitate provision of alternative arrangements for water supply to the area. GMC supplies water in tanker lorries to the affected areas, causing additional expense to authorities along with the cost of maintenance or replacements. There is

also the expense of medical treatment for the general public if they consume contaminated water for medical treatment. All these constitute the consequences of failures in the water supply and drainage network.

For risk analysis the pipes were classified based on their diameters as major (diameter > 300 mm) and minor (diameter <=300 mm). Data collected for each group of failures showed that major failures occurred less frequently than minor failures. However, the consequences are large in the case of a major failure. A risk table (Table F.5) was created to calculate the total consequences, probability and hence the risk. Table F.7 shows the ranking of component failures based on risk. It can be seen that minor failures at the joints in the water supply network have significantly higher risk than other components. This indicates that utmost importance is to be given to the maintenance works for joints in a water supply network. Now the sensitivity of each component has to be considered as to how much the maintenance activity contributes in reducing the risk. The sensitivity analysis is done by reducing the probability of failures of each of the basic events and determining the resultant probability of contamination.

Table F.6. Calculation of risk involved in water distribution network of zone VIII of Guntur

SI No	Failure event	Type of failure	Cost of maintenance [Rs/year]	Cost of replacement after failure [Rs/year]	Cost to GMC for alternative arrangements [Rs/year]	Probability of failure	No. of people affected [.../year]	Cost incurred in medical treatment [Rs/year]	Total consequences [Rs/year]	Failure risk [Rs/year]	Contamination risk [Rs/year]	Total risk [Rs/year]
a	b	c	d	E	f	g	h	i	j	k	L	m
			No. of failures x Cost of repair	No. of failures x Replacement cost	No. of failures x cost of alternative arrangement	from fault tree	field survey data	@ 500/head	e + f + i	g x (e + f)	Contamination Probability = 3.42E-02	k + l
1	Joint failure (WDN)	MINOR	2,482,000	3,723,000	2,482,000	0.0287	225	112,500	6,317,500	178,034	3,854.00	**181,888**
		MAJOR	42,000	105,000	31,500	0.0016	450	225,000	361,500	214	7,707.00	**7,921**
2	Pipe failure (WDN)	MINOR	350,400	876,000	438,000	0.00338	225	112,500	1,426,500	4,435	3,854.00	**8,289**
		MAJOR	6,000	30,000	6,000	0.00022	450	225,000	261,000	8	7,707.00	**7,715**
3	Valves (WDN)	MINOR	438,000	438,000	219,000	0.04000	225	112,500	769,500	26,280	3,854.00	**30,134**
		MAJOR	6,000	50,000	2,000	0.00082	450	225,000	277,000	43	7,707.00	**7,750**
4	Joint failure (Sewer)	MINOR	520,500	2,082,000	520,500	0.00972	225	112,500	2,715,000	25,290	3,854.00	**29,144**
		MAJOR	10,000	45,000	10,000	0.00077	450	225,000	280,000	42	7,707.00	**7,749**
5	Pipe failure (Sewer)	MINOR	55,500	111,000	27,750	0.00052	225	112,500	251,250	72	3,854.00	**3,926**
		MAJOR	2,000	10,000	1,000	0.00008	450	225,000	236,000	0.8	7,707.00	**7,708**

Table F.7. Ranking of component failures based on risk		
Rank	Event	Risk [Rs]
1	Minor joint failure in WDN	1,81,888
2	Minor valve failure in WDN	30,134
3	Minor joint failure in sewer line	29,144
4	Minor pipe failure in WDN	8,289
5	Major joint failure in WDN	7,921
6	Major valve failure in WDN	7,750
7	Major joint failure in sewer line	7,749
8	Major pipe failure in WDN	7,715
9	Major pipe failure in sewer line	7,708
10	Minor pipe failure in sewer line	3,926

By improving the quality of work and materials used, the probability of occurrence of basic events was decreased. For sensitivity analysis, it was assumed that by adopting suitable measures the probability of each basic event was reduced to 20 per cent of the actual value and the resulting probability of contamination could be determined. For example, the probability of a minor failure at joints in the water distribution network is 0.0287 (Table F.6). Adopting better maintenance methods and providing proper bedding at possible locations, it is assumed that the probability of failure is reduced to 0.0287 x 0.20 = 0.00574. Then using the fault tree it is determined that the reduced contamination probability is 0.02265. Thus there is a decrease of 33.87 per cent compared to the earlier value of contamination probability. Similarly, the probabilities of occurrence of other types of failures were also reduced and the percentage reduction in contamination probability was determined. The results are given in Table F.6.

From the results of sensitivity analysis it can be observed that the minor valve failures in water distribution network are the most sensitive event. This implies that a reduction in minor valve failures can significantly reduce the contamination probability. It can also be observed that minor joints failures in the water distribution network and sewer lines hold the second and third ranks respectively.

Table F.8. Results of sensitivity analysis for the failure events						
Failure	Event type	Actual probability	Reduced probability	Resultant contamination probability	Percentage reduction	Rank
Joint failure	MINOR	0.0287	0.00574	0.02265	33.87%	2
(WDN)	MAJOR	0.00157	0.00031	0.034162	0.25%	5
Pipe failure	MINOR	0.00338	0.00068	0.032878	4.00%	4
(WDN)	MAJOR	0.00022	0.00004	0.034247	0.01%	6
Valves	MINOR	0.04000	0.00800	0.02015	41.17%	1
(WDN)	MAJOR	0.00082	0.00016	0.034247	0.01%	7
Joint failure	MINOR	0.00972	0.00194	0.025484	25.59%	3
(Sewer)	MAJOR	0.00077	0.00015	0.034247	0.01%	8
Pipe failure	MINOR	0.00052	0.00010	0.034248	0.00%	9
(Sewer)	MAJOR	0.00008	0.00002	0.034248	0.00%	10

Table F.9. Combined results from risk and sensitivity analysis					
Failure	Event type	Risk	Ranks based on risk	Sensitivity	Ranks for sensitivity analysis
Joint failure	MINOR	181888	1	33.87%	2
(WDN)	MAJOR	7921	5	0.25%	5
Pipe failure	MINOR	8289	4	4.00%	4
(WDN)	MAJOR	7715	8	0.01%	6
Valves	MINOR	30134	2	41.17%	1
(WDN)	MAJOR	7750	6	0.01%	7
Joint failure	MINOR	29144	3	25.59%	3
(Sewer)	MAJOR	7749	7	0.01%	8
Pipe failure	MINOR	3926	10	0.00%	9
(Sewer)	MAJOR	7708	9	0.00%	10

For decision-making based on risk assessment, both the risk analysis results and the sensitivity analysis results are to be considered simultaneously. An extract from Tables F.6 and F.8 is given as Table F.9. It can be seen from the table that minor joint failure in the water supply network has the highest risk and is next to minor valve failure in sensitivity, whereas minor valve failure has the highest sensitivity and has a significantly lower value of risk than minor joint failures. Thus the decision can be to give more immediate attention to minor joint failures than to minor valve failures.

This is the case when the constraint is the fund availability for maintenance works. When more concern is given to public health and funding is not a constraint, however, the most sensitive event must be looked for, and in this case it is minor valve failure in water supply networks. This decision can also be taken when there is an outbreak of contagious diseases, especially those spread by water. In such cases, much care is to be given to prevent the spread of disease.

Often it requires case-specific decisions to be made. For example, which failure event to be given importance at any point of time? Such decisions cannot be easily made from the above results alone, as they are for the whole system. In such cases, the area affected by the particular event of contamination has to be considered, which is obtained earlier from the water quality analysis with GIS. This gives the area to which the contamination has spread. Then, depending upon the importance of the area, population density, presence of schools or hospitals etc. decisions can be made on events that require immediate attention.

Thus risk assessment proves to be an efficient decision support system. It provides an easy way of deciding upon the activity to be undertaken immediately, especially in situations of limited resource availability.

Conclusions

The integrated model was developed for water quality analysis within water distribution networks with the GIS environment. The network analysis model EPANET 2.0 was integrated into the GIS software package ArcGIS 8.3 by ESRI. The data required for analysis will be retrieved from the GIS tables and the results will be loaded back to the tables. Analysis was done for contamination occurring at a single node in the network and at multiple nodes in the network with varying rates of contaminant intrusion into the water supply pipeline. The results are displayed in the GIS interface and using the Spatial Analyst tool the area affected was mapped.

A field survey in the study area, i.e. zone VIII of Guntur City, revealed that around seven or eight failures occur in the water supply pipes per day and two or three in sewer lines. The average time taken for attending the failure by the authorities was about three days. The leakage in the water supply lines mostly occurs at the joints and this was attributed to the poor workmanship, soil settlement and heavy traffic. Leakages in sewer lines occur mainly due to blocks. Similarly the causes of failures of other components were also obtained and the fault tree was prepared from the information. Events of contamination in water supply were reported to occur many times a day at different locations. In many such cases the contamination was identified by changes in colour, odour and taste of water and so the water was discarded. There were cases when contamination was unidentified and resulted in

health hazards to the public. The details of expenditure on maintenance and replacement activities, cost of alternative arrangements for water supply, and health care expenses were also obtained from the field survey.

The fault tree was constructed from information obtained from the field survey and the contamination probability was calculated as 0.034249. Sensitivity analysis of the failure events revealed that minor failures in the valve and joints in water supply networks have the highest sensitivity; i.e. reducing the probability of these failures significantly reduced the probability of contamination. A risk table was prepared to analyse the risk involved in each type of failure. This revealed that minor joint failure in water supply networks has a significantly higher risk than failure in the other components, implying the importance of attending to such failures with top priority.

The final decision depends upon other factors such as location of failure, importance of the affected area, presence of schools, hospitals etc. in the affected area (which are obtained from the GIS maps) and population density. In case of limited resource availability the priority may be given to reducing the risk and if resource availability is not the constraint then priority goes to reduction of probability of occurrence of contamination.

From the results the following conclusions are arrived at.

- Integration of the water quality model with GIS software helps as a decision-making tool for water supply management.
- Head dependent flow in intermittent water supply systems can be handled with EPANET 2.0 by imposing the emitter status to the nodes.
- Fault tree analysis not only helps to assess the probability of contamination in water distribution networks but also to prioritize the maintenance activities based on their sensitivity or impact on likely occurrence of contamination to the water supply.
- A risk table helps in deriving general management policies for the water supply system and along with GIS mapping it helps in arriving at location-specific decisions.