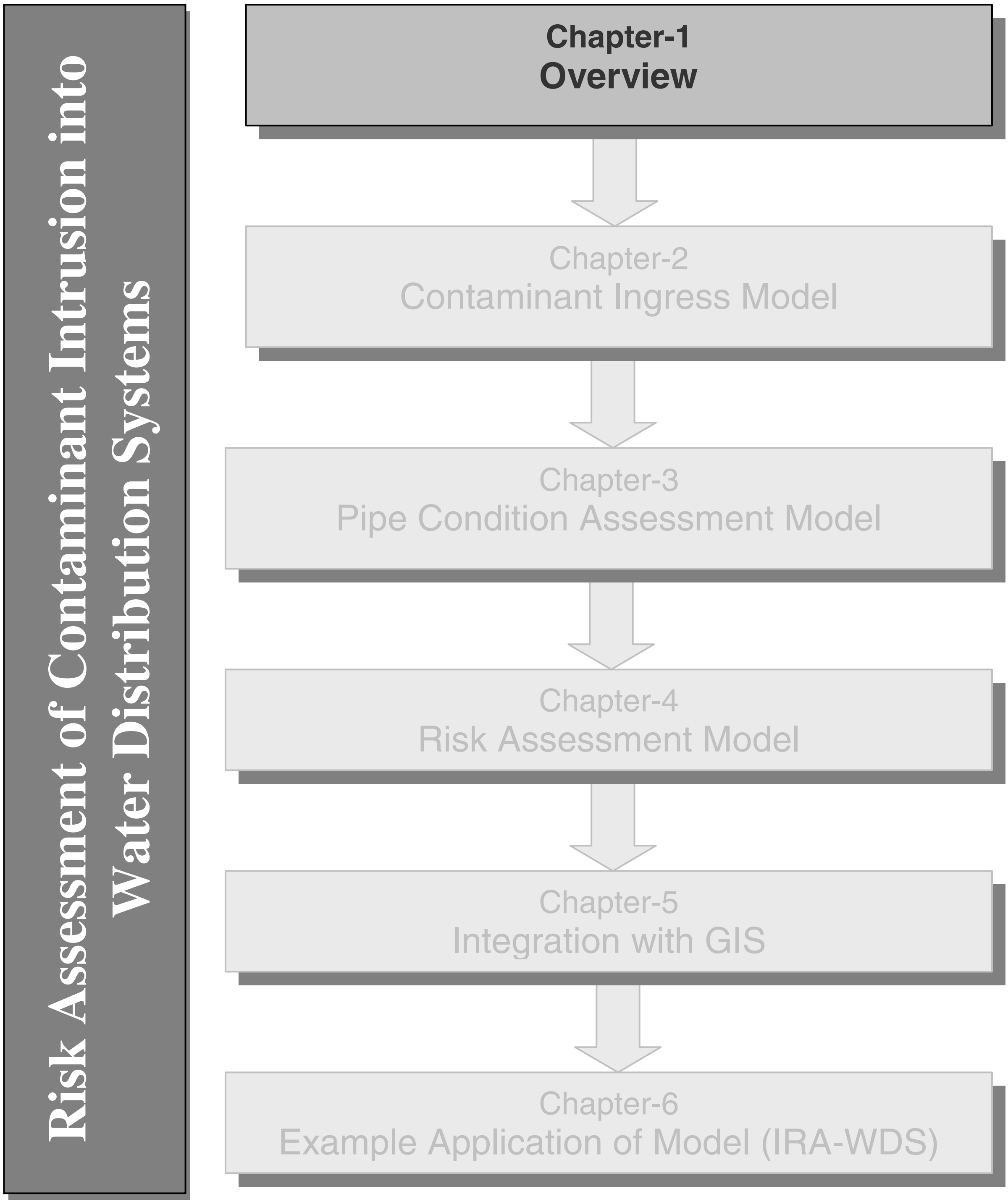
CHAPTER ONE

Overview


Risk Assessment of Contaminant Intrusion into Water Distribution Systems
Chapter-1
Overview
Chapter-2
Contaminant Ingress Model
Chapter-3
Pipe Condition Assessment Model
Chapter-4
Risk Assessment Model
Chapter-5
Integration with GIS
Chapter-6
Example Application of Model (IRA-WDS)

Chapter 1: Overview

1.1 Introduction

In most developing countries water supplies are intermittent due to the prevailing water scarcity that results from depletion of existing water sources. Intermittent systems are those in which there are no supplies for long periods of time. In addition to the inadequate supply of water, other major shortcomings of such systems are the inequitable distribution of supply and the risk of contamination resulting from insufficient pressures when the distribution system is empty.

The importance of water supply with sufficient quantity and acceptable quality has been emphasized in the Millennium Development Goals (MDGs), drawn from the United Nations Millennium Declaration. Goal 7 of the MDGs says, 'Ensure environmental sustainability,' and Target 10 of Goal 7 says: 'Halve, by 2015, the proportion of the people without sustainable access to safe drinking water and basic sanitation' (United Nations 2005).

The quality of water received by the consumer is determined by the quality of water at source, water treatment and condition of water distribution system (WDS). Until recently, water quality was generally considered a treatment issue and not a distribution issue. As a result, distribution factors are often overlooked (Smith et al. 2000). Due to the ignorance of the influence of the deteriorating condition of WDS on water quality, several cases in which distribution pipes contributed to water quality problems were reported (Danon-Schaffer 2001; Geldreich 1996; Kirmeyer et al. 2001; Wyatt et al. 1998). Hence there is a growing concern about water quality variability within the distribution system (Galbraith et al. 1987; Payment et al. 1991; Payment et al. 1997).

Distribution systems with intermittent water supplies are prevalent among countries where rapid urbanization is taking place. It has been reported that around 50 per cent of utilities in 50 Asian cities supplied water for less than 24 hours a day in 1995. Supplies in six of the 50 cities were found to be a mere six hours a day (McIntosh and Yniguez 1997). More than 90 per cent of the population with a piped supply in South Asia receive water for less than 24 hours (McIntosh 2003). Similar situations exist in Africa and Latin America. In Zaria, Nigeria, in 1995, only 11 per cent of the consumers with a piped supply received water one day in two. It has also been reported that in Mombasa the average duration of the service is 2.9 hours per day (Hardoy et al. 2001). In Latin America, 10 of its major cities receive rationed supplies (Choe and Varley 1997).

A serious problem arising from intermittent supplies, which is generally ignored, is the associated high levels of contamination. This occurs in networks where there are prolonged periods of interruption of supply due to negligible or zero pressures in the system and when the pipes of the water distribution system criss-cross with the pollution sources, which is often a case in developing countries.

Boxes 1.1, 1.2 and 1.3 present the typical water distribution system, pollution sources and interaction of pollution sources with the water distribution system that deteriorate the water quality. Water distribution pipes lie below the pollution sources (surface foul water bodies, leaky sewers, open drains and canals) from which the contaminants seep into the surrounding soil and move towards the water pipes. Low dissolved oxygen, high nutrient loads, fecal matter, pathogens, objectionable floatable material, toxins, and solids are all found in abundance in these contaminants (Moffa 1990). These contaminants enter the deteriorated pipes through joints and cracks developed due to ageing, physical stresses and chemical processes (corrosion) and pollute the water in the distribution system. Such problems lead to increased health risks as water becomes contaminated with pathogens.

Thus the contamination risk is high when prolonged periods of interruption of supply due to negligible or zero pressures (loss of system integrity) in water distribution system are coupled with the movement of contaminated water from various pollution sources (surface foul water bodies, sewers, open drains and canals etc.). Figure 1.1 (a) shows the process of contaminant intrusion into the distribution system.

Box 1.1. Characteristics of typical water distribution systems in developing countries

The water distribution systems in the developing countries are at risk of contaminant intrusion for the following reasons.

1. ***Pipe deterioration:*** The pipes of water distribution system are deteriorated due to physical, environmental and operational factors. These deteriorated pipes develop cracks and leaks and pollutants surrounding the pipes can find entry into the pipes.
2. ***Intermittent water supply:*** The design of water distribution systems in the cities of developing countries assumes continuous water supply. However, in these cities the actual water supply is not continuous but intermittent, mostly because of the shortage of water. In intermittent systems, the pipes are empty for many hours of the day, during which time the pollutants surrounding the pipes can enter into the pipes through cracks and leaks.

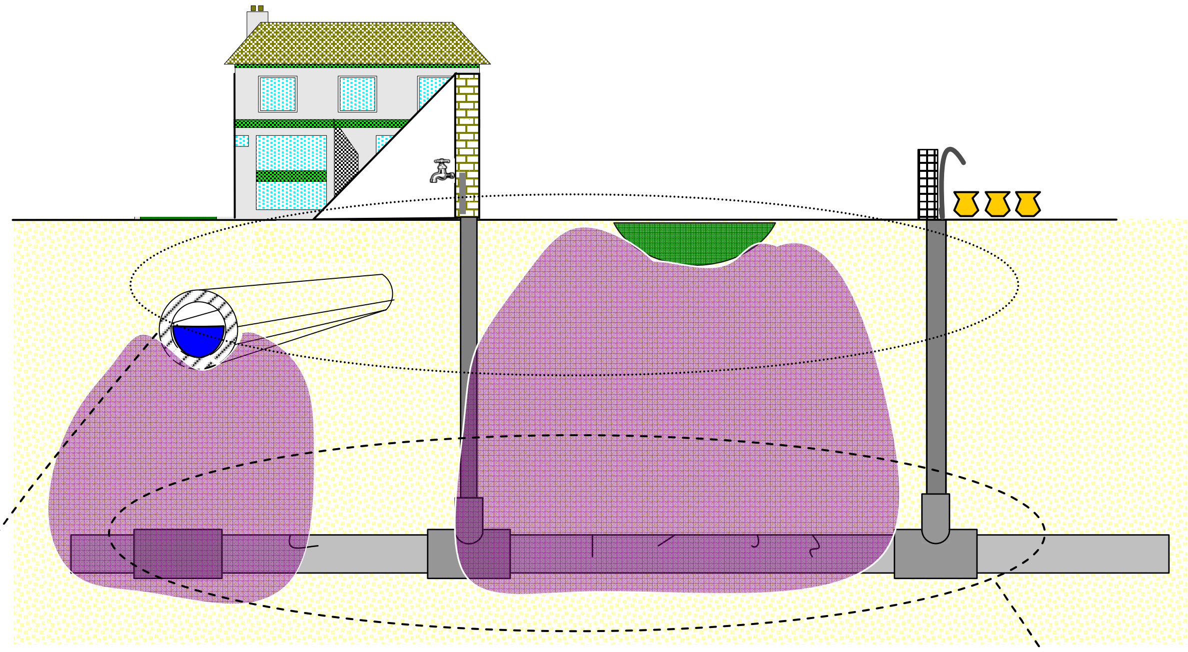


Figure 1.1 (a). Contaminant intrusion process into water distribution network

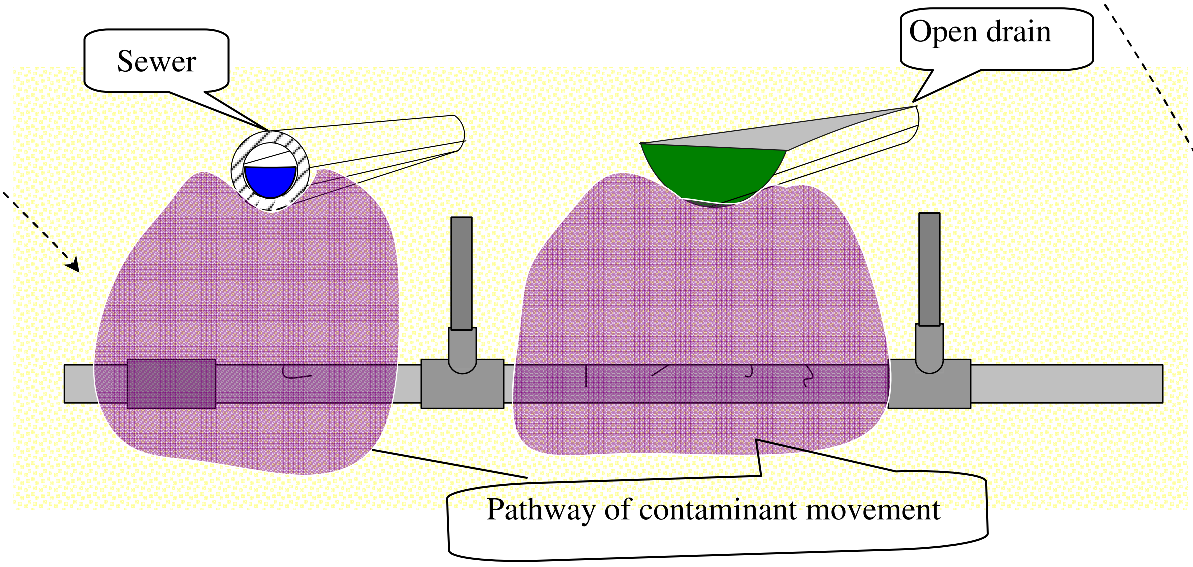


Figure 1.1 (b). Contaminant ingress process

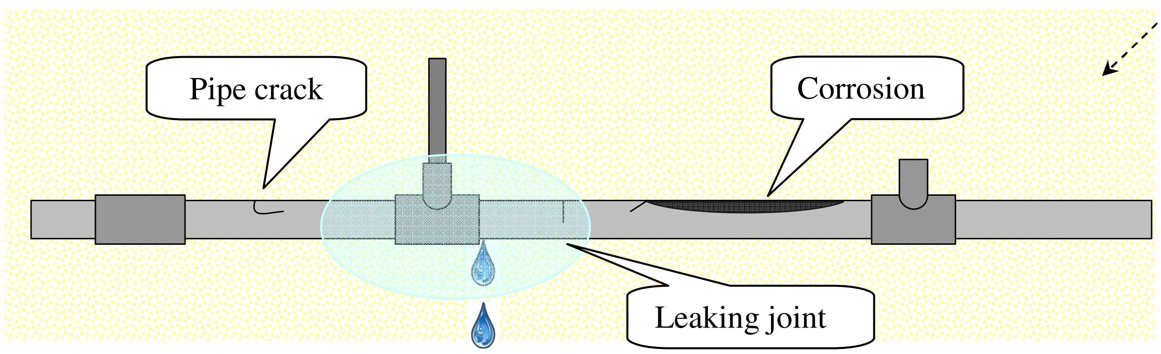


Figure 1.1 (c). Water distribution pipe deterioration

Box 1.2. Pollution sources

The pollution sources are the sewerage system and open surface foul water bodies. The sewerage system collects the wastewater or sewage from the homes through sewers. The sewers of sewerage systems in developing countries consist of closed pipes/conduits and open drains/canals. These conduits and drains are often the source of pollution to soil and groundwater. The wastewater carried through these conduits and drains contains pollutants which can be hazardous to health. The pollutants find their way out to the surrounding soil and groundwater through cracks and leaks that develop in damaged pipes/conduits and seep through the unlined open drains/canals into the soil.

Damaged conduits/pipes in the sewerage system cause leakage of contaminants into the soil. ***These conduits/pipes can be damaged in different ways at various locations.*** The primary causes are:

- Ground movement
- Ground erosion or soil loss
- Material deterioration of sewers
- Improper layout and installation
- Natural damage, such as minor earthquakes or proximity of trees.

For these reasons***, the most common defects which might give rise to the sewage leakage*** from conduits/pipes are:

- Cracks and fractures
- Joint displacement
- Deformation and collapse
- Reverse gradients
- Siltation, blockage
- Poorly constructed connections
- Abandoned laterals left unsealed
- Root intrusion.

Apart from sewer pipes and open drains, there are other pollution sources from which water distribution system may be contaminated, the major one being the open surface water bodies such as wastewater disposal ponds. Thus the three important sources of pollution are:

- Sewer pipes/conduits (Figure 1.2 (a))
- Open drains/canals (Figure 1.2 (b))
- Open surface foul water bodies (Figure 1.2 (c))

(a) Sewer pipe (b) Open drain (c) Foul water body

Figure 1.2. The sources of pollution

Box 1.3. Interaction of water distribution systems and pollution sources

Water distribution and sewerage systems are two important components of the infrastructures in a city. However, in many cities these are not considered as a unit. Often these systems are planned individually rather than as a unit. This happens mainly because of the expansion of the city area and uncontrolled growth in population. Design, construction and operation of these systems are very important and they require a high degree of skill and judgement, both because of the nature of the work and because each phase of the problem involves the health of the citizens. In the absence of a proper decision support tool for the design, construction and operation, these systems can deteriorate quickly.

According to pipeline installation practices (Smith et al. 2000), the water distribution pipe should be located a minimum of about 3 metres away from a sewer pipe. If conditions require these pipes to be located close together (e.g. a narrow throughway or perpendicular crossing), the water distribution pipe should be located at least half a metre above the sewer pipe. However, in developing countries, the pipes of water distribution system and sewerage system often criss-cross each other. On many occasions, the pipes of the water distribution system are laid below the pipes of sewerage system. The contaminants from the leaky sewerage lines, open drains and surface foul-water bodies seep into the soil and subsequently enter the water distribution pipes and reach the groundwater. The contamination of water supply systems and groundwater by these pollution sources is increasingly a serious matter of public and regulatory concerns. Polluted water affects public health and even poisons people (Lerner 1994). Eiswirth and Hotzl (1994) reported that in the Federal Republic of Germany several 100 million m^3 of wastewater leak every year from partly damaged sewer systems into soil and groundwater. In developing and underdeveloped countries, the extent may be much greater as the piped sewer system is combined with open drains and surface foul water bodies. Such a situation is potentially dangerous for public health, as any further lapses in operation and maintenance of these systems will lead to intrusion of hazardous elements in the water distribution system and poses a risk to human life.

Causes of damage

In the present study, seepage of contaminants from the surface foul water bodies, open drains and sewer conduits are considered as the main pollution sources and that the drinking water distribution system is likely to be influenced by the movement of the contaminants through the soil from these pollution sources. Water distribution pipes are vulnerable to contaminant intrusion when they are below a sewer, surface foul water body or open drain. Under such circumstances, contaminants may enter water distribution pipes if:

- The contaminant flows out of pollution sources e.g. through cracks in a sewer pipe
- The water distribution pipe is within the contaminant zone of the pollution sources (Figure 1.3)
- The water distribution pipe has cracks where a pollutant might enter.

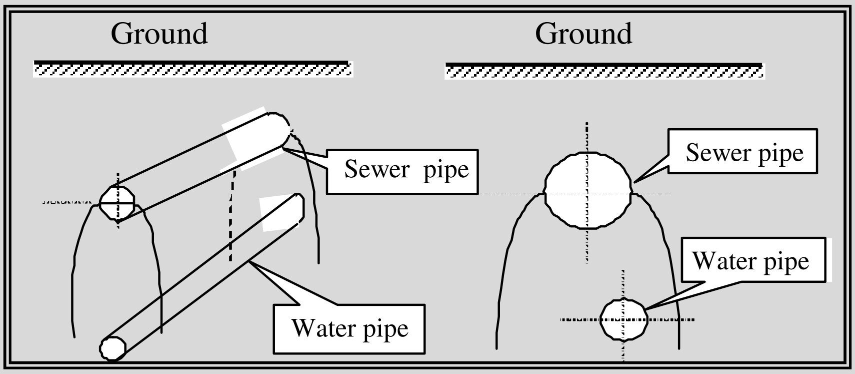


Figure 1.3. Water pipes in potentially polluted area

1.2 Why IRA-WDS?

In intermittent systems the loss of system integrity due to the prolonged periods of interruption of supply, coupled with the unique conditions of pollution sources interfering with the water distribution network, has meant that such systems pose a very serious contamination problem. Thus in developing countries where intermittent supplies are the norm, the water distribution network has become a point at which contamination frequently occurs to unacceptably high levels, posing a threat to public health. Hence, in developing countries there is a need to develop control measures to minimize the risks associated with contamination of drinking water, and improve management of water quality in drinking water distribution systems.

By identifying the relative risks associated with contaminant intrusion into water distribution systems, it may be possible for decision-makers to prioritize their operational maintenance strategies in order to achieve maximum benefits from their investments in terms of improvements to water quality. Hence **I**ntegrated **R**isk **A**ssessment**-W**ater **D**istribution **S**ystem (IRA-WDS), a GIS-based spatial decision support system (SDSS), has been developed to assist the authorities in improving water quality.

The next section of this chapter presents an introduction to the development of IRA-WDS. The remaining chapters of this book present the details of the mathematical models that form the basis of the enclosed IRA-WDS software (Book 4), followed by a case study. The manual for use of IRA-WDS is presented in Book 4.

It should be noted that in order to use IRA-WDS, one does not require a detailed understanding of the models presented in this book. The information provided in the book is to give the user an insight into the basis of the model, the significance of the data required to drive the model and assistance in interpreting the results.

1.3 IRA-WDS and its components

Water distribution pipes lie below the pollution sources from which the contaminants seep into the surrounding soil and move towards water distribution pipes. Contaminants enter water distribution pipes which have deteriorated due to ageing, physical stresses and chemical processes such as corrosion.

Figure 1.1 (a) shows the process of contaminant intrusion into the distribution system. Three conditions need to exist for contaminant intrusion to occur in the water distribution system. These are: pollution sources, intrusion pathway, and intrusion condition. Figure 1.1 (b) is an extension of the 'pollution sources' part of Figure 1.1 (a) and shows the 'pathway' of contaminant movement through soil until it reaches the water distribution pipe. Figure 1.1 (c) expands the water distribution section of Figure 1.1 (a) and shows the deterioration of the water distribution pipe that provides the opportunity for contaminant intrusion to occur during non-supply hours or when low or negative pressure occurs.

In previous studies, pollution sources have not been taken into account when considering contaminant intrusion into the water distribution system. The contaminant source is either assumed to exist around the water distribution pipes or considered through simple spatial analysis (e.g. cross-connections between sewer conduits and distribution pipes). Neither the type of pollution sources nor their interaction with the distribution system has been addressed before. Most work has focused on hydraulic transients; however, many networks in the world (particularly in developing countries) have many hours of non-supply. This factor has not been considered previously.

IRA-WDS is based on a risk-based modelling approach that assesses the risk associated with contaminant intrusion into the water distribution system during non-supply hours (especially for intermittent water supplies). IRA-WDS overcomes many of the limitations of previous approaches. IRA-WDS is a GIS-based decision support system that predicts the risks associated with contaminated water entering the water distribution system from surrounding surface foul water bodies, sewer pipes, drains and ditches. Several modelling tools are included in IRA-WDS that simulate and predict the susceptibility conditions for contaminant intrusion (contamination sources, intrusion pathway) and obtain the risk of contaminant intrusion into the water distribution. The IRA-WDS also develops a risk map that highlights the risk areas of the water distribution system to display the risk spatially.

The IRA-WDS model consists of following three main components (Figure 1.4):

- Contaminant ingress model
- Pipe condition assessment model
- Risk assessment model.

The next three sections will give brief details of these components of the model.

1.3.1 Contaminant ingress model

This model simulates the movement of contaminated water from different pollution sources (surface foul water bodies, sewers, drains etc.) through typical soils and towards drinking water distribution pipes (see Figure 1.1 (b)). Table 1.1 shows the data required to implement the contaminant ingress model component of IRA-WDS.

The contaminant ingress model is divided into two components.

- Contaminant zone model: This model predicts the zone or envelope of contaminant (contaminant zone-CZ) emanating from a pollution source and the section of pipes in a water distribution system in the contaminant zone (SPCZ).
- Contaminant seepage model: This model simulates the variable concentration of the contaminants within the contaminant zone and predicts the contaminant loading on the SPCZ.

Thus, by considering the route of a drinking water distribution pipe and how it intersects with the contaminant zone of pollution sources (surface foul water body, sewer or ditches etc.), it is possible to estimate the potential contaminant load that might enter the water distribution pipe from the pollution sources. This is considered as ‘hazard’ in the risk assessment model.

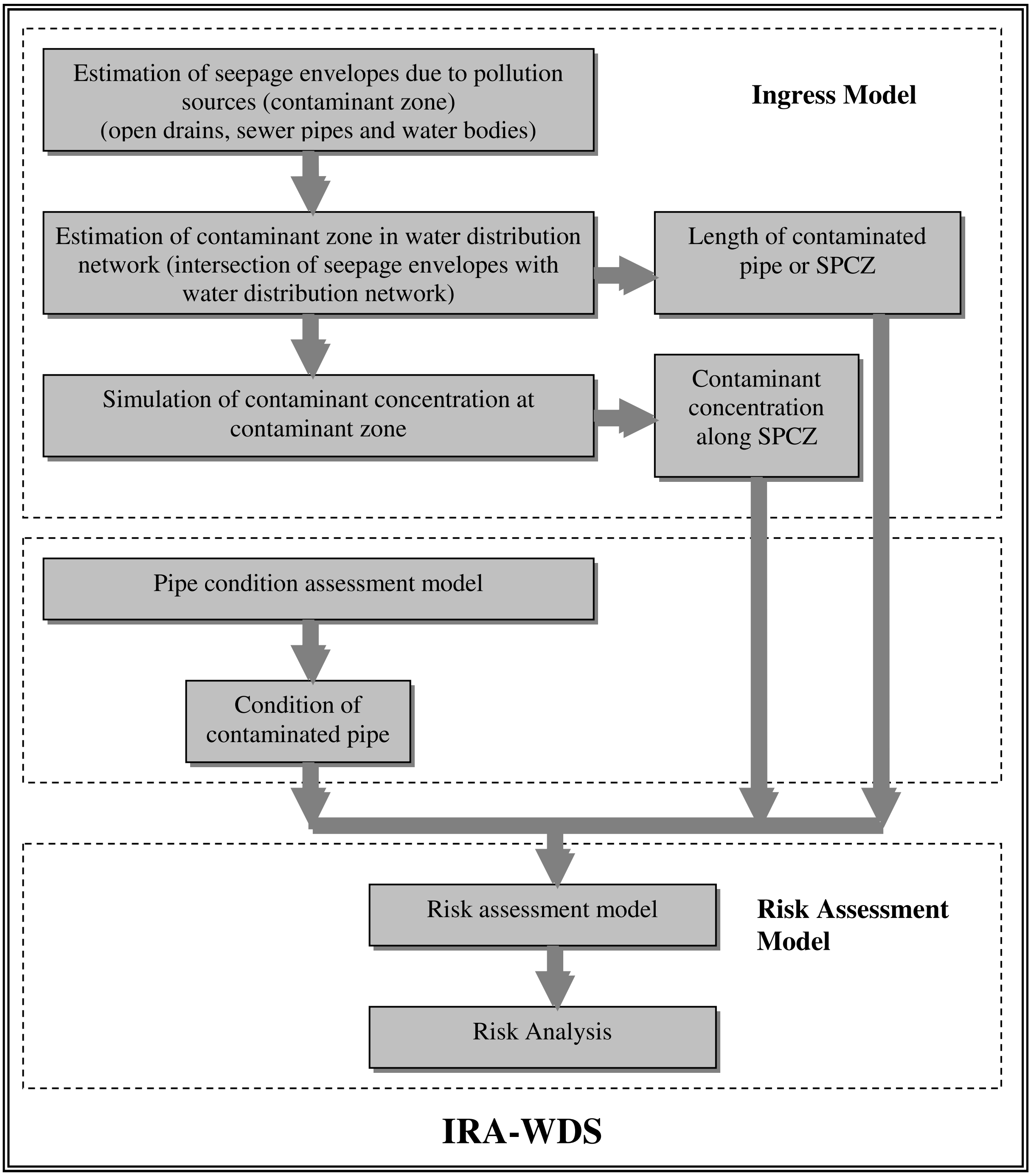


Figure 1.4. Main components of IRA-WDS

The output from the model is the prediction of the contaminant zone, SPCZ, variable concentration of contaminant in CZ, and contaminant loading along the SPCZ due to different pollution sources. Figure 1.5 shows contaminated pipes in the water distribution system.

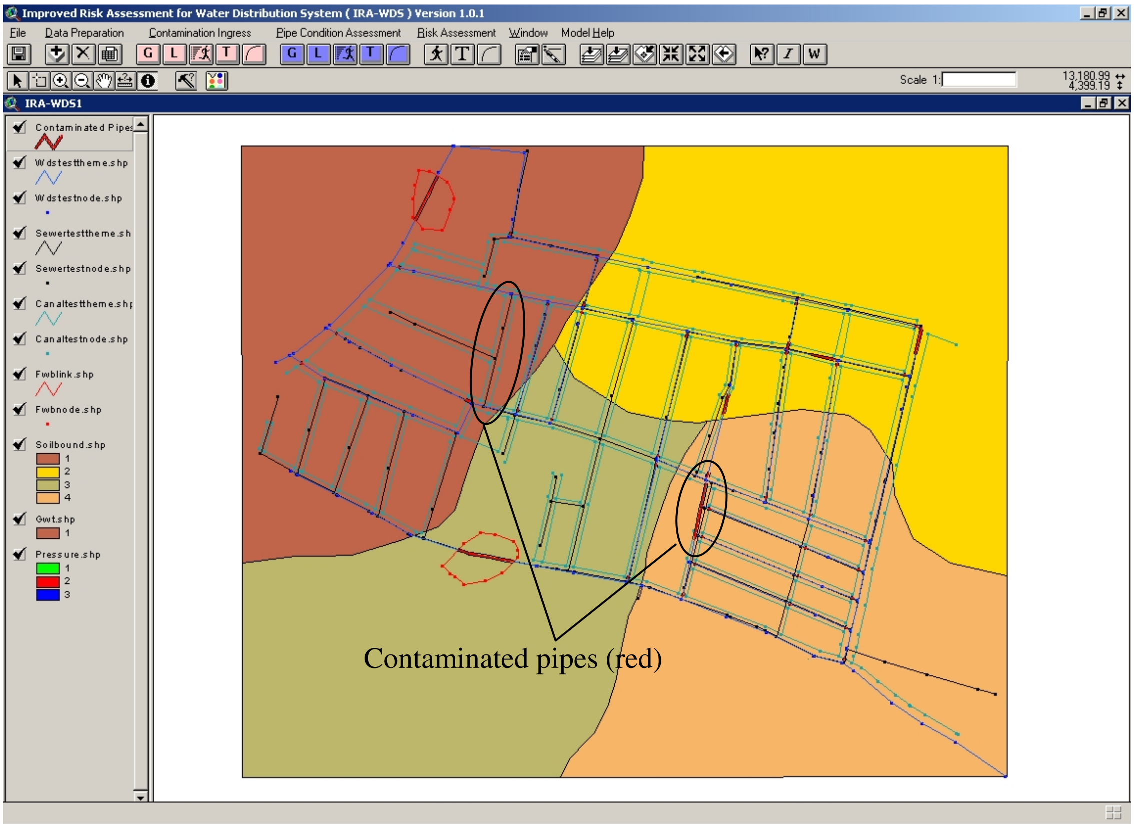


Figure 1.5. Example output from IRA-WDS that shows contaminated pipes or SPCZ in a water distribution system

The contaminant ingress model is discussed in detail in Chapter 2 of this book and the implementation of IRA-WDS is given in Chapter 3 of Book 4 (IRA-WDS user manual).

Table 1.1. Data requirement for contaminant ingress model

Properties	Purpose
Sources of pollution	For estimating the contaminant zone or potentially polluted area
Spatial location of different pollution sources	
Properties of pollution sources	
Spatial location of water distribution network	For identifying the section of water distribution pipe in contaminant zone or potentially polluted area developed due to pollution sources (SPCZ)
Types of soils	For estimating the relative contaminant concentration in the contaminant zone
Characteristics of different soils	
Characteristics of contaminants/pollutants	

1.3.2 Pipe condition assessment model

This model assesses the condition of pipes in a water distribution network (see Figure 1.1 (c)) and identifies the pipes which are subject to the most risk. Table 1.2 shows the data required to complete this component of IRA-WDS.

Table 1.2. Data requirement for pipe condition assessment model

Properties	Purpose
Spatial location of water distribution network	For identifying the sections of distribution system that are vulnerable to contaminant intrusion
Physical properties of pipes in the water distribution network	For pipe condition assessment based on physical condition
Environmental data such as soil, groundwater, surface characteristics, traffic load etc.	For pipe condition assessment based on deterioration due to environmental condition
Operational data such as duration of water supply, breakage history etc.	For pipe condition assessment based on deterioration due to operational parameters
Weightings for different pipe condition assessment indicators and groups of indicators	For indicating the relative importance of indicators in the same group
Balance factors for different groups of pipe condition indicators	For indicating the degree of compromise between indicators of the same group

The model considers each pipe in a water distribution system and estimates their relative condition. The condition of each pipe is assessed by means of numerous factors related to physical, environmental and operational aspects of the water distribution system. These factors are grouped into different indicators at three levels, depending on the nature of influence of each factor on the deterioration process of the pipe. These indicators are combined to give a single measure of the relative condition of each pipe. The outputs from the model are therefore a measure of the relative condition of each pipe in the water distribution system being studied. This is considered as 'vulnerability' in the risk assessment model. Figure 1.6 shows the relative pipe conditions in a water distribution system.

The relative condition of each pipe (vulnerability) (output from this section), coupled with the contaminant loading along the SPCZ (hazard) (outputs from contaminant ingress model presented in Section 1.2.1), provides an estimate of the potential pollutant load entering each pipe (risk of contaminant intrusion).

The pipe condition assessment model is discussed in detail in Chapter 3 of this book and the implementation of IRA-WDS is given in Chapter 4 of Book 4 (IRA-WDS user manual).

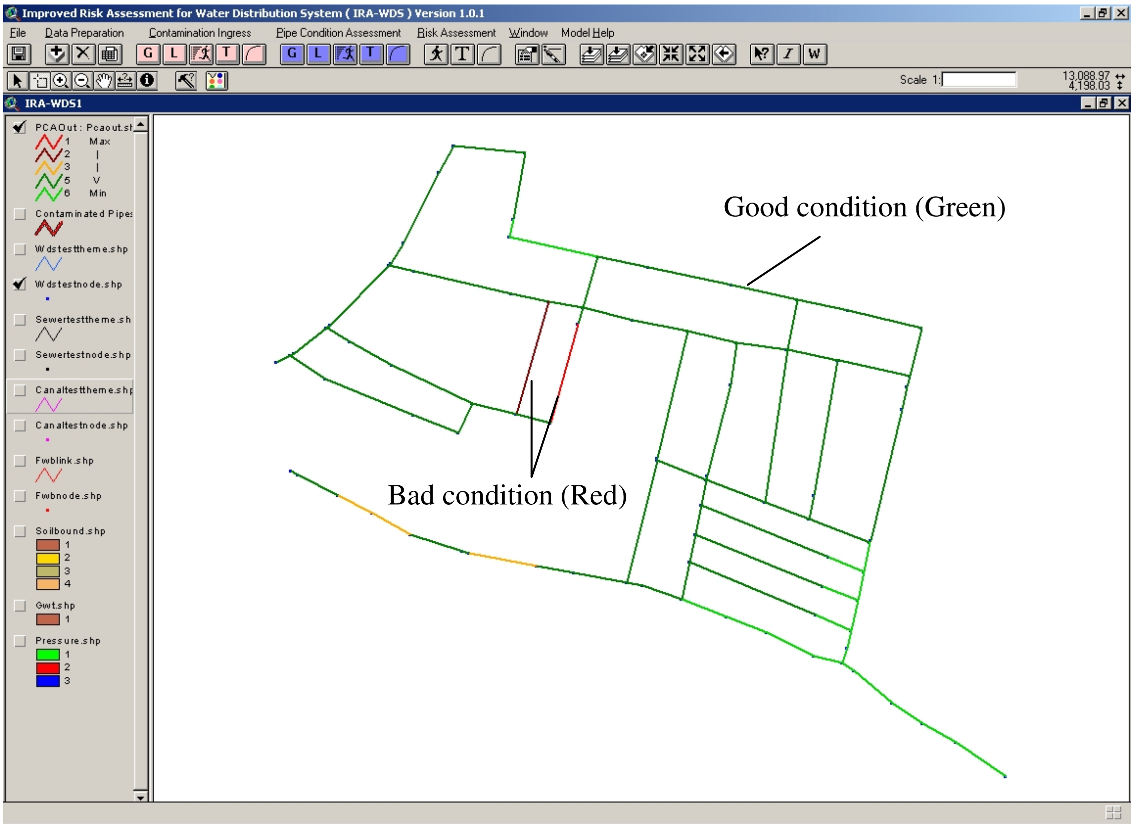


Figure 1.6. Example output from IRA-WDS that shows the relative condition of different pipes in a water distribution system

1.3.3 Risk assessment model

The risk assessment model estimates the risk of contaminant intrusion into the pipes of water distribution system. This model uses the outputs from the contaminant ingress model (hazard) and pipe condition assessment model (vulnerability). The model combines these outputs by using appropriate weightings to hazard and vulnerability and generate relative risk of contaminant intrusion due to each pipe of WDS. Table 1.3 shows the data required to implement this component of IRA-WDS.

The outputs from the model are relative risk maps showing the relative risk of contaminant intrusion into the entire water distribution system. Figure 1.7 shows an example of a relative risk map.

Table 1.3. Data requirement for risk assessment model

Properties	Purpose
Spatial location of water distribution network	For identifying sections of the distribution system that are most vulnerable to risk
Weightings for SPCZ or potential polluted area and contaminant concentration	For indicating the relative importance of SPCZ or potential polluted area and contaminant concentration for hazard
Weightings for hazard and vulnerability	For indicating the relative importance of hazard and vulnerability for risk.

The risk assessment model is discussed in detail in Chapter 4 of this book and the implementation of IRA-WDS is given in Chapter 5 of Book 4 (IRA-WDS user manual).

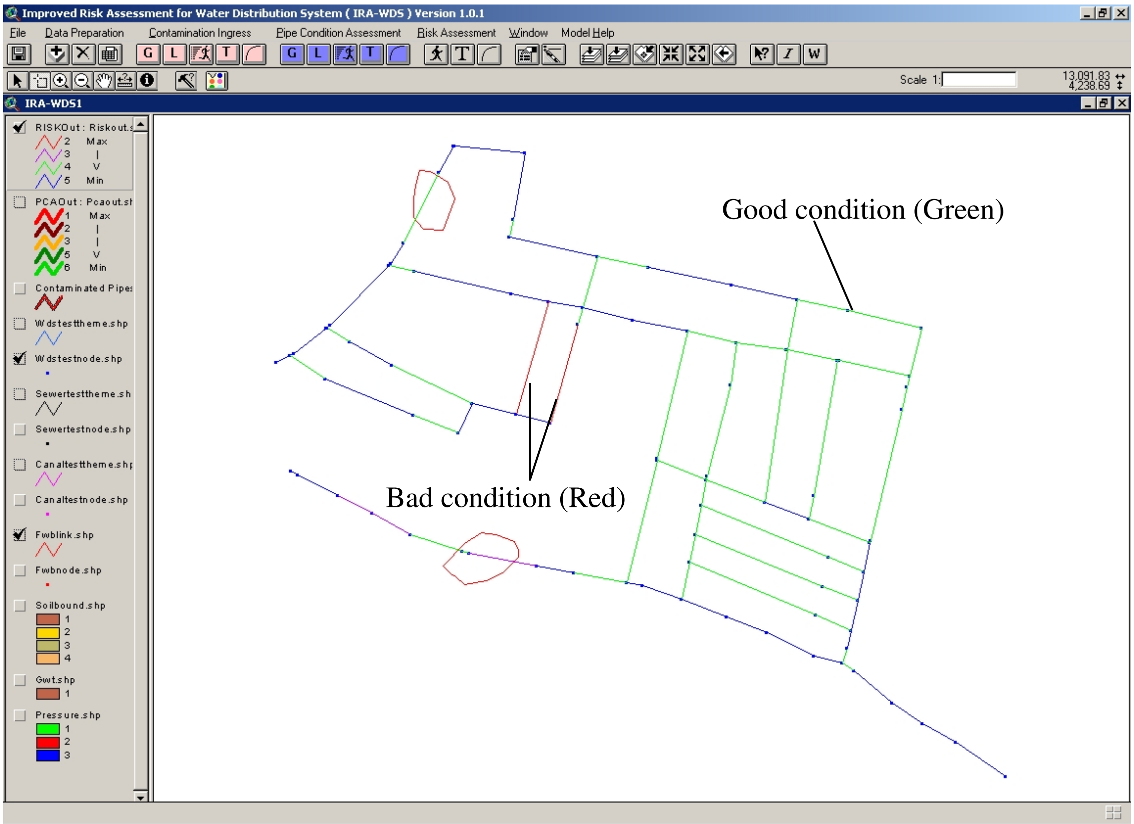


Figure 1.7. Example output from IRA-WDS that shows a relative risk map

It should be noted that the outputs from the risk assessment model can then be coupled with a water network quality model (e.g. EPANET (Rossman 1994)) to show the movement of contamination within the distribution system and to identify those areas and consumers most at risk. Note that this is beyond the scope of this study (although an example is given in Appendix F).

1.3.4 GIS integration

All the models are integrated into a GIS platform to produce SDSS. The results of all three models can be displayed through the GIS and appropriate thematic maps generated. The final outputs from the IRA-WDS will be risk maps indicating the relative risks associated with contaminant intrusion for different parts of water distribution systems. The integration with the GIS is discussed in detail in Chapter 5 of this book and the implementation of IRA-WDS is given in Book 4 (IRA-WDS user manual).

1.4 How to Interpret the Results

The output from IRA-WDS will be risk maps showing the risk of contaminant intrusion into the various parts of the water distribution system. These risk maps will be invaluable to the decision-makers/engineers in that they enable them to:

- Identify sections of a water distribution system that are most vulnerable to contaminant intrusion
- Prioritize operational maintenance strategies to have maximum impact in terms of improving water quality
- Investigate potential improvements in water quality with changes to operational maintenance (by simulating the models for various scenarios)
- Plan strategically rehabilitation programmes that will have maximum returns in terms of water quality for their investments.

1.5 Capacity of Institutions to Use IRA-WDS

1.5.1 Undertaking an organizational and institutional review

In order to successfully implement IRA-WDS, there needs to be sufficient capacity within the institutions and authorities responsible for water supply. The areas that need to be strengthened within an institution to effectively implement IRA-WDS include:

- *Appropriate staffing level:* Sufficient number of skilled competent staff who will carry out the tasks.
- *Staff education and training:* Delivered through awareness seminars (for senior staff), training workshops (for engineers and technical staff) and continuous practical training (for operations staff).
- *Operation and maintenance (O&M):* Important, as lack of O&M leads to inefficient practice, ineffective services and waste of resources.
- *Assessing and monitoring:* On-going monitoring to maintain water quality targets. This should be applied at three levels: *Strategic (*analysis of trends and projections); *Tactical (*maintenance and periodic inspections of facilities that have been established during the implementation of IRA-WDS); *Operational* (regular monitoring of systems performance).

Therefore it is important, when considering the use of IRA-WDS, to understand the institutional framework in which the water supply is currently being operated (i.e. who is involved). It is not only important to explore the institutional landscape in which IRA-WDS is to be used; it is also essential to understand the organizational set-up of each of the stakeholders, i.e. know who owns and operates the water treatment and distribution systems, and how they are operated, as well as who is responsible for quality control. Therefore it will be useful to review the current organizational and institutional structure of the water supplier and other sector stakeholders in order to establish which organizations have an interest in and/or responsibility for water quality in the distribution system. See Chapter 7 of Book 1 and Chapter 2 of Book 2 for further information.

A good starting point would be to analyse the management of water services including private and public roles. Box 1 in Chapter 2 of Book 2 gives a model of options for management of urban water supply, as far as private sector participation is concerned. The model provides several combinations of ownership and operation of assets. The analysis of these management models provides basic information on the operation and management of a water supply.

1.5.2 Commitment from managers and operational staff

Before the process of developing the IRA-WDS approach for authorities and institution responsible for water supply, it is imperative that all members of the water supplier agree on the benefits. Technical staff need a commitment to the IRA-WDS approach from all management level staff. Chapter 1 of Book 1 outlines examples of appropriate ways to achieve this agreement from different groups and emphasizes the importance of obtaining commitment from all levels of staff from field managers to the managing director. It further emphasizes that different tools and approaches are recommended for different groups of staff.

1.6 Summary

This chapter has provided an overview of the main components of IRA-WDS. The following three chapters will provide technical details of the mathematical model that underpins IRA-WDS. These chapters should be read in conjunction with Book 4, which outlines how to use the IRA-WDS software. It should be noted that the user is not required to understand all the technical details presented in Chapters 2, 3 and 4. The main purpose of these chapters is to provide an insight into the model, the data requirement and how to interpret the results.