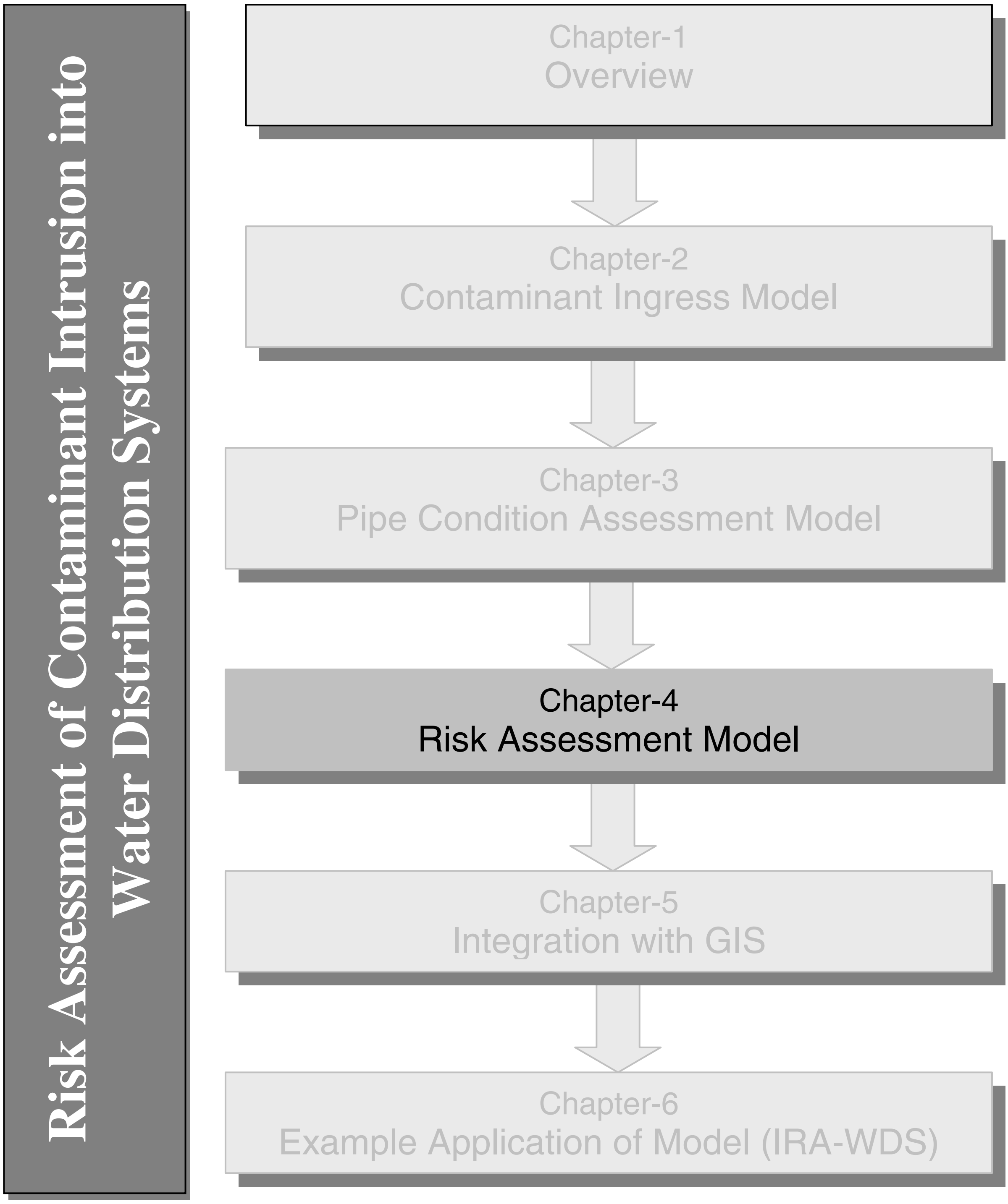
CHAPTER FOUR

Risk Assessment Model


Risk Assessment of Contaminant Intrusion into Water Distribution Systems
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Chapter 4: Risk Assessment Model

4.1 Introduction

This chapter presents the background to the risk assessment model part of IRA-WDS. The risk assessment model uses the outputs from the contaminant ingress model presented in Chapter 2 and pipe condition assessment model presented in Chapter 3. The model combines these outputs by using appropriate weights to generate a risk score for each pipe.

The outputs from the risk assessment model are risk maps showing the relative risk of contaminant intrusion into the entire water distribution system.

The purpose of this chapter is to provide an insight into the background and the techniques that underpin the risk assessment model, and to show how the outputs from the contaminant ingress and pipe condition model are combined to predict relative risk. This should enable the user of IRA-WDS to appreciate the significance of the data required and will aid in interpreting the results of the model. On completion of this chapter, the user should be able to complete Table 4.1, which holds the input data required to run the risk assessment model of IRA-WDS.

It should be noted, however, that to use IRA-WDS does not require a detailed understanding of the model presented in this chapter.

Table 4.1. Weights for different indicators

Indicator	**Weight**
Hazard agent (contaminant load)	TO BE COMPLETED
Vulnerability of water pipe (pipe condition)	BY THE USERS

4.2 Background

There is growing concern about water quality variability within the distribution system. Treated water may undergo substantial changes in quality while being transported through the distribution system before reaching the end consumers. Recent evidence has demonstrated that external contaminant intrusion into water distribution network may be more frequent and of a greater importance than previously suspected (Besner et al. 2001; LeChevallier 1999). Both continuous and intermittent water distribution networks might suffer from the contaminant intrusion problem, although intermittent systems were found more vulnerable of contaminant intrusion.

The intrusion of contaminants into a water distribution system can have catastrophic consequences. Water-borne diseases have been reported historically. From 1971 to 1998, 619 water-borne disease outbreaks were reported in United States, of which 113 (18.3 per cent) outbreaks have been attributed to chemical and microbial contaminants intrusion into water distribution networks or water corrosive to plumbing systems within building or homes (Craun and Calderon 2001). More than half (53.1 per cent) of those 113 outbreaks are caused by cross-connection and back syphonage (Lindley and Buchberger 2002; USEPA 2002). It has been reported that approximately 40 per cent of outbreaks of water-borne disease have been caused by water distribution problems (Kramer et al. 1996; Lippy and Waltrip 1984). The consequence of outbreak posed on public health is enormous. Worldwide numerous cases of outbreak of different diseases were reported due to contamination of water distribution system (Craun and Calderon 2001; Danon-Schaffer 2001; Galbraith et al. 1992; Geldreich 1996; Kirmeyer et al. 2001; Wyatt et al. 1998).

Until now there has been no means of addressing the risk of contaminant intrusion into a water distribution system, even though it is widely recognized as a serious threat to public health. This is mainly due to the lack of methods for estimating the components of risk, i.e. hazards and vulnerability. In this chapter, the development of a risk assessment model for contaminant intrusion into the water distribution system is presented. This model makes use of the information on the section of water distribution pipes in a contaminant zone that has developed as a result of pollution sources (SPCZ), and the contaminant loading along the SPCZ, to estimate the hazard (Chapter 2); it uses the pipe condition assessment indicator to estimate the vulnerability of the pipe to contaminant intrusion (Chapter 3); and combines the two to estimate the risk of contaminant intrusion in the different pipes of the water distribution system. This enables engineers to undertake a rehabilitation programme to minimize the contamination of the water distribution system and thus the outbreaks of diseases; eventually it would provide safety to public health.

4.3 Methodology

To assess the risk of contaminant intrusion intoa water distribution system systematically, we need to look into the process of contaminant intrusion from the contaminant sources to the receptor system through the migration route (pathway). There are many pollution sources that exist around a water distribution system. These are the potential causes of drinking water contamination. The contaminants will migrate through their pathway to the receptor. Drinking water is contaminated if the water distribution pipe is vulnerable and passes through a contaminant migration route. Risk of contamination results from the interaction between a hazard agent and a vulnerable water distribution pipe. Risk assessment therefore requires information about water pipe vulnerability and any hazard agents resulting from the contamination sources. Hence the risk assessment model developed in this study consists of two components: hazard and vulnerability. These are obtained from the models developed in Chapters 2 and 3. The links between risk assessment model, pipe condition assessment model, contaminant ingress model are depicted in Figure 4.1.

4.3.1 Hazard assessment

The hazards are specific physical, chemical or biological agents that may cause an adverse health event. In the context of a water distribution system, hazards may be due to the polluted environment in which water distribution pipes are located such as those caused by surface or underground pollution sources. Hence, in this study, the hazard agent is considered to be any pollution sources around the water distribution pipeline that will potentially contaminate it. Three pollution sources, i.e. sewer pipes, open drains/canal and surface foul water bodies, are considered as the sources of hazards in this study. The contaminant load along the SPCZ is considered as the measure of hazard and is given by equation (4.1). The output of the contaminant ingress model in terms of SPCZ and the contaminant concentration at upstream and downstream ends of the SPCZ for each water distribution pipe are used to estimate the contaminant load along the SPCZ.

This is the input for hazard assessment (see Chapter 2).

$$HA_k = CL_k \tag{4.1}$$

where

HA_k - hazard agent

CL_k - contaminant load given by equation (2.31) in Chapter 3

4.3.2 Vulnerability assessment

The vulnerability is the susceptibility of infrastructure to a hazard. In the context of a water distribution system, this may include the deterioration of water distribution pipe due to the physical, environmental and operational factors. The vulnerability of water distribution pipes is used to indicate the potential of contaminant ingress into the water distribution system in this study. The vulnerability assessment is performed using the pipe condition assessment (PCA) model presented in Chapter 3. For each pipe in the network, the PCA model assesses the vulnerability by assigning an index using fuzzy composite programming. This index combines the impacts of physical, environmental and operational indicators on water distribution pipe deterioration. The index is a fuzzy number represented by a membership function, and is defuzzified. The defuzzified value is used as a surrogate for pipe vulnerability, as given in equation (4.2).

$$VU_i = df(TF_i) \qquad i = 1, 2, \ldots NP \tag{4.2}$$

where
VU_i - vulnerability of water distribution pipe i
df - method for defuzzification
TF_i - Trapezoidal fuzzy number for pipe I and NP - number of water distribution pipe

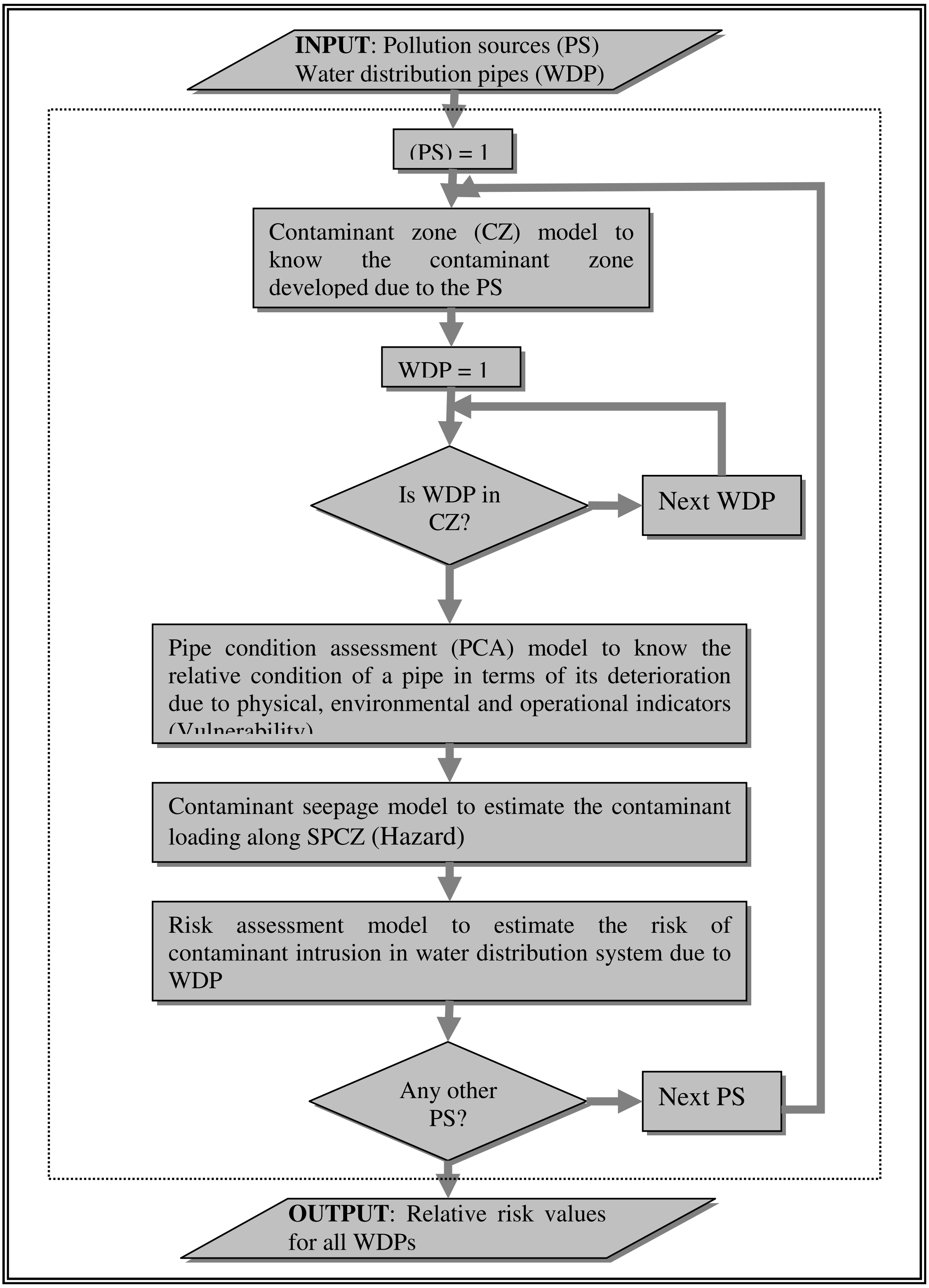

Figure 4.1. The linkage of contaminant ingress and pipe condition assessment models with the risk assessment model

4.3.3 Weight assignment

The relative risk of any particular combination of hazard and vulnerability will depend on the significance of each of these processes in relation to each other. This is expressed through weights that need to be established. Clearly, establishing the relative importance of the above processes is a difficult task. Details of procedures to obtain weights by different methods can be found in Section 3.4.2 of Chapter 3. In this study, the analytical hierarchy process (AHP) is recommended for generating the weights for multiple risk factors. Interviews with experts are required to perform pair-wise comparisons of risk factors to generate the weights (Appendix B). These weights will be used to perform risk assessment by the method proposed in Section 4.3.4.

By using one of the proposed procedures for generation of weights for risk factors (hazard and vulnerability), the user will be able to complete Table 4.1. On completion of this table, the data can be entered into IRA-WDS by means of an input dialogue window.

4.3.4 Multi-criteria evaluation method for risk assessment

The risk of contaminant intrusion into water distribution system results from the interaction between a hazard agent and a vulnerable water distribution pipe. These two risk components are combined using multi-criteria decision-making (MCDM) methods. MCDM (see Figure 4.2) allows us to tackle multiple factors simultaneously, provide insight into various value judgements and help decision-makers and experts penetrate complex and implicit decision-making tasks (Thill 1999). Two types of multi-criteria evaluation (MCE) methods are possible: conventional methods (e.g. weighted linear combination (WLC)) and artificial intelligence based methods (e.g. artificial neural networks (ANN)), fuzzy logic approximate reasoning, optimization methods such as genetic algorithms (GA) and simulated annealing). In this study a weighted linear combination (WLC) method is chosen to assemble weights, and synthesize and analyse different risk criteria.

In WLC methods, the risk factors are integrated to produce the risk index of contaminant intrusion into water distribution. The risk index (RI) for contaminant intrusion into water distribution systems is a function of the hazard agent and vulnerability of water pipe and is obtained by equation (4.3).

$$RI_k = (w_h \times HA_k) + (w_v \times VU_k) \qquad k = 1, 2, \ldots NC \tag{4.3}$$

where

RI - risk index

w_h - weight for hazard agent

w_v - weight for vulnerability of water pipe

Note that the model uses output from the contaminant ingress and pipe condition assessment models to perform the hazard and vulnerability assessment. Hence the user is only required to input data related to the weights.

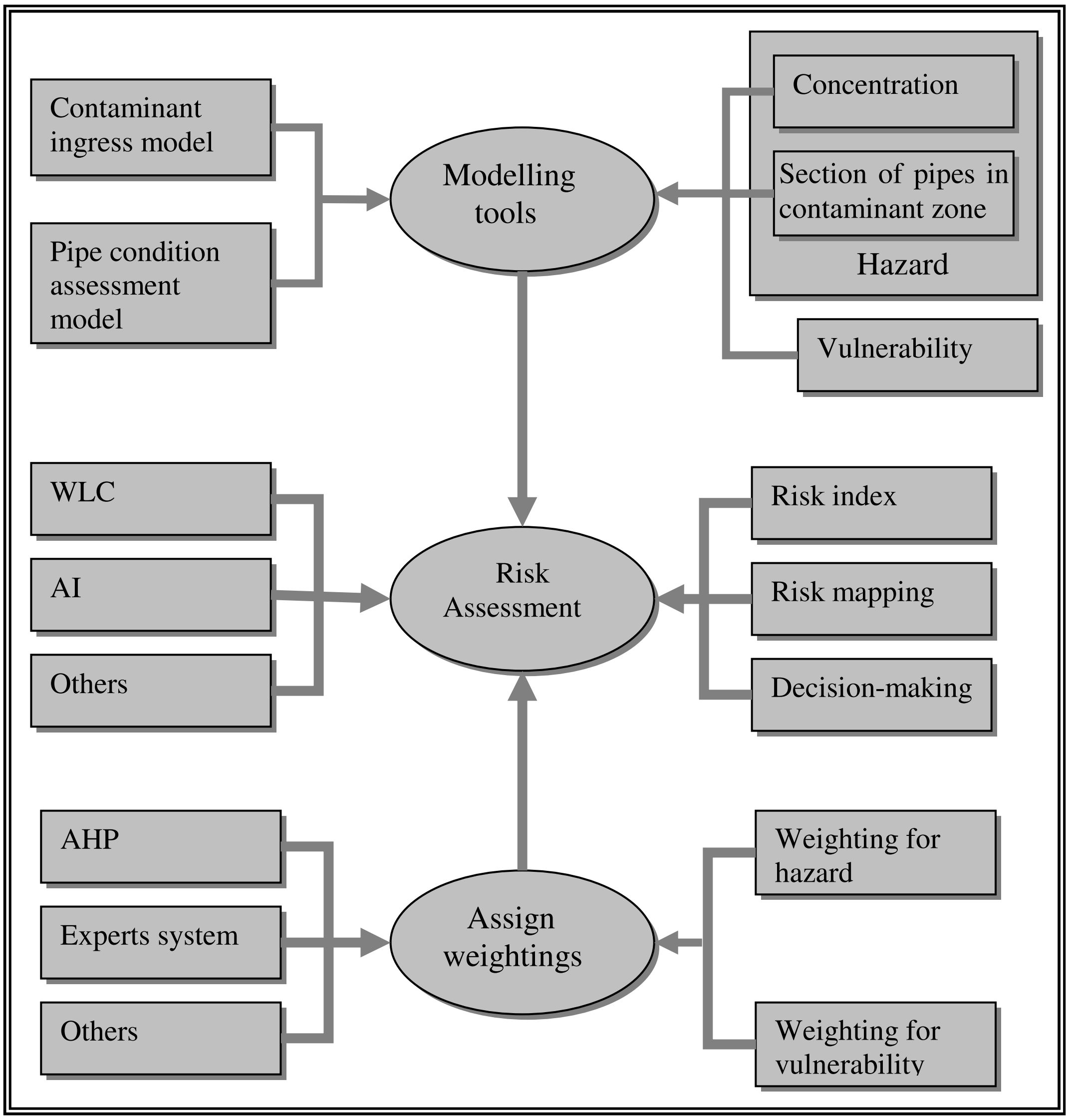

Figure 4.2. Flowchart for risk assessment of contaminant intrusion into WDS

4.4 Conclusions

Based on the risk map, engineers can take decisions for the rehabilitation programme.

At this stage of the chapter the reader should be able to complete Table 4.1 for their particular area of study. This table forms the basis of the input data for the risk assessment model part of IRA-WDS. The data contained in Table 4.1 is entered into IRA-WDS by means of the input dialog window within the software.

Figure 4.3 shows an example of the input dialog window and more details of this can be found in Chapter 5 of Book 4.

An example of the output from a successful run of the risk assessment model part of IRA-WDS is shown in Figure 4.4. Using these outputs the decision-maker can identify sections of the distribution system that are of particular concern (high risk areas), and take appropriate remedial action.

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. Note that this extension is beyond the scope of this study.

The use of a water quality model will enable the decision-makers to identify areas and consumers most at risk to contaminated water. Water quality models are able to track the fate of discrete parcels of water as they move along pipes and mix together at junctions between fixed-length time steps. To develop a water quality model of the distribution system, a fully calibrated hydraulic network model will be required. This will require additional investment in terms of time and effort for data collection.

If a fully calibrated network model is developed then water quality simulation can be performed by first adding dummy input pollutant nodes to areas where the risk assessment model shows a high risk of contamination. Then, by adding pollutant loads at these nodes it is possible to simulate their propagation. It is recommended that, when performing water quality analysis, source tracing is performed. Source tracing tracks over time the percentage of water reaching any node in the network that had its origin at a particular node (in this case the dummy pollutant node). In the analysis the pollutant will be treated as a non-reacting constituent. Source tracing can show to what degree water from a given source blends with that from other sources, and how the spatial pattern of this blending changes over time.

Note that although the use of water quality models is beyond the scope of this study, an example application to the case study area (described in Chapter 6) is shown in Appendix F.

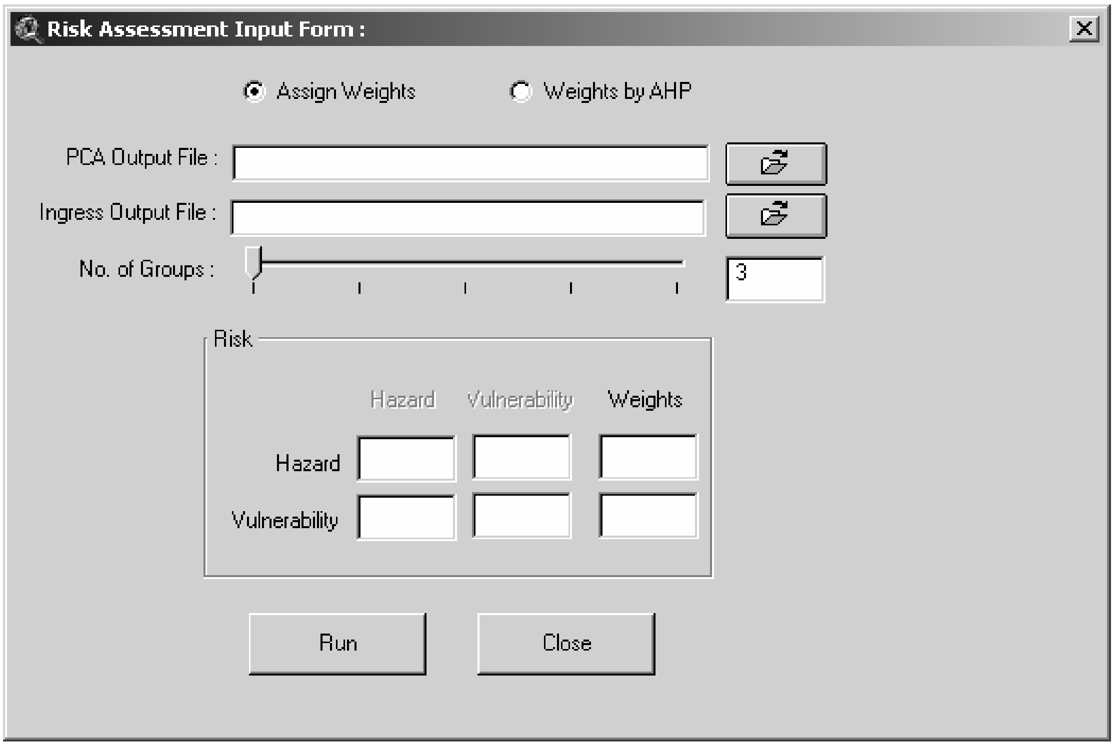

Figure 4.3. An example of the input dialog window of the risk assessment model part of IRA-WDS

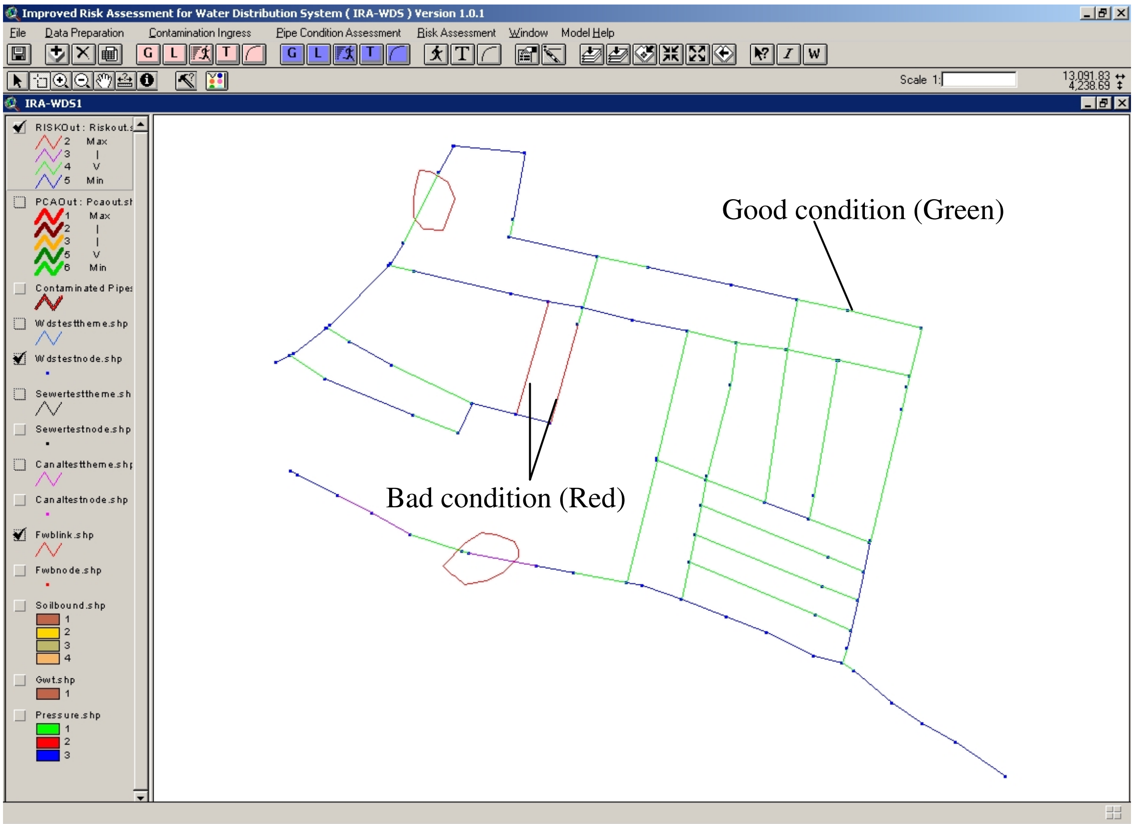

Figure 4.4. An example of the output from a successful run of the risk assessment model part of IRA-WDS