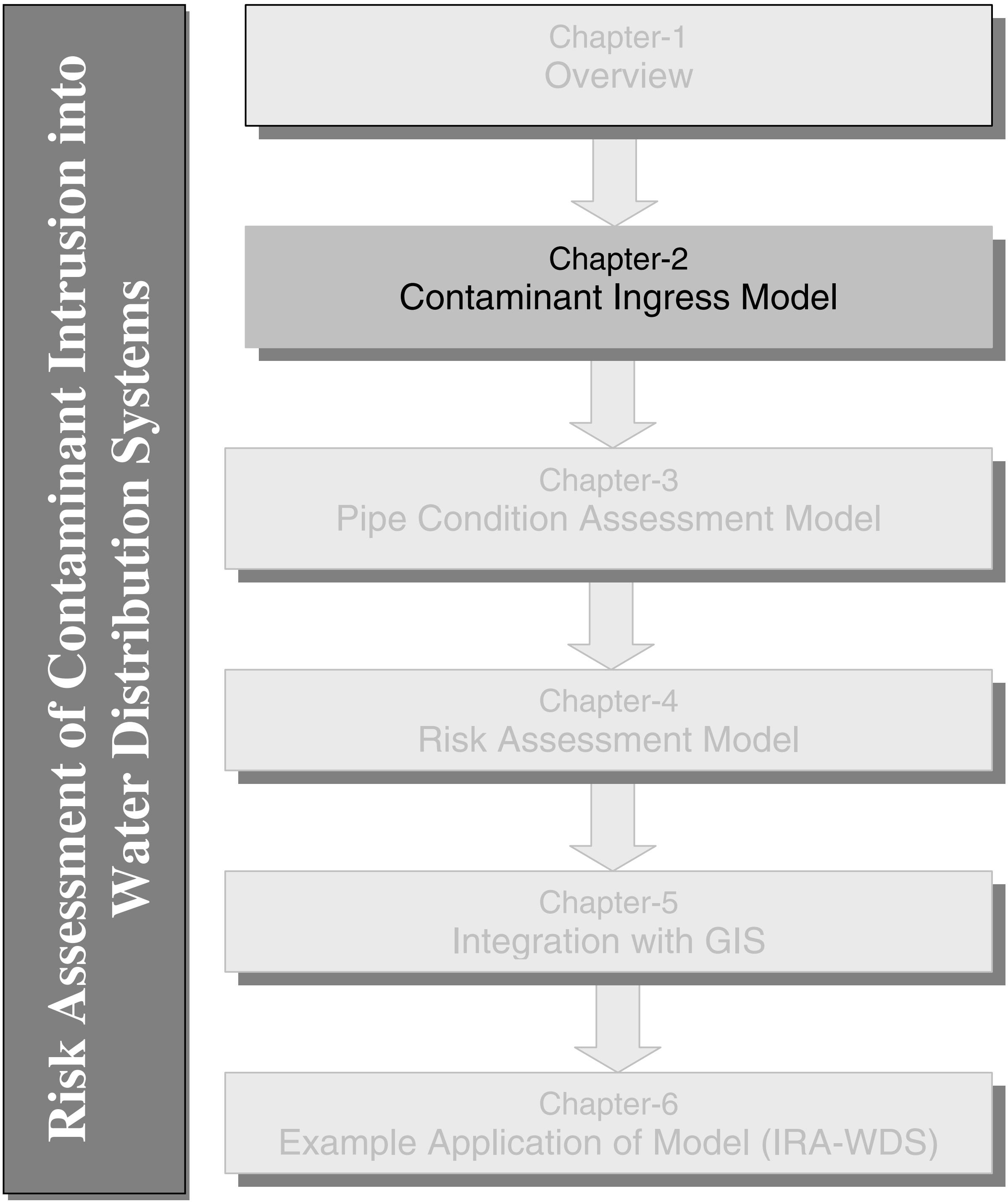
CHAPTER TWO

Contaminant Ingress Model


Risk Assessment of Contaminant Intrusion into Water Distribution Systems
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Chapter 2: Contaminant Ingress Model

2.1 Introduction

This chapter presents details of the contaminant ingress model component of IRA-WDS. The contaminant ingress model simulates the movement of contaminated water from pollution sources such as open surface foul water bodies, sewers, drains etc. through typical soils, predicts the contaminant zone developed around these pollution sources, identifies the section of water distribution pipes in the contaminant zone (SPCZ) and estimates contaminant loading along SPCZ (see Figure 2.1).

The output from the model is the contaminant zone, SPCZ, variable concentration of contaminant in CZ and contaminant loading along the SPCZ due to different pollution sources (see Figure 2.24 at the end of this chapter).

The purpose of this chapter is to provide an insight into the background and the techniques that underpin the contaminant ingress model. This should enable the user of IRA-WDS to appreciate the significance of the data required and also aid in interpreting the results of the model. On completion of this chapter, the user should be able to complete Tables 2.1 to 2.4 that form the input data required to run the contaminant ingress model component of IRA-WDS.

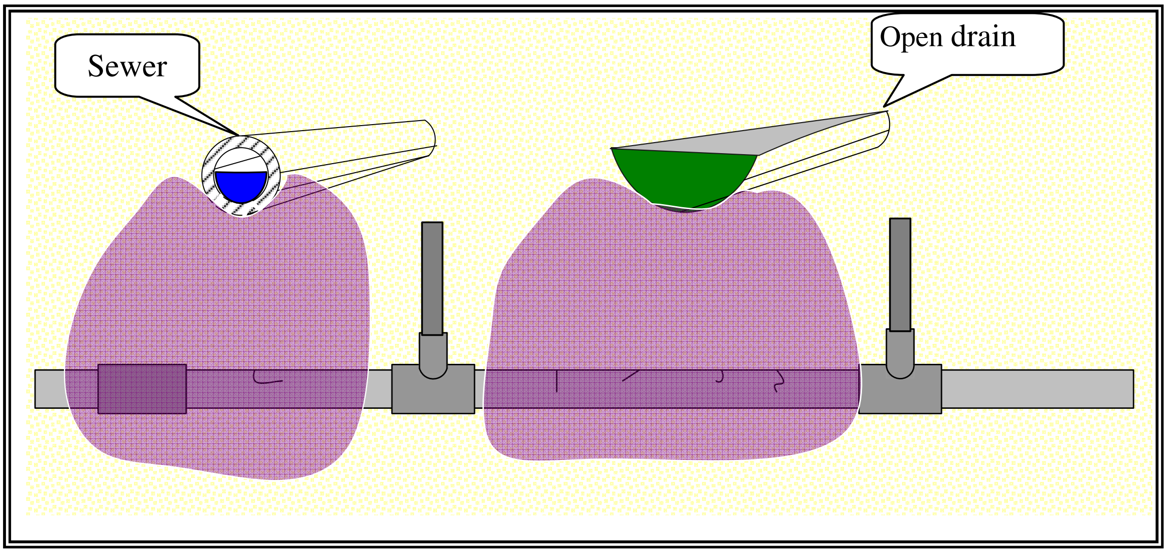

Figure 2.1. Movement of contaminated water (the shaded area) from pollution sources towards water distribution pipes

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

The contaminant ingress model is divided into two components.

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

Table 2.1. Type of pollution source and its properties

Properties of pollution source	**Unit**	**Value**
Underground sewer pipe		
Network map	*Shape file*	
For each pipe		
Length	*m*	
Bury depth	*m*	
Material		
Leakage rate	*cm/hr*	
Diameter	*cm*	
Lined open ditch/drain		
Network map	*Shape file*	
For each ditch/drain		
Length	*m*	
Material		
Leakage rate	*cm/hr*	
Depth	*cm*	
Unlined open ditch/drain		
Network map	*Shape file*	
For each ditch/drain		
Length	*m*	
Soil type		
Seepage rate	*cm/hr*	
Depth	*cm*	
Open surface foul water bodies		
Foul water body map	*Shape file*	
For each foul water body		
Area	m^2	
Soil type		
Seepage rate	*cm/hr*	
Depth	*cm*	

TO BE COMPLETED BY THE USERS

If the route of a drinking water supply pipe intersects the contaminant zone developed by the pollution source, there is a possibility that these contaminants might enter the water distribution pipes. It should be noted, however, that the potential contaminants that might enter the drinking water distribution pipe will also be a function of the condition of the water distribution pipe. Therefore, the outputs from the contaminant ingress model will be coupled with the pipe condition assessment model that is presented in the next chapter.

Table 2.2. Soil properties		
Soil map (shape file) and for each soil type:		
Soil property	**Unit**	**Value**
Saturated volumetric water content	*cm^3/cm^3*	
Initial volumetric water content	*cm^3/cm^3*	
Saturated hydraulic conductivity	*cm/hour*	
Soil characteristic curve coefficient	-	TO BE COMPLETED BY THE USERS
Soil porosity	*cm^3/cm^3*	
Air entry head	*cm*	
Pore size index	-	
Bulk density	*g/cc*	
Fraction organic content	*cc/g*	

Table 2.3. Contaminant properties		
Contaminant property	**Unit**	**Value**
Liquid phase decay	*/hour*	
Diffusion coefficient	*cm^2/day*	TO BE COMPLETED BY THE USERS
Organic carbon partition coefficient of the pollutant		

Table 2.4. Properties of pipes of water distribution network		
Parameter	**Unit**	**Value**
Network map For each pipe of network *Length* *Bury depth*	*Shape file* *m* *m*	TO BE COMPLETED BY THE USERS

2.2 Background

In developing countries, water distribution systems often criss-cross with the pollution sources and in particular with the sewerage systems. If there is movement of contaminants from the pollution sources towards the water distribution system, the water distribution system might become polluted. The following two models are developed to identify the location and sections of polluted water distribution pipes and estimate contaminant concentration at these pipes:

- Contaminant zone model
- Contaminant seepage model

The contaminant zone model estimates the contaminant zone developed in a water distribution system due to pollution sources and thus identifies the location of polluted pipes in the water distribution system.

The contaminant seepage model estimates the relative contaminant concentration profile in the contaminant zone. The combination of these two models would give the relative contaminant concentration in polluted pipes of the water distribution system (Figure 2.2).

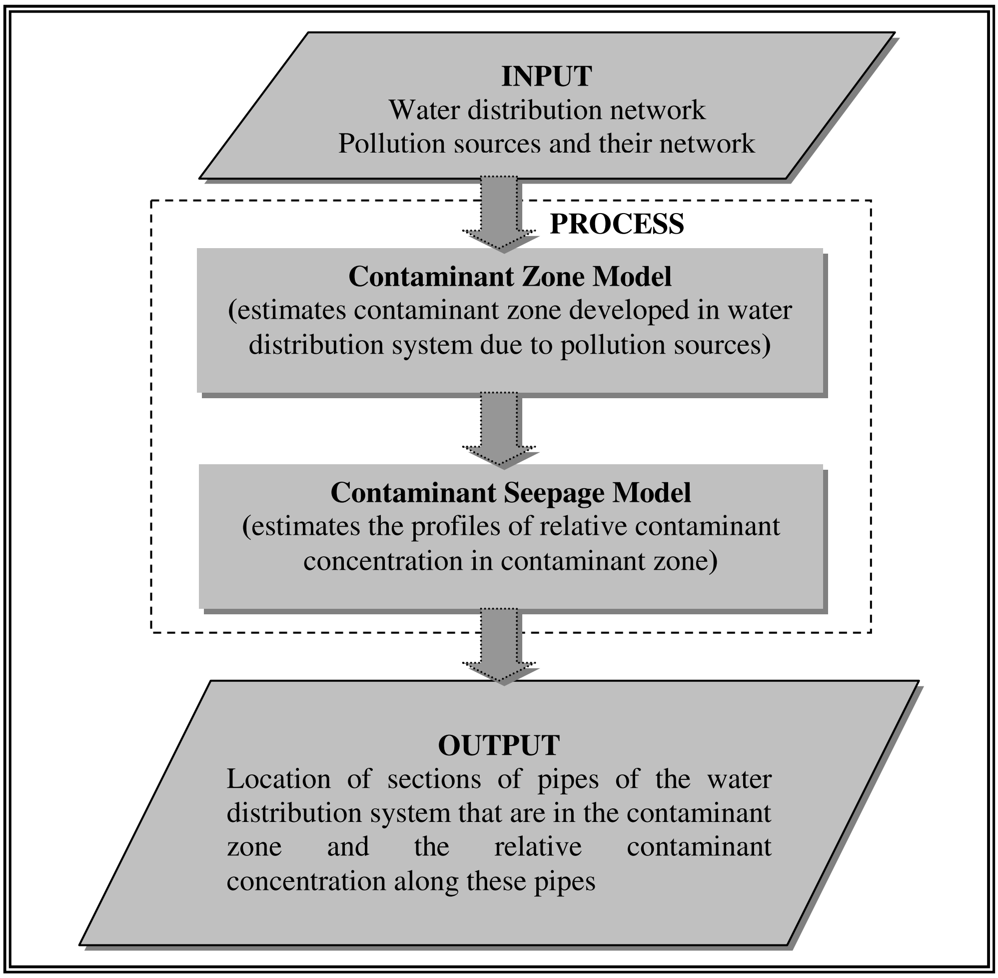

Figure 2.2. Contaminant ingress model

2.3 Contaminant Zone Model

In this section a contaminant zone model is developed and presented, based on the seepage process of soil mechanical theory. This model makes it possible to identify the potential polluted area developed in a water distribution system due to pollution through contaminants intruding into water distribution pipes. Thus this model also allows design engineers to identify reasonable locations for laying new water pipes below sewers without the danger of contaminant intrusion. This model essentially consists of following two parts.

1. Estimation of the contaminant zone or potentially polluted area around pollution sources (sewer pipes, drains and foul water bodies).
2. Identification of sections of water distribution pipes that intersect with the contaminant zone (sections of the pipe that lie in the contaminant zone – SPCZ).

Figures 2.3 and 2.4 show typical scenarios that this model tries to simulate. The flowchart in Figure 2.5 summarizes the model.

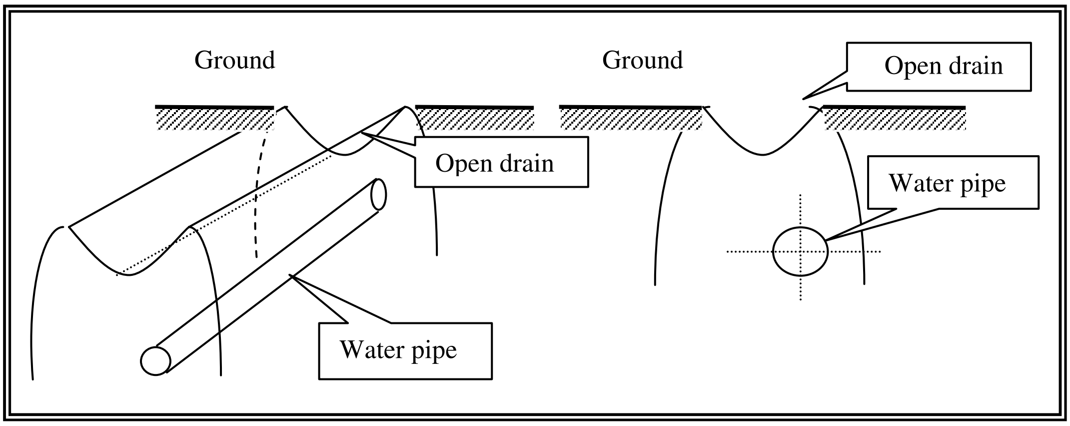

Figure 2.3. A typical scenario in which the model tries to simulate a water distribution network being influenced by a ditch/canal

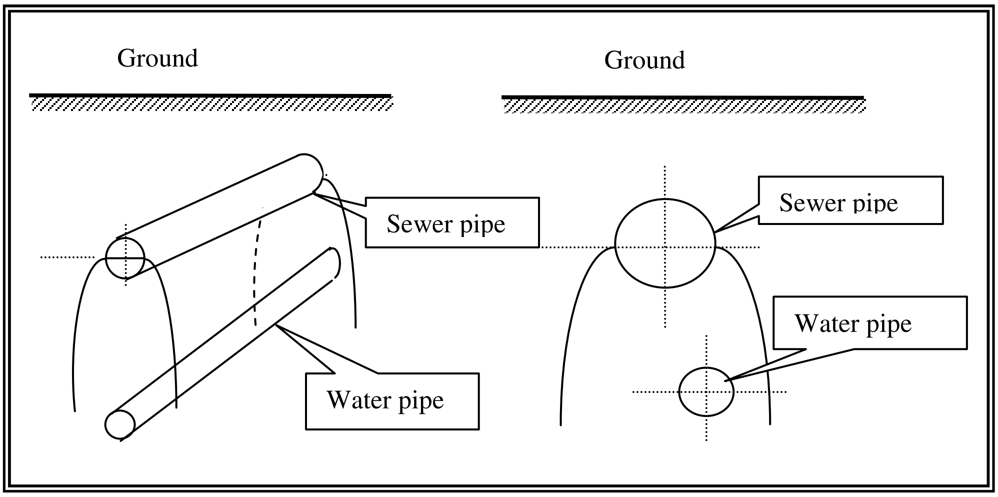

Figure 2.4. A typical scenario in which the model tries to simulate a water distribution network being influenced by a sewer pipe

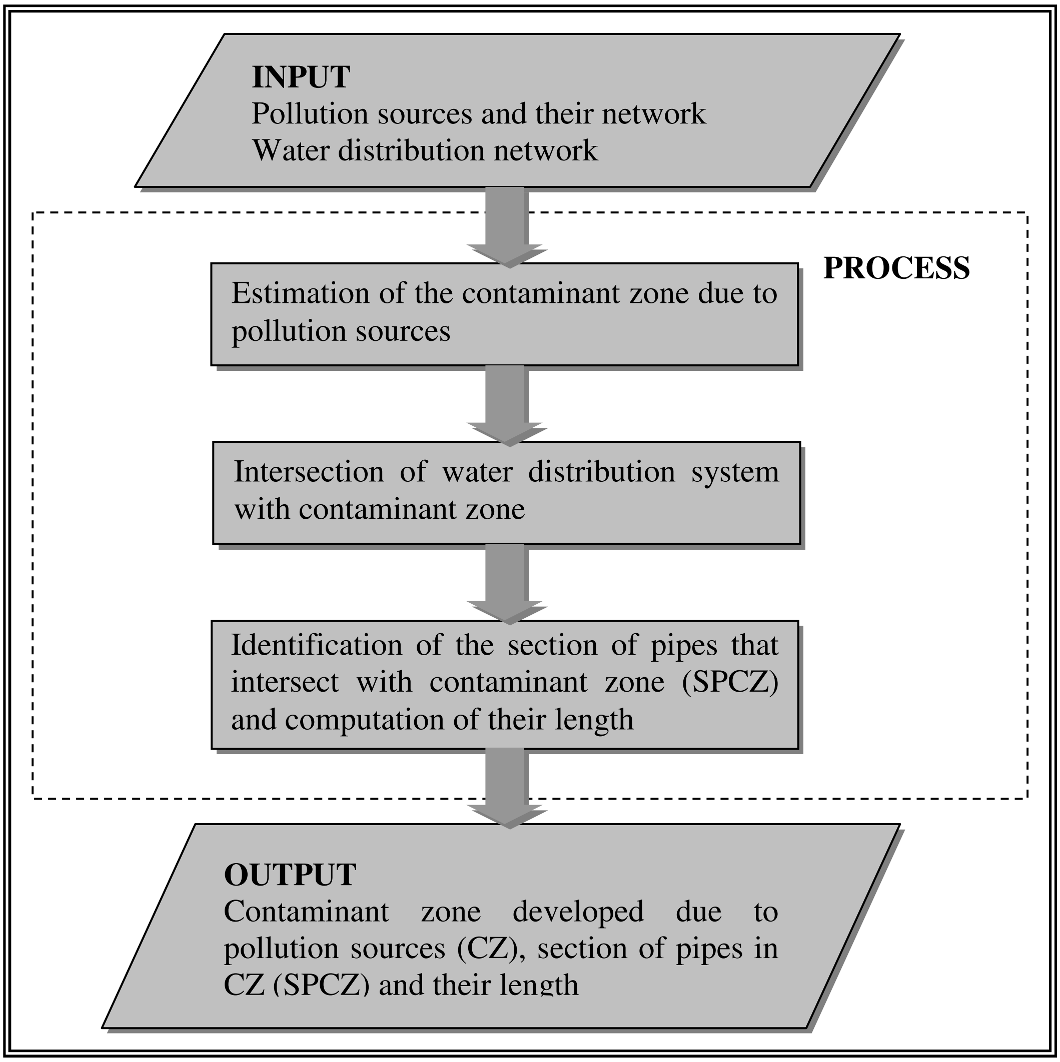

Figure 2.5. Contaminant zone model

2.3.1 Estimation of the contaminant zone due to pollution sources (CZ)

When contaminated water seeps from the pollution sources, it creates a seepage zone underneath. This zone is called a contamination zone (CZ). It is essential to know the shape of the contamination zone, as this zone determines the sections of water distribution pipe that may be subjected to contaminant intrusion. This zone is based on the seepage of the contaminated water from the pollution source into the soil. When considering seepage, important parameters include dimensions and shapes of the boundaries of pollution sources. The procedure for estimating the contaminant zone due to different pollution sources is described in this section. The different pollution sources are:

1. Unlined ditch/canal
2. Lined ditch/canal
3. Sewer pipe
4. Open surface foul water bodies

The procedure is described in the flowchart in Figure 2.6.

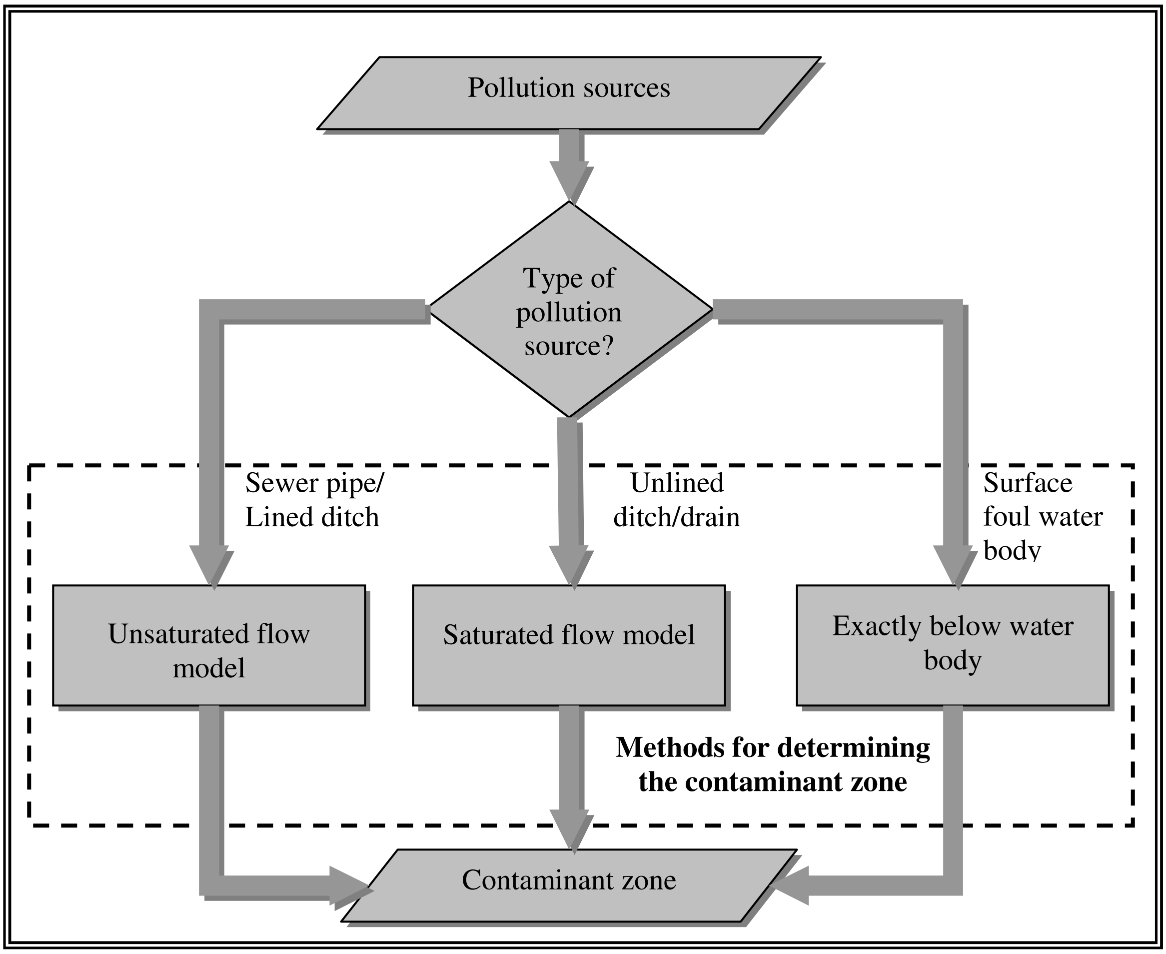

Figure 2.6. Estimation of contaminant zone due to different pollution sources

2.3.1.1 Contaminant zone due to unlined ditch/canal

Figure 2.7 shows the typical scenario in the canal or ditch. The width and depth of the contaminated water in the ditch are B and H respectively. Contaminated water in the ditch seeps into soil from the bottom of the ditch, forming the contaminant zone or envelope as shown in the figure. As the depth (z) increases, the distance (x) will increase, which means that the seepage envelope will enlarge during the process of seepage. The procedure used to establish the shape of this seepage envelope is elaborated below.

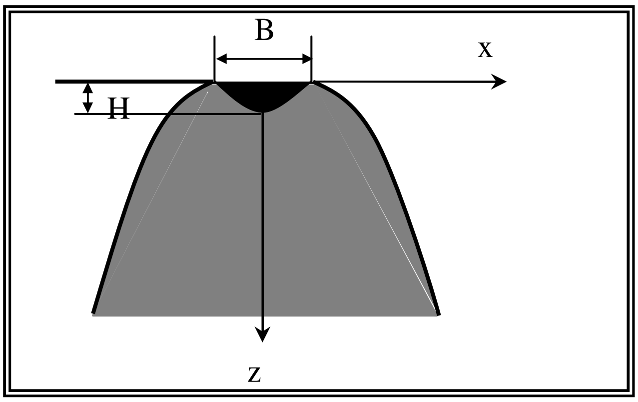

Figure 2.7. Seepage of contaminated water from ditch

Seepage equations: The flow of water in soil due to seepage from unlined ditch/canal is saturated flow. In order to solve this flow problem, Harr (1962) examined Zhukovsky's function as given by equation (2.1).

$$\theta = ip + \frac{w}{k} = Ae^{\frac{w}{\alpha}} \qquad (2.1)$$

$$p = x + z\,i$$

$$w = \varphi + \psi i$$

where

α - a parameter

A - a real constant

k - permeability of soil

φ - potential function

ψ - stream function

w - potential complex

p - spatial complex.

Separating this expression into real and imaginary parts gives equation (2.2).

$$\begin{aligned} \frac{\varphi}{k} - z &= Ae^{\frac{\varphi}{\alpha}}\cos(\frac{\Psi}{a}) \\ \frac{\Psi}{k} + x &= Ae^{\frac{\varphi}{a}}\sin(\frac{\Psi}{a}) \end{aligned} \qquad (2.2)$$

Substituting $-\psi$ for ψ and $-x$ for x in equation (2.2), we see that the system of streamlines defined by ψ in these equations is symmetrical about the y-axis. Hence, the y-axis can be taken as the streamline $\psi = 0$. The free surface must satisfy the condition $-z + \frac{\varphi}{k} = 0$, and $\psi = -\frac{q}{2}$, and hence from the first of equation (2.2) we find

$$\begin{aligned} &\cos(-\frac{q}{2\alpha}) = 0 \\ &q = -(2n+1)\alpha\pi \end{aligned} \qquad (2.3)$$

where

q - flow rate

In particular, taking $n = 0$ and substituting equation (2.3) with $\psi = -\frac{q}{2}$ and $\varphi = kz$ into the second of equation (2.2), we obtain for the free surface

$$x - \frac{q}{2k} = -Ae^{-\frac{k\pi}{q}z} \qquad (2.4)$$

Letting $z = 0$ in equation (2.4), we obtain for the half width of the ditch

$$x_{z=0} = \frac{B}{2} = \frac{q}{2k} - A \tag{2.5}$$

Now taking $\varphi = 0$ in equation (2.2), as $\psi = 0$ at the bottom of the ditch, from the parametric equation for the perimeter of the ditch, we find $z = -A = H$, where H is the maximum depth of water in the ditch. Hence, the quantity of seepage from the ditch section is found from equation (2.5) to be $q = k(B + 2H)$. Rearranging equation (2.4), we can find the seepage free surface equation:

$$x = \frac{1}{2}(2H + B) - He^{-\frac{\pi}{2H+B}z} \tag{2.6}$$

For practical purposes, the seepage free surface of the flow net can be considered to approach its vertical asymptote, and the equipotential lines can be taken as horizontal at a depth of $z = 3(B + 2H)/2$ (Harr 1962). From equation (2.6), when $z > 3(B + 2H)/2$, $x = (B + 2H)/2$, and the width between the two vertical asymptotes is $B + 2H$. Thus the characteristics of the seepage envelope for an unlined ditch/canal are (see Figure 2.8):

1. The depth at which flow lines become vertical (z) = $3(B + 2H)/2$
2. The width of the vertical seepage envelope = $B + 2H$
3. The equation of the curved seepage envelope: $x = \frac{1}{2}(2H + B) - He^{-\frac{\pi}{2H+B}z}$

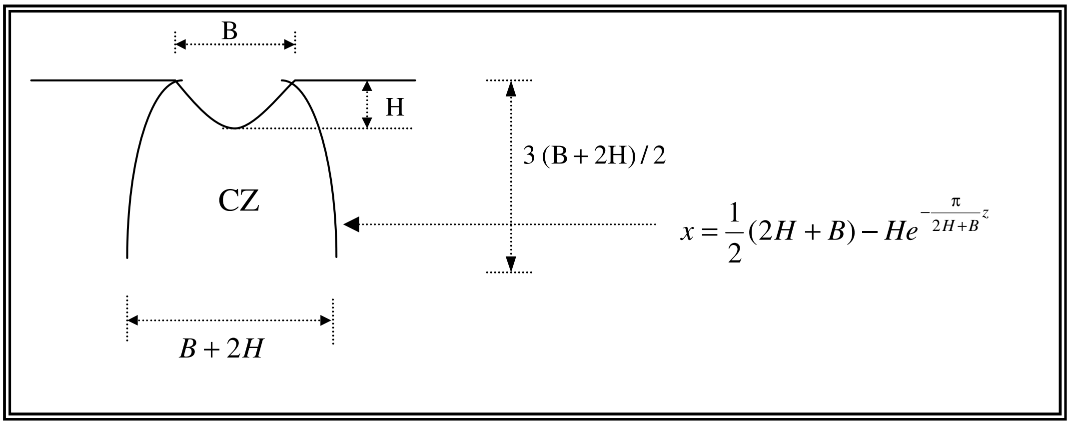

Figure 2.8. Characteristics of the seepage envelope for an unlined ditch/canal

2.3.1.2 Contaminant zone due to sewer pipe and lined ditch/canal

The flow of water in soil due to seepage from a sewer pipe or lined ditch/canal is unsaturated flow. Therefore the seepage envelope is not governed by the equation (2.6). However, for the purpose of simplicity, it is assumed that the maximum width of the seepage envelope at any depth below the sewer pipe and lined ditch/canal is half the width obtained for unlined ditch/canal (saturated flow). Thus the characteristics of the seepage envelope due to sewer pipe and lined ditch/canal are (see Figure 2.9):

1. The depth at which flow lines become vertical (z) = $3\,(B+2H)/2$
2. The width of the vertical seepage envelope = $(B+2H)/2$
3. The equation of the curved seepage envelope: $x = \dfrac{\frac{1}{2}(2H+B) - He^{-\frac{\pi}{2H+B}z}}{2}$

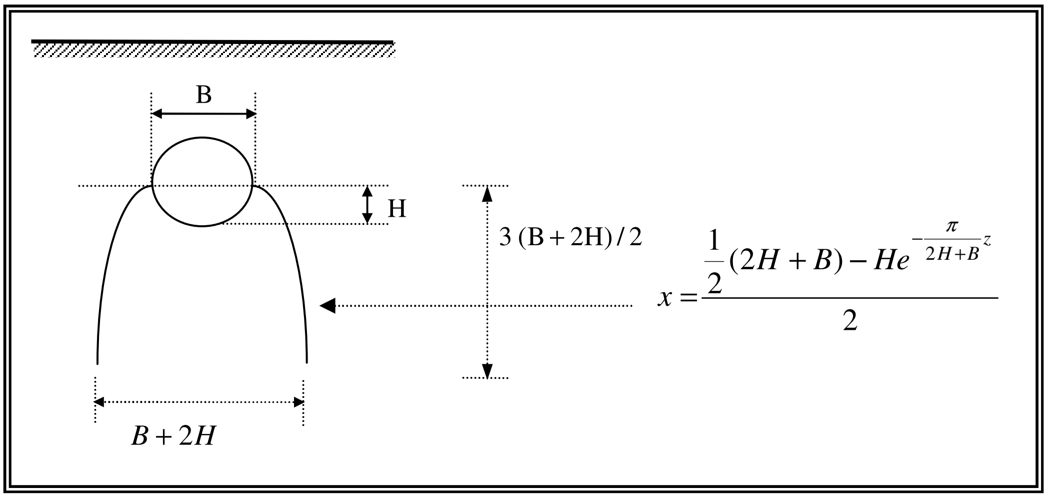

Figure 2.9. Characteristics of the seepage envelope for a sewer pipe and a lined ditch/canal

2.3.1.3 Contaminant zone due to open surface foul water bodies

The width of the open surface foul water bodies is usually large compared to sewer pipes or drains. The flow of water in soil due to seepage from the foul water bodies is saturated flow. Therefore it is assumed that the seepage envelope due to a surface foul water body lies exactly below it. Thus the width and breadth of seepage envelope due to a foul water body are the width and breadth of foul water body itself.

2.3.2 Identification of the section of water distribution pipes in contaminant zone – SPCZ

In order to identify the section of water distribution pipes in a contaminant zone (SPCZ) or the potential polluted area in the water distribution system due to pollution sources (open ditch, sewer pipe and foul water bodies), it is necessary to establish the intersection of the contaminant zone developed by pollution sources, with the paths of the water pipe. The procedure used to establish the intersection is described in this section for line pollution sources (sewer pipes, ditches, canals etc.) and surface foul water bodies.

2.3.2.1 Open ditch/canals (lined and unlined) and sewer pipes

Identification of the intersection of contaminant zone due to open drains and sewer pipes with the water distribution network requires extensive computational efforts, as the envelope of the potential polluted area or contaminant zone is three-dimensional in nature (see Figure 2.10).

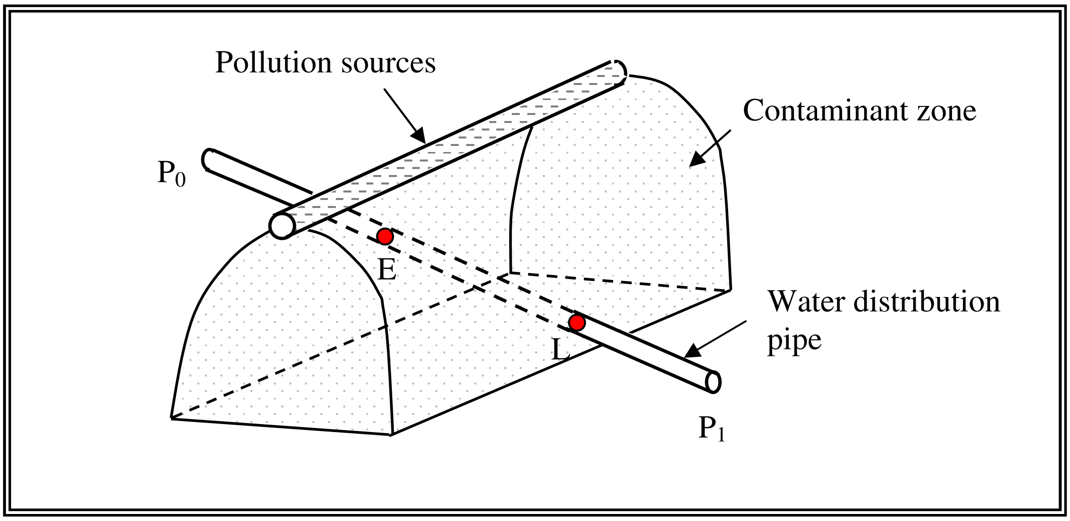

Figure 2.10. Three-dimensional view of the intersection of a water distribution pipe with a contaminant zone

The boundary of the contaminant zone approximates to the parabola. The portion of the water distribution pipe which intersects with the parabola of contaminant zone formed by the pollution sources is SPCZ (Figures 2.11 (a) and 2.11 (b)).

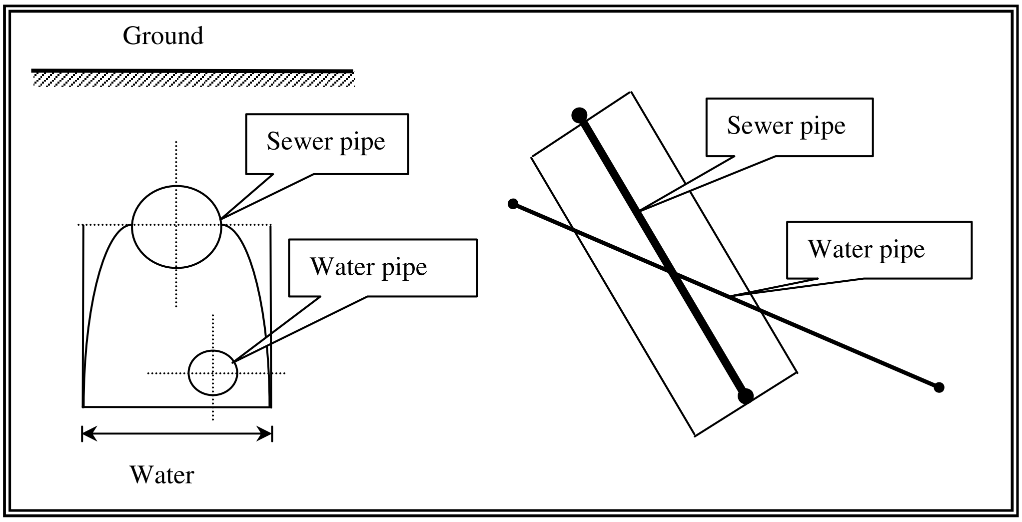

Figure 2.11 (a). Identification of SPCZ due to the intersection of water distribution pipe and contaminant zone formed by sewer pipe

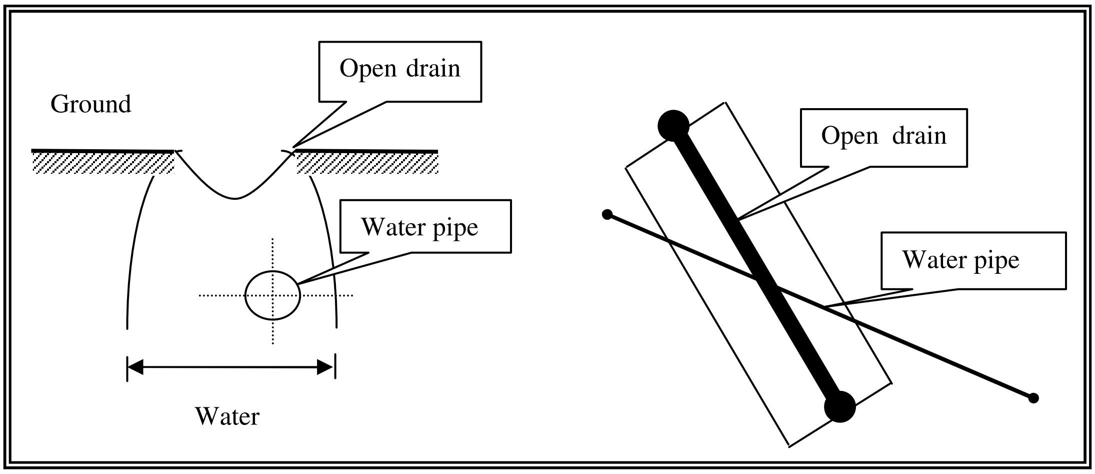

Figure 2.11 (b). Identification of SPCZ due to the intersection of water distribution pipe and contaminant zone formed by an open drain

The methodology used for obtaining the segment of intersection of water distribution pipe with the contaminant zone is described below.

Procedure: The intersection points of the water distribution pipe with the contaminant zone are required to be obtained by three-dimensional (3D) spatial geometry analysis. However the 3D spatial geometry analysis can be projected into a 2D space by projecting both water distribution pipe and contaminant zone on to the same horizontal plane. The 2D solutions are then substituted into the water distribution pipe segment equation to obtain a 3D solution of intersection point. The procedures used are as follows.

1) Establish the coordinates of contaminant zone: Figure 2.10 shows a 3D contaminant zone. This contamination zone is simplified as a polyhedron (3D) to simplify the geometry calculation. Figures 2.12 (a) and (b) show a two-dimensional (2D) front view and top view respectively. The top view transfers a spatial 3D problem into a 2D problem on a horizontal plane. Thus in 2D the contaminant zone is represented as a rectangle with four vertices, V1, V2, V3 and V4. (Figure 2.12 (b)). The coordinates of these vertices are obtained with the help of coordinates at start and end nodes of sewer pipe/drain and their dimensions (diameter for sewer, width and length for open drain).
2) Establish the coordinates of water distribution pipe: The top view of water distribution pipe (Figure 2.12) transfers a spatial three-dimensional problem into a two-dimensional problem on a horizontal plane. In 2D, the water distribution pipe is thus simplified to a segment between start and end nodes of the pipe, P_0P_1. The 3D coordinates for the start and end nodes of the water distribution pipe are obtained from the geo-database.
3) Calculate the intersection: The intersection of water distribution pipe with contaminant zone is performed on a horizontal projection (2D). The intersection points are E (enter or upstream) and L (leave or downstream), as shown in Figure 2.12. The 2D coordinates for the intersection points are then entered into the segment equation of water distribution pipe to obtain its 3D coordinates.
4) Length of pipe segment in contaminant zone: The length of water distribution pipe in the contaminant zone (LC) is calculated using the upstream and downstream intersection points:

$$LC_k = \left|\overrightarrow{up_k dp_k}\right| \qquad k = 1, 2, \ldots NC \qquad (2.7)$$

where

LC_k - the length of pipe k in the contaminant zone (m)

up_k and dp_k - the upstream and downstream intersection points of pipe k with the contaminant zone

NC - the number of water distribution pipes within contaminant zone

Projecting a 3D problem to 2D simplifies the computational process involved in determining the intersection of water distribution pipe with the contaminant zone. The resulting contamination zone is usually larger than the actual one shown in Figure 2.12 (a), where the solid points indicate the result after simplification whereas the hollow points represent the true solution. However, as we are concerned about the risk of contaminant intrusion into water distribution pipes, considering these overestimated scenarios adds a factor of safety. The complete procedure is presented in the flowchart in Figure 2.13.

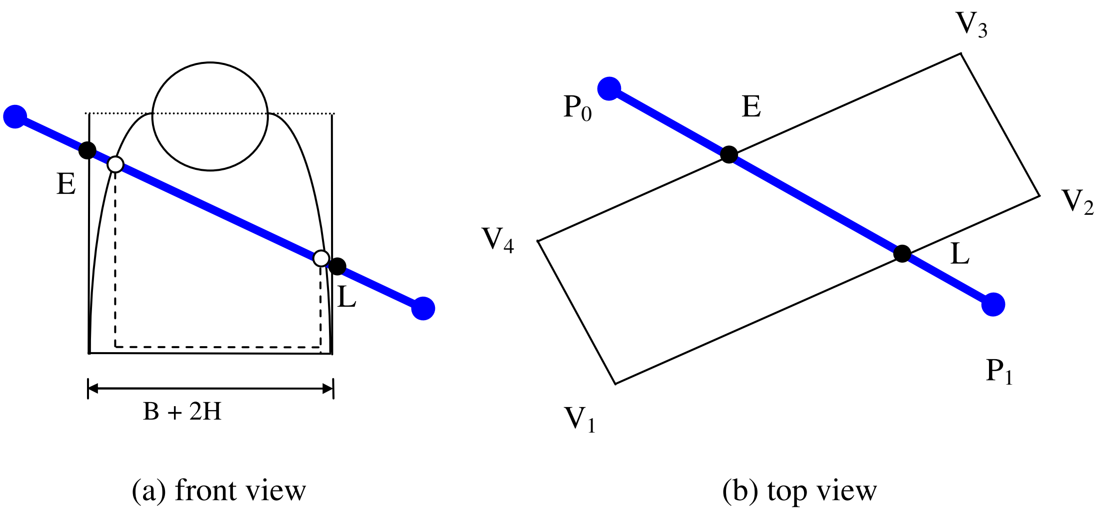

Figure 2.12. Two-dimensional simplification of intersection of the contaminant zone with the water distribution pipe

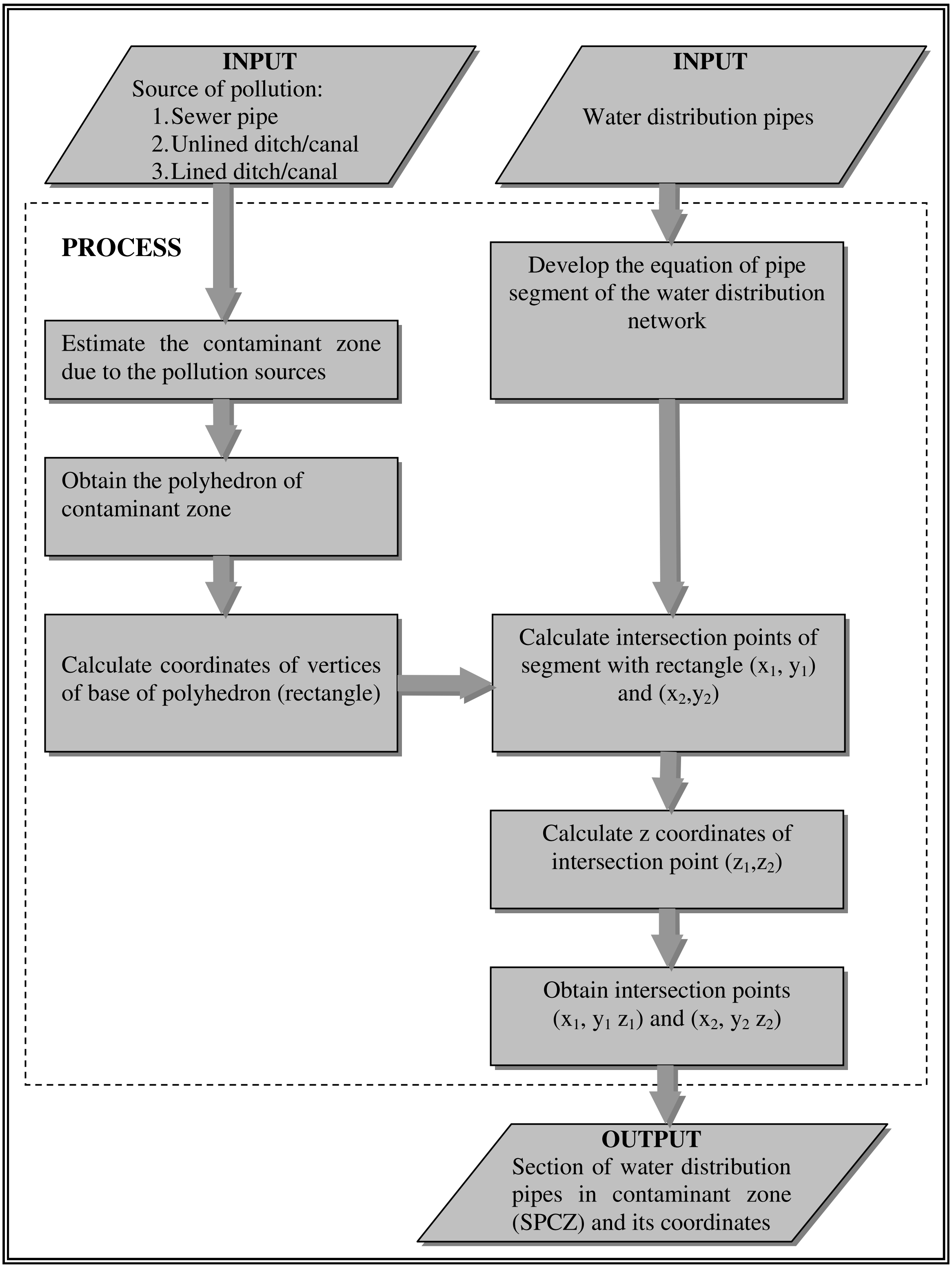

Figure 2.13. The methodology for obtaining coordinates for the section of water distribution pipes in a contaminant zone (SPCZ)

2.3.2.2 Foul water bodies

Apart from sewer pipes and drains/ditches, there are other pollution sources such as a wastewater disposal pond, buried waste, spills or landfills etc., from which a water distribution system may become contaminated. The boundaries of these water bodies can be simplified to polygons. When considering such water bodies, whose area is vast but which are shallow in depth, the seepage boundary can be assumed to be uniform during the movement of contaminant through the soil. This assumption simplifies the computational process involved in determining the potential polluted area in the water distribution system. Otherwise, numerical methods such as Finite Element Method (FEM) need to be employed. The 2D projection of the contaminant zone developed by these large surface foul water bodies is a polygon instead of a rectangle as in the case of contaminant zone developed by sewer pipes and ditches. The procedure described above (in Section 2.3.2.1) is followed to obtain the coordinates of the SPCZ, i.e. the intersection of polygon and water distribution pipe. If the polygon is convex, it is divided into several concave polygons (as shown on the right of Figure 2.14) and the SPCZ arising from each individual polygon is identified.

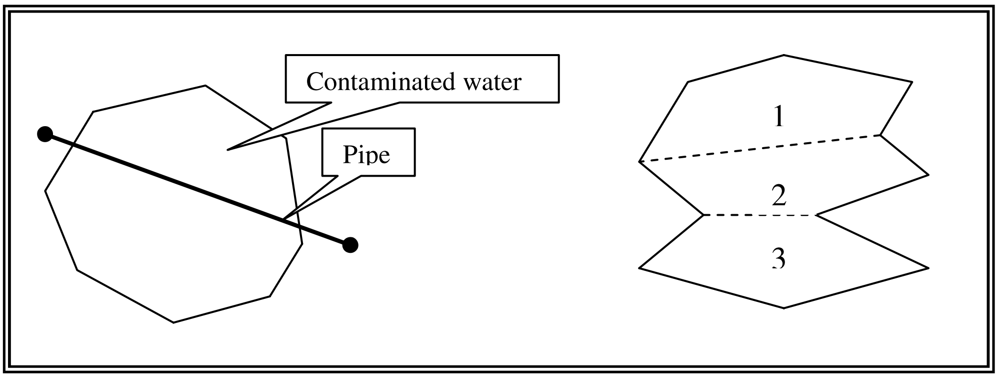

Figure 2.14. Water distribution network as influenced by the pollution source of surface water body

2.4 Contaminant Seepage Model

The procedure developed for the prediction of the contaminant zone due to different pollution sources and identification of the section of water distribution pipe in the contaminant zone (SPCZ) is described in the preceding sections. It is now required to estimate the contaminant loading along the SPCZ. This can be estimated by simulating the variable contaminant concentration in the contaminant zone.

Simulation of the contaminant concentration requires knowledge of the movement of contaminants through the soil due to seepage from open drains/canals, sewer pipes and surface foul water bodies. A mathematical model has been developed for this purpose. The concentration of contaminant is changed during seepage due to filtration by the soil. Therefore the model consists of two components, the first modelling the seepage process and the second modelling the variable concentration of contaminant migration through the soil. The output of this model in terms of variable contaminant concentration from the pollution sources is used to evaluate the magnitude of pollution when contaminants intrude into water distribution systems.

Three sources of contaminant seepage are grouped into two for the purpose of modelling the movement or transport of contaminants through the soil. These are:

1. Sewer pipes and open ditch/canal (lined): The seepage in soil due to water flowing in pipes and lined ditch/canal is considered as unsaturated flow. The contaminant transport model (CTM) for unsaturated flow is developed.
2. Surface foul water bodies and open ditch/canal (unlined): The seepage in soil due to water ponding or flowing over the surface and in unlined ditches/canals is considered as saturated flow. The contaminant transport model (CTM) for saturated flow is developed.

The procedure is described in Figure 2.15.

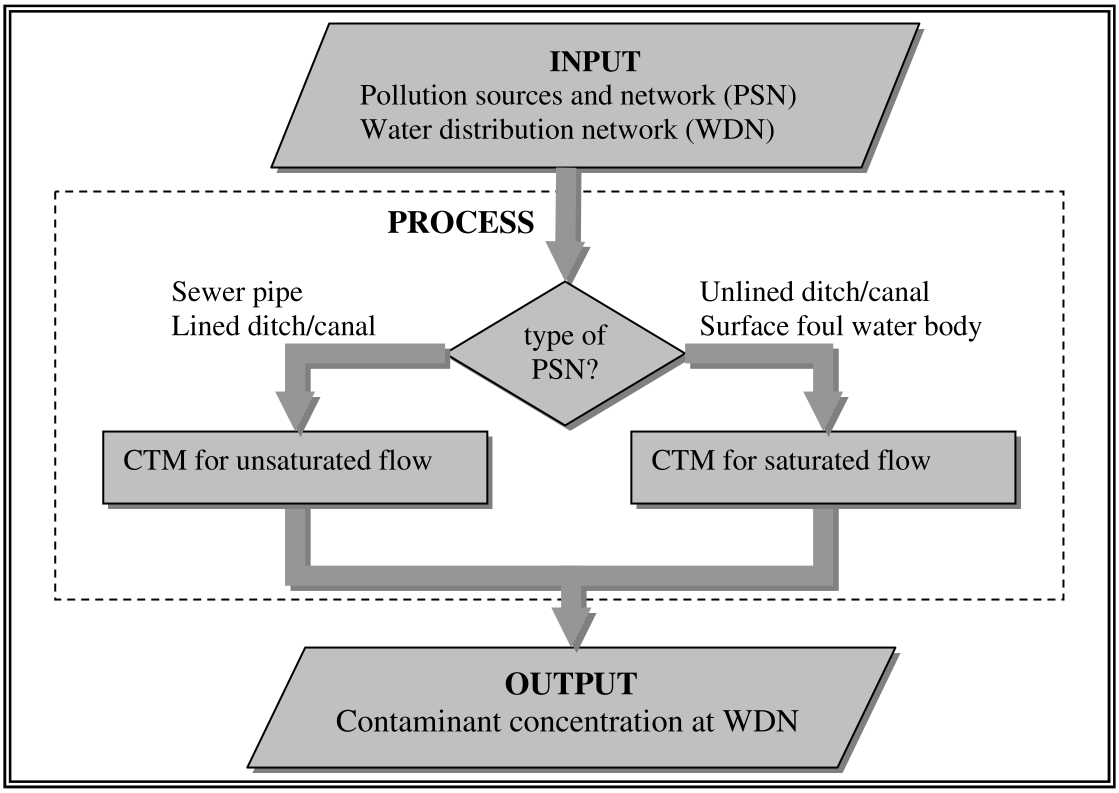

Figure 2.15. The contaminant seepage model

2.4.1 The contaminant transport model for unsaturated flow

The contaminant transport model (CTM) for unsaturated flow consists of the following two parts:

1. Modelling of seepage from sewer pipes and open drains/canals (lined)
2. Modelling of contaminant transport.

2.4.1.1 Modelling of seepage from sewer pipes and open drains/canals (lined)

Water flow into unsaturated soil is a very complex process due to various climatic conditions, the soil's physical and hydraulic properties, and geological conditions. Therefore, the appropriate model should be selected for the different boundary conditions of the modelling scenario. In this study, water flow and contaminant transport under surface ponding conditions were considered. Several infiltration models for ponding conditions have been developed, including those by Parlange et al. (1985), Haverkamp et al. (1990; 1994) and Salvucci and Entekhabi (1994).

The Green-Ampt model (Green and Ampt 1911) is the first physically based equation describing water flow into soil. The Green-Ampt model has been subject to considerable developments in applied soil physics and hydrology. This model can be applied to a great variety of hydrological problems such as homogeneous and non-homogeneous soils, ponding and non-ponding conditions. The use of a more sophisticated approach (e.g. the models based on the non-linear Richards equation), is both impractical and inefficient as more information on soil hydraulic parameters (e.g. water retention and hydraulic conductivity functions) is required (USEPA 1998a). The Explicit Green-Ampt model (Salvucci and Entekhabi 1994) was chosen as a quick and easy method of modelling water flow into unsaturated soil under surface ponding conditions. In this section, the mathematical formulation of the Explicit Green-Ampt model is presented. First the terminologies used in the model are explained, and then the equations.

- Air entry head, or bubbling pressure head (ψ_b): The point where desaturation commences in the soil located above the water table is referred to as the air-entry point. The hydraulic head associated with this point is referred to as the air-entry head.
- Air exit head (h_e): The air exit head may be taken as equal to one half of the air entry head.
- Capillary pressure head at the wetting front (h_f): The capillary pressure is the suction of water in the pore space due to surface tension or capillary force. This parameter is a function of soil water content, and can be determined from experimental measurements (Hillel 1982) or from the following equation $h = 2L/r$, where L is the surface tension of water and r is the radius of capillary.
- Exponent of the Brooks-Corey conductivity model (η_b): This is the exponent of the Brook-Corey conductivity model.
- Initial volumetric water content (θ_0): Initial volumetric water content present in the soil (see Table 2.5 for the residual volumetric contents for different types of soils).
- Ponding depth or capillary pressure at the surface (h_s): This parameter defines the thickness of water accumulated at the soil surface during water infiltration. The extent of ponding depth depends on soil types and is thus site-specific (see *hs* in Figure 2.16).
- Saturated hydraulic conductivity (K_s): This parameter is a coefficient of proportionality that describes the rate at which water can move through a soil at saturation. It should be noted that the density and kinematic viscosity of the water are considered in the measurement. The standard value of hydraulic

conductivity is defined for pure water at a temperature of 15.6°C. The values for different soil textures are given in Table 2.5.

- Saturated volumetric water content ($\theta_{s,}$): The saturated water content of the soil is the volume of water at saturation relative to the bulk volume density. Typical values for saturated water content for different soil textures are given in Table 2.5.
- Pore size index (λ_b): This is the exponent of the Brook-Corey water retention model.
- Van Genuchten soil parameter (m): This is the parameter for Genuchten soil model.
- Water flux (q): It is the seepage rate (Table 2.6)

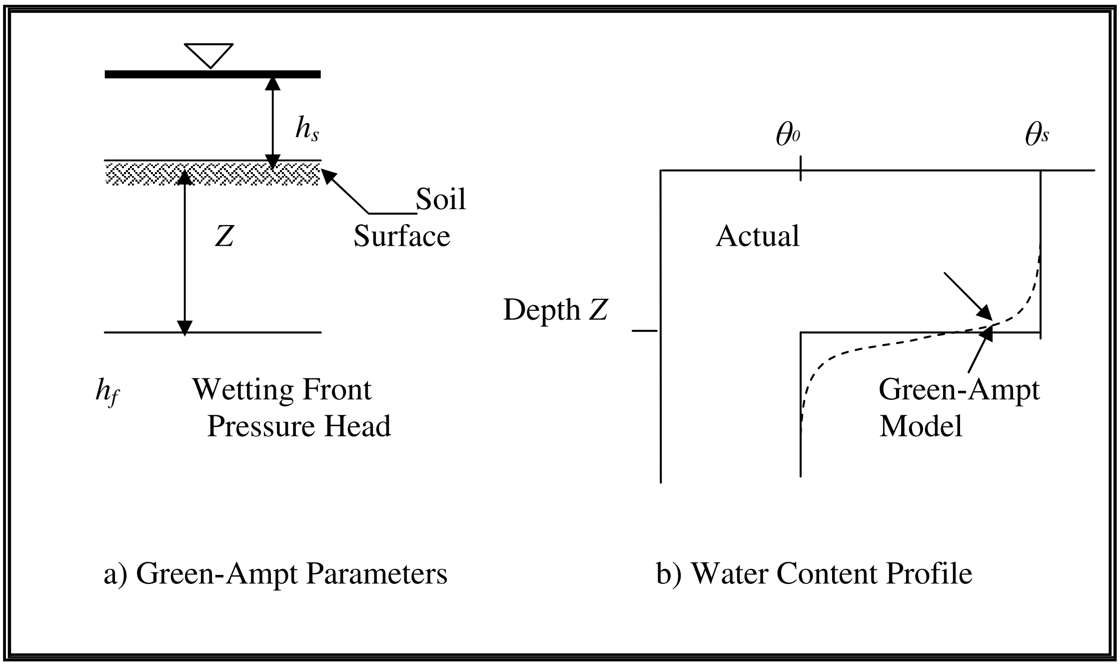

Figure 2.16. Illustration of Green-Ampt parameters and the conceptualized water content profile, which demonstrates the sharp wetting front (USEPA 1998b)

The mathematical formulations for this model are given in equations (2.8) to (2.12):

$$\frac{q}{K(\theta)} = \frac{\sqrt{2}}{2}\left(\frac{t}{\chi + t}\right)^{-1/2} + \frac{2}{3} - \frac{\sqrt{2}}{6}\left(\frac{t}{\chi + t}\right)^{1/2} + \frac{1-\sqrt{2}}{3}\left(\frac{t}{\chi + t}\right) \quad (2.8)$$

$$\chi = \frac{(h_s - h_f)(\theta - \theta_0)}{K(\theta)}$$

where

q - water flux (L/T)

θ - volumetric water content at soil surface (L^3/L^3)

$K(\theta)$ - hydraulic conductivity (L/T) at water content equals to θ

t - elapsed time (T)
h_s - ponding depth or capillary pressure at the surface (L)
h_f - is capillary pressure head at the wetting front (L)
θ_0 - initial volumetric water content (L^3/L^3)

$K(\theta)$ is estimated by van Genuchten (1980) and is given by equation (2.9).

$$K(\theta) = K_s S_e^{1/2} \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{2.9}$$

where
$S_e = (\theta - \theta_o)/(\theta_s - \theta_o)$
K_s - saturated hydraulic conductivity (L/T)
θ_s - saturated volumetric water content (L^3/L^3)
m - van Genuchten soil parameter.

Among these parameters, θ_0 is assumed as residual volumetric water content, h_s is considered to be the constant surface ponding depth, while h_f is given by Brakensiek and Onstad (1977) as presented in equation (2.10):

$$h_f = \frac{\eta_b}{\eta_b - 1} h_e \tag{2.10}$$

where
η_b - exponent of the Brooks-Corey conductivity model, as given in equation (2.11)
h_e - the air exit head, as given in equation (2.12):

$$\eta_b = 2 + 3\lambda_b \tag{2.11}$$

$$h_e = \frac{\psi_b}{2} \tag{2.12}$$

where
λ_b - pore size index
ψ_b - air entry head, or the bubbling pressure head.

2.4.1.2 Modelling of contaminant transport

The concentration of contaminant will vary during movement through soil. The mechanism of contaminant transport through soil is advection, hydrodynamic dispersion, and interactive processes between pollutant and soil surface (Harvey and Garabedian 1991). A simple one-dimensional equation for transport of pollutant dissolved in water through soil (Enfield et al. 1982) is used. The terminologies associated with the equation are described first and then the equation is given.

- Dispersion coefficient (*D*): The process by which a substance or chemical spreads and dilutes in flowing groundwater or soil gas. A measure of the spreading of a flowing substance as a result of the nature of the porous medium is known as dispersion coefficient.

- Pore-water velocity (v): Seepage velocity.
- Bulk density (ρ_b): This parameter defines the mass of dry soil relative to the bulk volume of soil. Ranges for bulk density with respect to different soil types are given in Table 2.5.
- Porosity (n): The ratio of the volume of pore spaces in a soil to the total volume of the soil. n is assumed as equivalent to θ_s.
- First-order decay coefficient in liquid phase (λ): This describes those processes where pollutant mass is lost within the soil system. In general, degradation occurs primarily by soil micro-organisms and may vary depending upon soil temperature and moisture. It depends on the interaction of chemical with soil and hence is site specific.
- Sorption constant (K_d): The sorption constant is the linear partition coefficient which describes the relative distribution of the pollutant between that which is sorbed to the solid phase and that which is dissolved in water. The higher the value of the partition coefficient the greater the tendency for sorption to the solid phase; in contrast, low partition values indicate most of pollutant distribution is retained in the water. The partition coefficient is a constant for a given set of conditions. As a result, it is a site specific value. In particular, it is a function of the fraction organic content of the soil and can be estimated as the product of the fraction organic content (f_{oc}) and the organic carbon partition coefficient of the pollutant (K_{oc}). Thus $Kd = f_{oc} K_{oc}$.
- Diffusion coefficient of the chemical in soil (D_p): The process by which molecules in a single phase equilibrate to a zero concentration gradient by random molecular motion (Brownian motion). The flux of molecules is from regions of high concentration to low concentration and is governed by Fick's Second Law. A parameter that measures how rapidly a constituent will diffuse in water is known as diffusion coefficient. It depends on the interaction of chemical with soil and hence is site specific.
- Characteristic curve coefficient for the soil (b): This parameter relates the relative saturation of the soil to the relative conductivity of the soil under steady-state conditions. If this constant cannot be determined, it can be obtained from Table 2.5. for different soil textures.

The mathematical formulation of this model is given below:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial^2 z} - v\frac{\partial C}{\partial z} - \frac{\rho_b}{n}\frac{\partial S}{\partial t} - \lambda C \qquad (2.13)$$

where
C - liquid-phase pollutant concentration (M/L^3)
t - time (T)
z - depth along the flow path (L)
D - dispersion coefficient (L^2/T)
v - pore-water velocity (L/T)
ρ_b - bulk density (M/L^3)
n - porosity
S - solid-phase concentration (M/L^3)
λ - first-order decay coefficient in liquid phase (1/T)

The term $\partial S/\partial t$ is the rate of loss of solute from liquid phase to solid phase due to sorption. Under the assumption of linear, instantaneous sorption, $\partial S/\partial t$ can be evaluated by equation (2.14):

$$\frac{\partial S}{\partial t} = K_d \frac{\partial C}{\partial t} \tag{2.14}$$

where
K_d - sorption constant

Two cases are considered in the model: Steady state and Unsteady state

Steady state

In steady state situations the contaminant concentration in the soil is not influenced by time. It varies only with depth. For a continuous steady flow with initial concentration c_0 seeping into the soil, the steady state outflow concentration is governed by equation (2.13) with $\partial C/\partial t = 0$ (Harter et al. 2000). The boundary condition of equation (2.13) are: $z = 0, C = C_0$ and $z = \infty, C = 0$. With the assumption of $\partial C/\partial t = 0$ and the above boundary conditions, we find the solution of equation (2.13) as:

$$\frac{C}{C_0} = e^{\frac{v-\sqrt{v^2+4D\lambda}}{2D}z} \tag{2.15}$$

where

C_0 - initial pollutant concentration (mg/l).

Unsteady state

In unsteady state situations the contaminant concentration in the soil varies with respect to time and depth. Substituting for $\partial S/\partial t$ from (2.14) into (2.13), one obtains

$$\frac{\partial RC}{\partial t} = D\frac{\partial^2 C}{\partial^2 z} - v\frac{\partial C}{\partial z} - \lambda C \tag{2.16}$$

where

$$R = 1 + \frac{\rho_b K_d}{n} \tag{2.17}$$

The dispersion coefficient can be calculated from the relationship developed by Biggar and Nielsen (1976), as given in equation (2.20):

$$D = D_p + 2.93(v)^{1.11} \tag{2.18}$$

where
D_p - diffusion coefficient of the chemical in soil (L^2/T)

The pore-water velocity may be determined from water flux (q) calculated from the water flow model given previously (equation 2.18) and projected water content (USEPA 1994) as shown in equation (2.19):

$$\begin{aligned} \theta &= \theta_s \left(\frac{q}{K_s} \right)^{\frac{1}{2b+3}}, \qquad && q \le K_s \\ \theta &= \theta_s, && q > K_s \end{aligned} \tag{2.19}$$

where
θ - projected water content
b - characteristic curve coefficient for the soil.

Therefore, the pore-water velocity (seepage velocity) is:

$$v = \frac{q}{\theta} \tag{2.20}$$

For a continuous source of infinite duration, the analytical solution subject to the following initial and boundary conditions may be found in literature

$$\begin{aligned} &C(z, t=0) = 0 \qquad && x \ge 0 \\ &C(z=0, t) = C_0 && t \ge 0 \\ &C(z=\infty, t) = 0 && t \ge 0 \end{aligned} \tag{2.21}$$

where
C_0 - initial pollutant concentration (M/L^3)

The analytical solution for no conservative solute ($\lambda \neq 0$) is presented by Bear (1972) and developed by O'Loughlin and Bowmer (1975) using Laplace transforms (Runkel 1996) as given in equation (2.22):

$$\frac{C}{C_0} = \frac{1}{2} \left\{ \exp\left[\frac{vz}{2D}(1-\Gamma) \right] \operatorname{erfc}\left(\frac{z - \frac{vt}{R}\Gamma}{2\sqrt{Dt/R}} \right) + \exp\left[\frac{vz}{2D}(1+\Gamma) \right] \operatorname{erfc}\left(\frac{z + \frac{vt}{R}\Gamma}{2\sqrt{Dt/R}} \right) \right\} \tag{2.22}$$

where

$$\Gamma = \sqrt{1 + 2H} \tag{2.23}$$

$$H = 2\lambda D / v^2 \tag{2.24}$$

erfc(z) is the complementary error function which is defined as

$$\operatorname{erfc}(z) = 1 - \frac{2}{\sqrt{\pi}} \int_0^z \exp(-z^2) dz \tag{2.25}$$

Table 2.5. Typical values of different input parameters for different soil types (Meyer et al. 1997) *Estimated

Soil type	Properties							
	Saturated volumetric content	Residual volumetric content	Saturated hydraulic conductivity	Soil characteristic curve coefficient	Air entry head	Pore size index	Bulk density	Fraction organic content of the soil
	θ_s, (m^3/m^3)	θ_r (m^3/m^3)	K_s (cm/hr)	b	ψ_b (cm)	λ_b	ρ_b (g/cm^3)	f_{oc}
Sand	0.430	0.0466	29.59	0.998	7.02	1.67	1.65	0.0071
Loamy sand	0.410	0.0569	14.36	1.40	9.58	1.27	1.6*	0.0061
Sandy loam	0.410	0.0644	4.212	1.96	17.7	0.892	1.50	0.0071
Sandy clay loam	0.39	0.101	1.163	4.27	26.2	0.479	1.45*	0.0019
Loam	0.43	0.0776	1.051	3.07	38.9	0.56	1.40	0.0052
Silt loam	0.45	0.067	0.3359	3.80	70.3	0.414	1.30	0.0058
Silt	0.456	0.0352	0.176	3.21	68.1	0.38	1.3*	0.0025*
Clay loam	0.410	0.0954	0.357	5.97	88.0	0.318	1.35	0.001
Silty clay loam	0.430	0.088	0.0554	7.13	132	0.230	1.35*	0.0013
Sandy clay	0.380	0.0993	0.1278	6.90	50.7	0.275	1.4*	0.0038
Silty clay	0.360	0.0706	0.0079	10.2	340	0.157	1.3*	0.002*
Clay	0.380	0.0685	0.1314	14.1	353	0.127	1.25	0.0038

Table 2.6. Typical values of seepage/leakage rate from canals of different types of lining		
Sr. No.	**Type of canal lining**	**Seepage/leakage rate $m^3/m^2/day$**
1	Clay	0.061119
2	Silt clay loam	0.09127
3	Clay loam	0.12183
4	Silt loam	0.182948
5	Loam	0.304778
6	Fine sandy loam	0.380973
7	Sandy loam	0.457167
8	Sand	0.586739
9	Plastic	0.077824
10	Concrete	0.066823
11	Gunite (spray applied concrete)	0.020373
12	Compacted earth	0.01365
13	One layer brick	0.05
14	Double layer brick	0.03

Note These values are derived from the following sources:
1. Texas Board of Water Engineers (1946)
2. Fipps and Pope (2004)
3. USBR (1963)
4. Nofziger (1979)

2.4.2 Contaminant transport model for saturated flow

The contaminant transport model (CTM) for saturated flow consists of the following two parts:

1. Modelling of seepage from open drains/canals (unlined) and surface foul water bodies
2. Modelling of contaminant transport.

2.4.2.1 Modelling of seepage from open drains/canals (unlined) and surface foul water bodies

The seepage of water into the soil through open drains/canals (unlined) and surface foul water bodies is considered as saturated flow. Hence the water flux is estimated using Darcy's law. The following procedure is used for simulating water flow from these pollution sources.

The seepage flow nets with different stream functions and potential functions are calculated using the equation (2.26).

$$\begin{aligned} \frac{\varphi}{k} - z &= Ae^{\frac{\varphi}{\alpha}} \cos(\frac{\Psi}{a}) \\ \frac{\Psi}{k} + x &= Ae^{\frac{\varphi}{a}} \sin(\frac{\Psi}{a}) \end{aligned} \tag{2.26}$$

where

α - a parameter
A - a real constant
k - permeability of soil
φ - potential function
ψ - stream function
w - potential complex
p - spatial complex.

Equation (2.15), which is developed for estimation of contaminant concentration for steady state flow, is a one-dimensional problem with the relationship of concentration (C) and depth (z). But another parameter, pore velocity, is a function of both depth (z) and distance (x), because the streamline and equipotential line is curved as shown in Figure 2.17. Therefore, equation (2.15) needs to be extended to a two-dimensional problem for accurate calculation. Therefore the flow region is divided into many flow pathways, consisting of streamlines, and then each flow pathway is subdivided into elements by equipotential lines. Thus the plane flow region is made into elements of flow lines and equipotential lines of curvilinear cells, as shown in Figure 2.17. The figure also illustrates that as depth increases, the streamlines approach the vertical asymptote, and equipotential lines approach straight lines.

In each cell, i, the velocity v_i is estimated by equation (2.29) obtained by combining equation (2.27) for velocity potential and equation (2.28), Darcy's law.

Velocity potential φ is defined as

$$\varphi = -K_s h + C \tag{2.27}$$

Darcy's law of could be written as

$$v = -K_s \frac{dh}{ds} \tag{2.28}$$

$$\nu_i = \frac{d\varphi_i}{ds_i} \tag{2.29}$$

$$v_i = \frac{\varphi_i - \varphi_{i-1}}{\frac{s_{ri} + s_{li}}{2}}$$

Figure 2.18 illustrates the seepage process in a single flow pathway. The distance Sr_i and Sl_i of the element is calculated using the coordinate of flow pathway. The equation (2.29) is solved in a loop from $i=0$ (the flow at the bottom of the ditch) to $i=n$ where n is the number of elements in the flow pathway. Equation (2.29) yields the flow at each element by knowing the change in flow along the selected flow pathway. The process in repeated for each flow pathway across the flow net, to yield the flow profile across the entire seepage envelope.

2.4.2.2 Modelling of contaminant transport

The relative concentration (C / C_0) distribution in all the flow nets is then estimated by using equation (2.15); parts of these are shown in the bottom and right of Figure 2.19. The contaminant concentration is then estimated at the desired depth. Using the calculated flow profile, we can find the concentration profile at the bottom and centre of the flow region. Figure 2.19 shows the change in relative concentration in both the x and y directions.

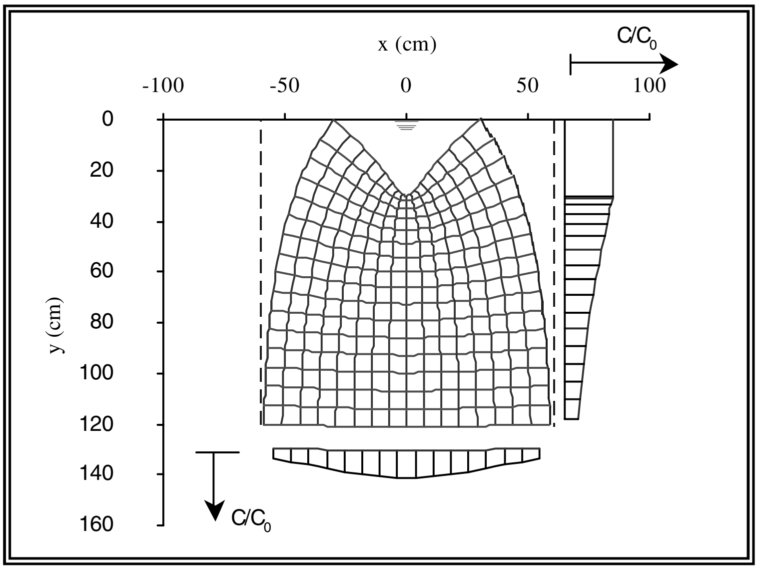

Figure 2.17. Flow net for the seepage beneath the unlined drain/canal and surface foul water bodies

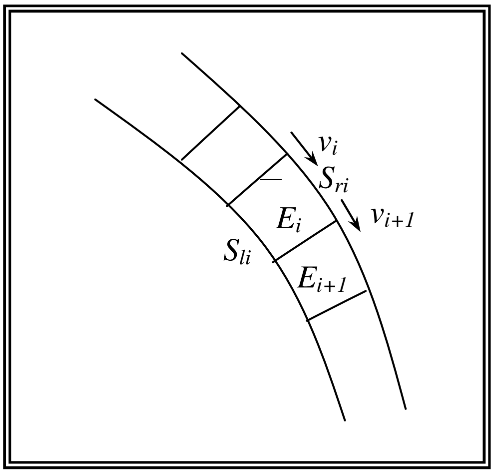

Figure 2.18. A flow channel of flow net

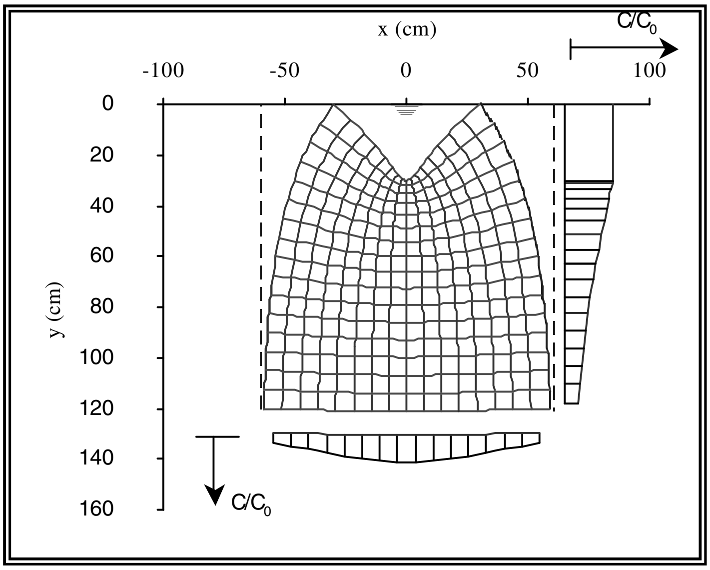

Figure 2.19. The concentration profile

2.5 Contaminant Loading

The output from contaminant zone model (Section 2.3) is the length of water distribution pipe in a contaminant zone calculated with the coordinates of upstream and downstream intersection points of the segment that represents the intersection of water distribution pipes with the contaminant zone (SPCZ). The concentration of contaminant at these intersection points can be obtained from the contaminant seepage model (Section 2.4). The concentration along SPCZ is assumed as the average of concentration of the upstream and downstream intersection points, as shown in Figure 2.20.

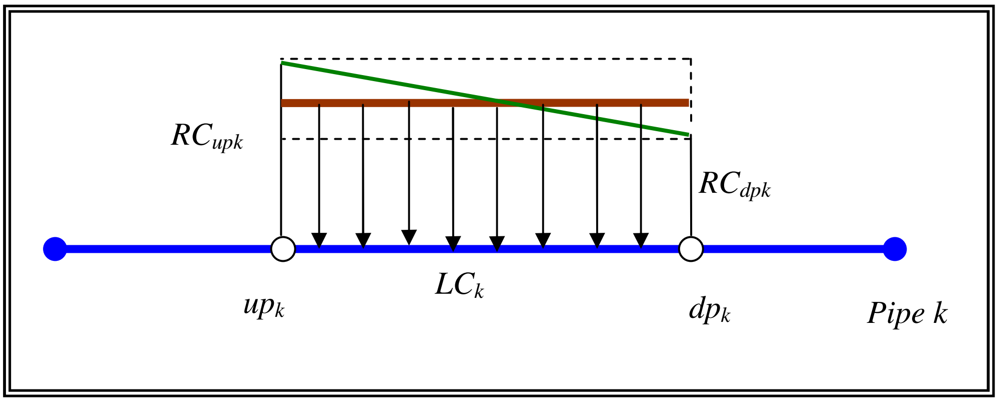

Figure 2.20. Contaminant loading along SPCZ

The contaminant seepage model simulates the contaminant concentration at upstream and downstream ends of SPCZ. The contaminant concentration along SPCZ is then determined by taking the average of the concentrations at its upstream and downstream ends (equation 2.30):

$$CC_k = \frac{RC_{upk} + RC_{dpk}}{2} \qquad k = 1, 2, \ldots NC \qquad (2.30)$$

where
CC_k - average contaminant concentration along SPCZ of pipe k (mg/l)
$RCup_k$ - contaminant concentration at upstream intersection point (mg/l)
$RCdp_k$ - contaminant concentration at downstream intersection point of pipe k (mg/l)

$RCup_k$ and $RCdp_k$ are estimated by equation (2.22) by knowing the value of contaminant concentration at source (C_0).

The contaminant load is then estimated by equation (2.30) that combines the section of pipe in the contaminant zone (SPCZ) and contaminant concentration along this section.

$$CL_k = LC_k \times \pi \times r_k \times CC_k \qquad k=1, 2, \ldots NC \qquad (2.31)$$

where
CL_k - estimation of contaminant load for pipe k (mg/m)
r_k - radius of pipe k (mm)

2.6 Implementation of the Contaminant Ingress Model in IRA-WDS

The IRA-WDS software has a default database for the characteristics of different soils. These default values are given in Table 2.5. These values of soil characteristics can be used if the soils are known. Alternatively, values of soil characteristics from other sources or measurements can be used. The different soil and contaminant parameters described in this chapter, required for the contaminant seepage model and data presented in Table 2.5, enable the user to decide upon the values of these parameters and complete Tables 2.2 and 2.4. The information provided in these tables is required for the contaminant ingress model of IRA-WDS for predicting the variable concentration of contaminants within the contaminant zone and obtaining results of the contaminant ingress model (see Chapter 3 of Book 4 (IRA-WDS user manual)).

Three examples are presented in this book (one example in this section and two in Appendix A) to illustrate the modelling of contaminant seepage from the pollution sources of sewer pipe, open drain and surface foul water body. Each example is presented in two parts: the model input data and the output in the form of a relative contaminant concentration profile along depth.

Figure 2.21 shows a water distribution pipe that lies below a leaky sewer pipe. The leaky sewer pipe develops a contaminant zone in which contaminant will seep down to the water distribution pipe. The contaminant concentration is modelled using the unsaturated flow model (Section 2.4.1). The properties of sewer pipe, soil and contaminant are given in Table 2.7. This shows the input for the contaminant ingress model. The profile of relative concentration is presented in Table 2.8 and Figure 2.22. It should be noted that the contaminant concentration at the upstream and downstream ends of the segment of water distribution pipe that lies in the contaminant zone can be estimated from these contaminant concentration profiles by knowing the location of the water distribution pipe in relation to pollution source.

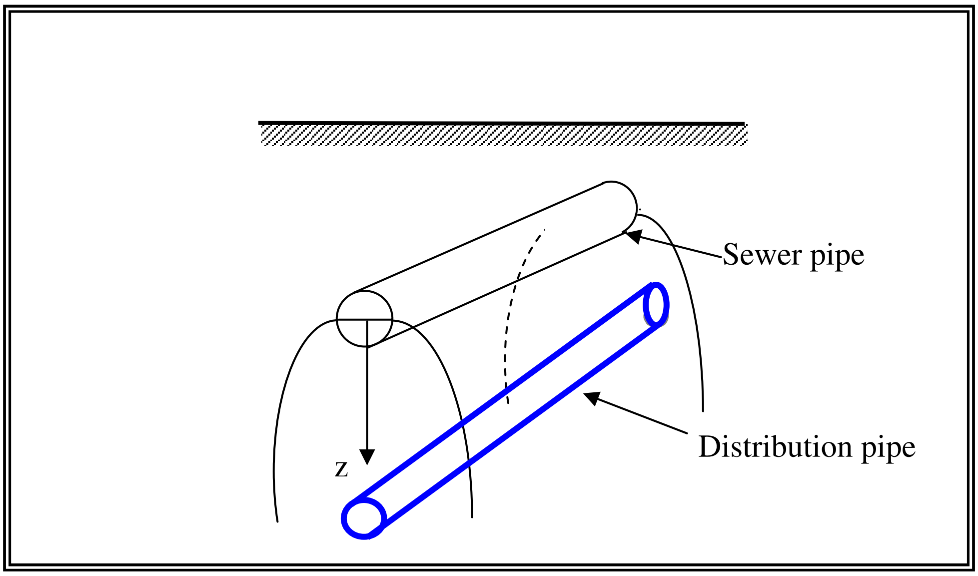

Figure 2.21. Contaminant seepage from leaky sewer pipe

Table 2.7. Example to demonstrate the estimation of contaminant concentration at water distribution pipe due to sewer pipe			
Sewer pipe			
Property	**Symbol**	**Value**	**Units**
Material	Concrete		
Leakage rate	r	0.066823	*m/day*
Diameter	h_s	10	*cm*
Soil properties			
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 properties			
Liquid phase decay	λ	2.22×10^{-4}	*/hour*
Diffusion coefficient	D_p	0.72	cm^2/day
Procedure used			
See Sections 2.3.1.2 and 2.4.1			
Results			
See Table 2.8 and Figure 2.22 for profile of relative contaminant concentration			

Table 2.8. Relative contaminant concentration in soil due to sewer pipe (for data presented in Table 2.7)	
Depth z (m)	**Relative concentration C/C_0**
0.0	1.000
0.5	0.938
1.0	0.880
1.5	0.826
2.0	0.775
2.5	0.727
3.0	0.682
3.5	0.639
4.0	0.600
4.5	0.563
5.0	0.528
5.5	0.495
6.0	0.465
6.5	0.436
7.0	0.409
7.5	0.384
8.0	0.360
8.5	0.338
9.0	0.317
9.5	0.297
10.0	0.279

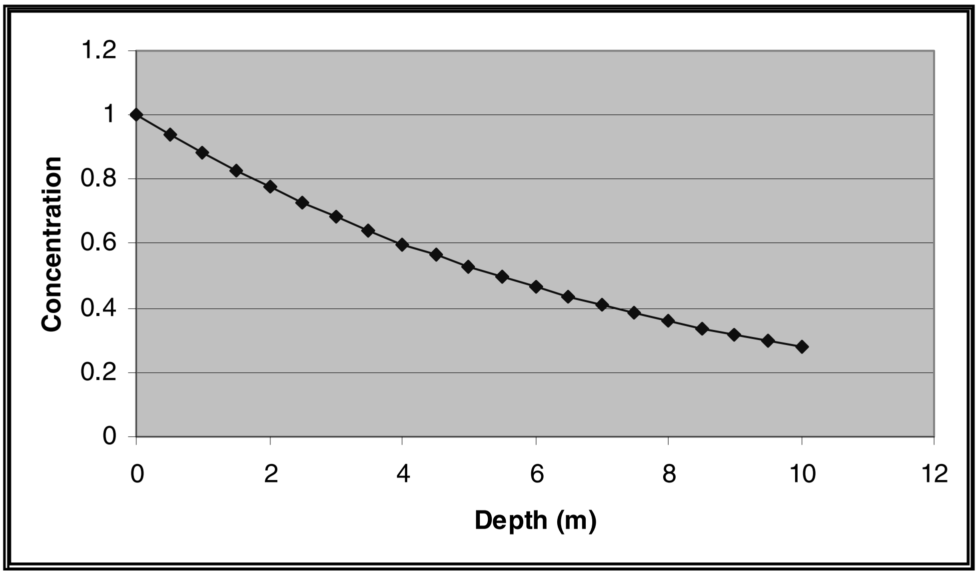

Figure 2.22. Relative contaminant concentration in soil due to sewer pipe (for data presented in Table 2.7)

2.7 Conclusions

At this stage of the chapter the reader should be able to complete Tables 2.1 to 2.4 for their particular area of study. These tables form the basis of the input data for the contaminant ingress model part of IRA-WDS. The data contained in Tables 2.1 to 2.4 are entered into IRA-WDS by means of the several input dialog windows within the software. Figure 2.23 shows an example of these input dialog windows and more details of this can be found in Chapter 3 of Book 4 (IRA-WDS user manual).

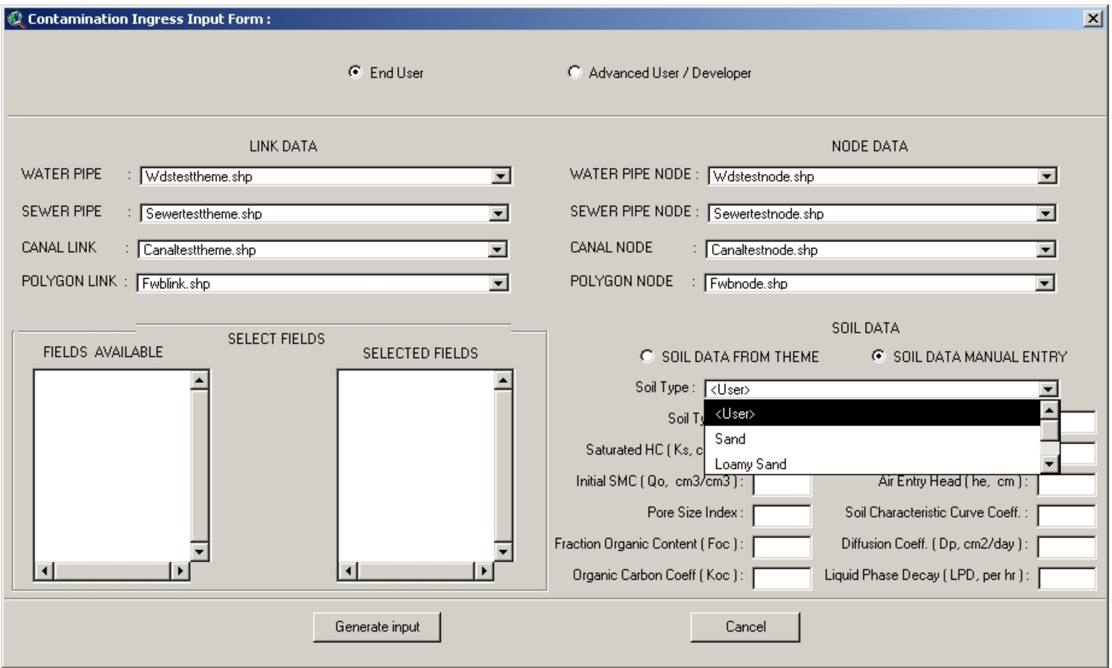

Figure 2.23. Example of input dialog window used for contaminant ingress model of IRA-WDS

An example of the output from a successful run of the contaminant ingress model part of IRA-WDS is shown in Figure 2.24. This output is combined with the outputs of the pipe condition assessment model part of IRA-WDS (discussed in Chapter 3), to give potential contaminant loads from pollution sources into the water supply pipes.

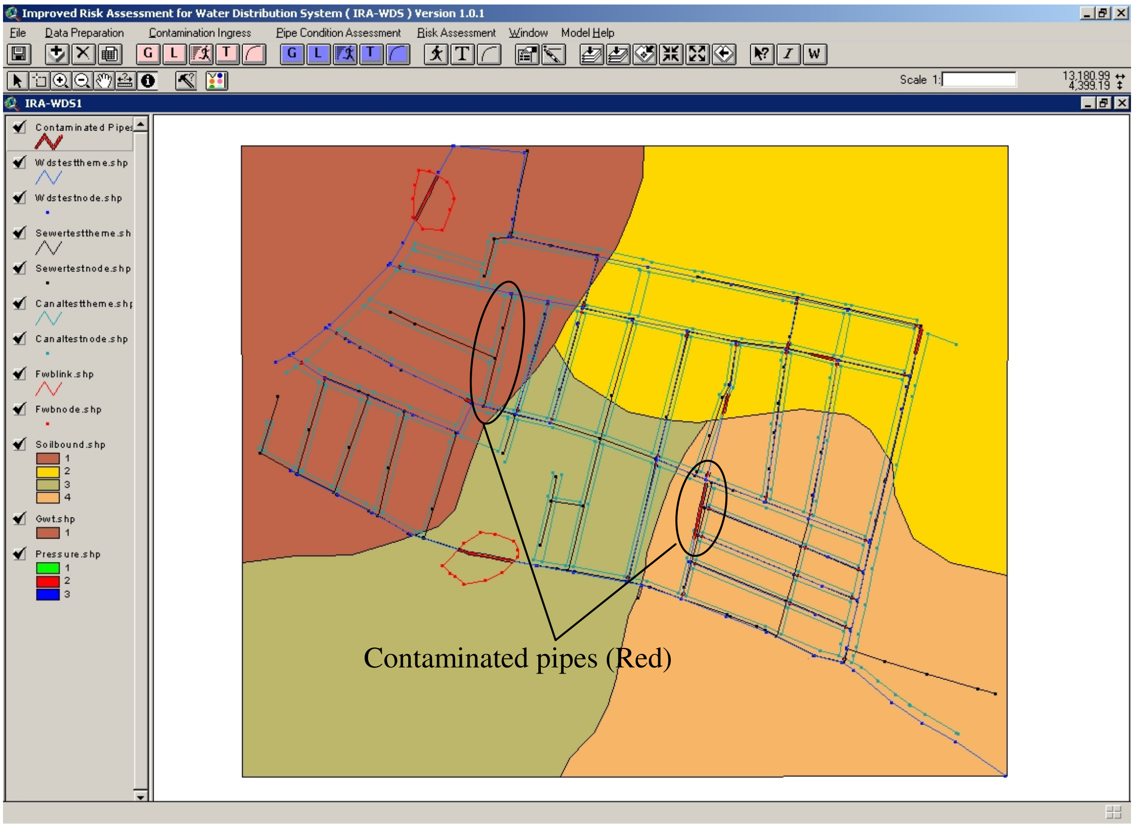

Figure 2.24. An example of the output from a successful run of the contaminant ingress model part of IRA-WDS