DRINKING WATER SOURCE PROTECTION
ACT FOR CLEAN WATER

Technical Bulletin: Delineation of Intake Protection Zone 3 Using the Event Based Approach (EBA)

Date: July 2009

1- Introduction

The Clean Water Act requires the Source Protection Committee to prepare an Assessment Report for each source protection area they represent, in accordance with the regulations, the Director's Technical Rules and the approved terms of reference for that source protection area.

As part of the Assessment Report, committees must identify four types of vulnerable areas within each Source Protection Area. These include wellhead protection areas (WHPAs), intake protection zones (IPZs), highly vulnerable aquifers (HVAs), and significant groundwater recharge areas (SGRAs). Once these areas are delineated, the rules require that vulnerability scores be assigned within these areas.

This technical bulletin provides guidance to Source Protection Committees on the process of identifying and delineating Intake Protection Zone 3 (IPZ-3) using the Event Based Approach (EBA) under the Technical Rules for the Assessment Report – Part VI.5 rules 68 and 69. The event based approach can be used for Type A and B intakes located at Great Lakes and Connecting Channels, and for Type C and D intakes located on Lake Nipissing, Lake Simcoe, Lake St. Clair and the Ottawa River. Requirements for assigning vulnerability scores to the IPZs are set out in Part VIII of the Technical Rules and are not addressed in this bulletin.

The Technical Rules allow the Source Protection Committees to use a number of methods to identify and delineate the IPZ-3 as set out below. This Technical Bulletin references that Director's Technical Rules published by the Ministry of the Environment on December 12, 2008.

Part VI.5 of the Technical Rules states,

68. An area known as IPZ-3 shall be delineated for each type A and type B surface water intake and each type C and type D surface water intake located in Lake Nippising, Lake Simcoe, Lake St. Clair or the Ottawa River, associated with a drinking water system described in rule 58 and shall be composed of the following areas:

> *(1) Subject to rule 69, the area within each surface water body through which, modeling demonstrates, contaminants released during an extreme event may be transported to the intake;*
>
> *(2) where the area delineated in accordance with subrule (1) abuts land,*
>
> *(a) a setback of not more than 120 metres inland along the abutted land measured from the high water mark of the surface water body that encompasses the area where overland flow drains into the surface water body; and*
>
> *(b) the area of the Regulation Limit along the abutted land.*

69. The area delineated in accordance with subrule 68(1) shall not exceed the area within each surface water body that may contribute water to the intake during or as a result of an extreme event.

The first step in the EBA is to delineate an IPZ-3 that includes areas beyond IPZ-1 and IPZ-2, based on extreme event conditions and an understanding of contaminant transport to the intake. The EBA then allows activities to be identified as a significant drinking water threat if it can be shown through modeling that a release of a specific contaminant from an activity would result in an issue at the intake. The identification of such an activity is governed under rule 130 of the Technical Rules, as follows:

130. An activity listed as a drinking water threat in accordance with rule 118 or 119 is a significant drinking water threat in an IPZ-3 delineated in accordance with rule 68 at the location where the activity is carried on if modeling demonstrates that a release of a chemical parameter or pathogen from the activity would be transported through the surface water intake protection zone to the intake and result in the deterioration of the water for use as a source of drinking water for the intake.

2- IPZ-3 Delineation Options

Figure 1 shows a flowchart with three options to delineate IPZ-3 using the EBA. The SPC may decide which option is appropriate for the drinking water system in question based on the data and information available on the water bodies and any activity(ies) they might be concerned about. The three options are discussed in more detail in sections 2.1 to 2.3.

Two relevant criteria in delineating IPZ-3 (EBA) for all three options are the flood event discharge and time of travel.

The flood event discharge can be estimated by considering an extreme wind storm event or 100 year flood event or snowmelt event during spring times (freshet) or any combination that in the opinion of the SPC represents the 100 year combined probability of an extreme event. The Technical Rules also allow less frequent storm events to be considered.

Time of travel (ToT) is a key issue in determining the IPZ-3 boundary. Based on the understanding of the flood event hydrograph (flood wave duration) and the stream-river system responses to flood events, a time of travel can be estimated with one of the following alternatives:

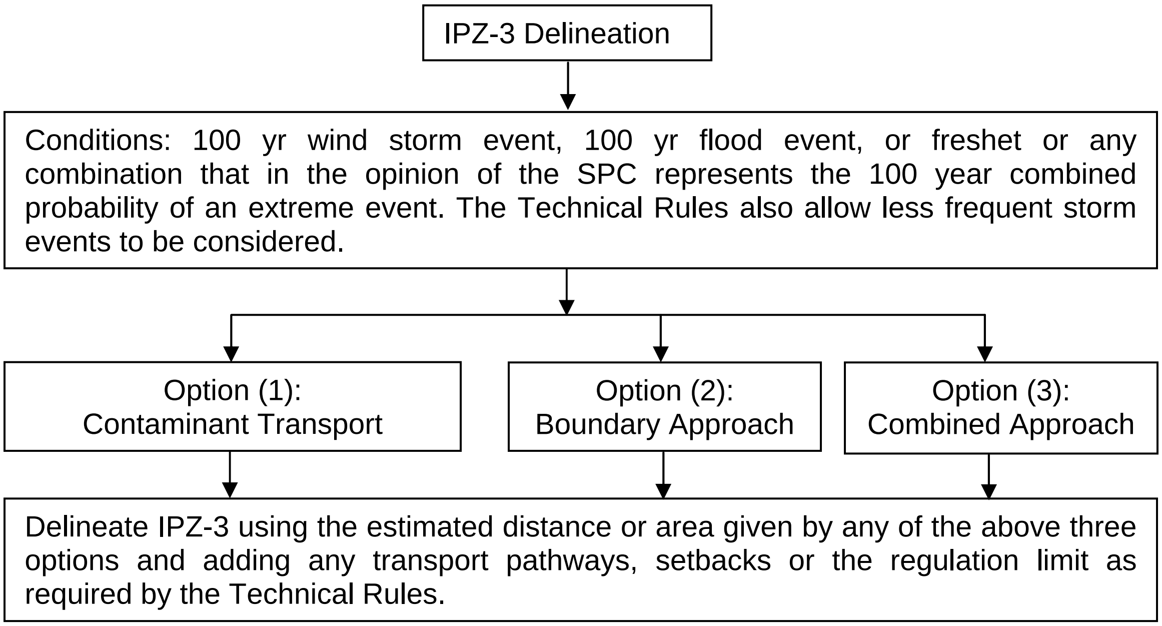


Fig. 1: Flowchart on options used for delineating IPZ-3.

Alternative 1: *Unit Hydrograph*

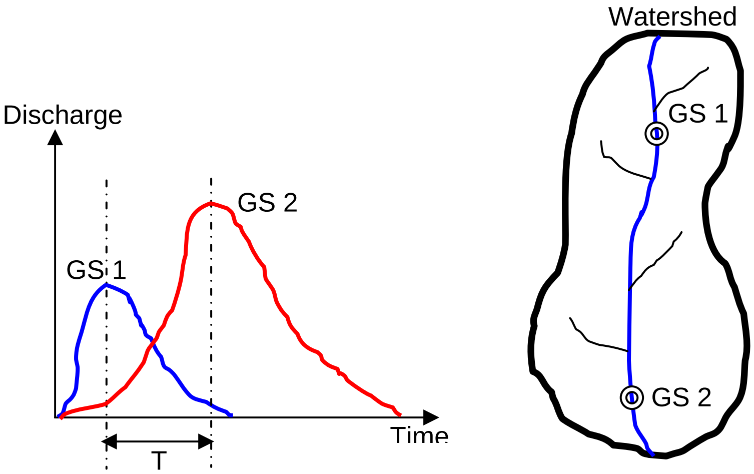


Fig.2: Illustration of unit hydrographs related to time of travel (ToT).

This method can be applied if the unit hydrographs are known at particular gauging stations. In figure 2, assume there are two gauging stations GS1 and GS2 where the unit flood hydrograph is measured or calculated at those stations. The time difference between the flood peaks, **T**, may represent the time of travel for the distance between the two gauging stations. The time of travel (ToT) from an activity that is being modeled to the intake can be interpolated or extrapolated depending on its distance to either of the gauging stations. For example, assume an activity is located at a certain distance between GS1 and GS2; the time of travel for that activity can be obtained by interpolating the time of travel between the two stations and the distance between the activity and the two stations.

The same concept can be applied if an activity is located outside the distance between GS1 and GS2 but in this case the ToT is obtained by extrapolation. The unit hydrograph method assumes that the flow is uniform and under steady state conditions along the entire stream/river reach, which is not always the case. The estimated time of travel depends on the accuracy of the data and an understanding of the input, output and storage volumes of water within that stream / river system.

Alternative 2: Time of Concentration

If the unit hydrographs mentioned in method (1) are not available, the time of concentration equation based the Soil Conservation Service (SCS) lag formula can be used, equation 1. The time of concentration, $\mathbf{t_c}$, is defined as the amount of time for the entire watershed to contribute to the outflow or the amount of time for the water to reach the outlet from the furthest point from the outlet. The $\mathbf{t_c}$ formula is a function of the watershed length, **L**, the watershed slope, **Sw**, and the curve number, **CN**. The length **L** can be estimated from the data set related to the watershed and it is the longest hydraulic path in the watershed. The slop, **Sw**, is the average slope of the watershed which equals to elevation difference between point **A** and point **B** over the watershed length, **L**, see figure 3.

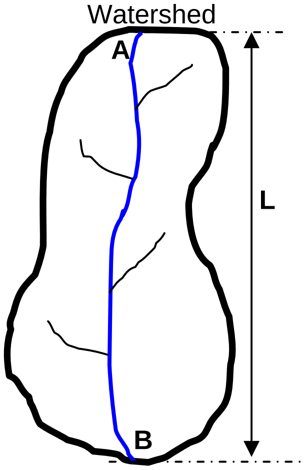


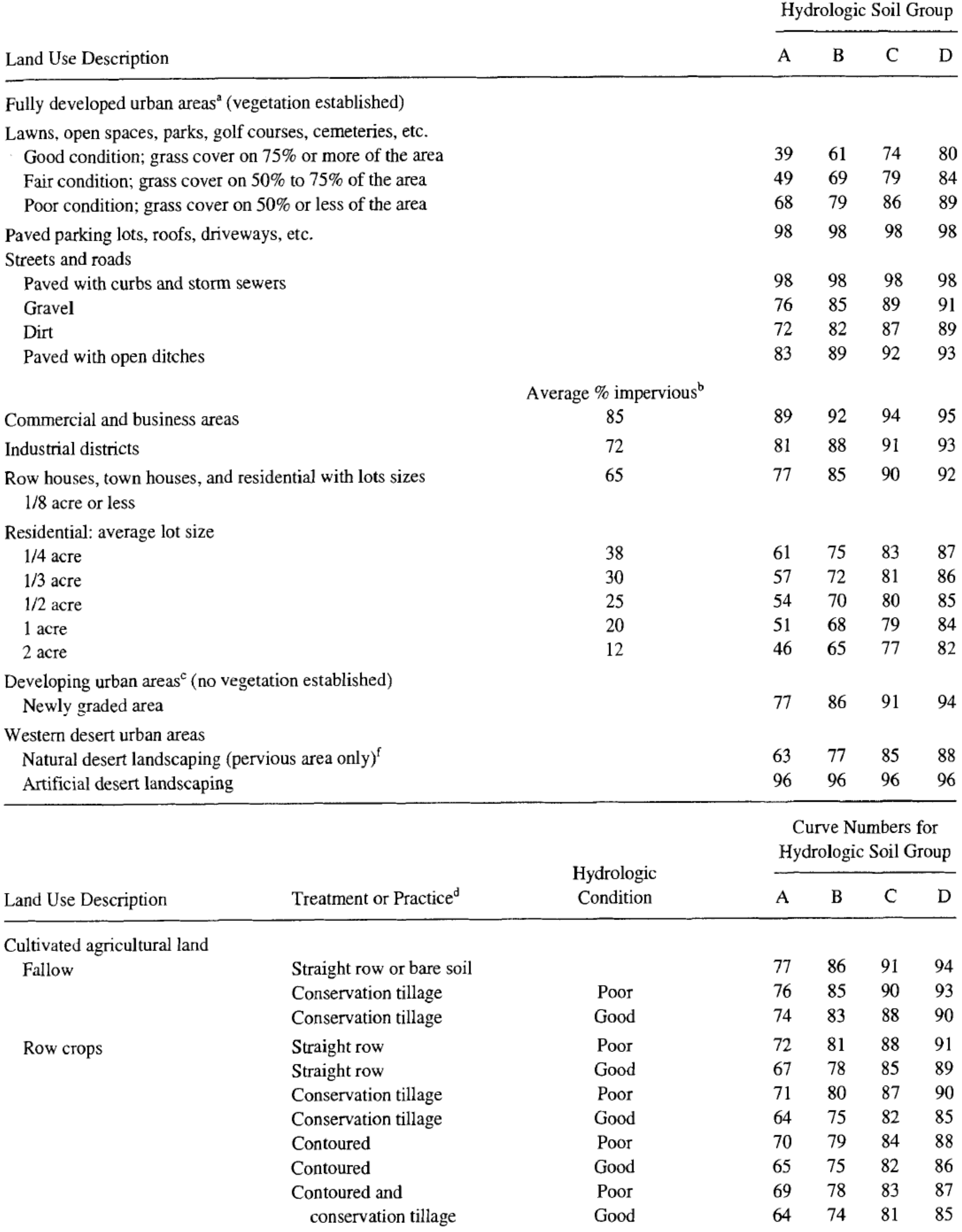
Fig.3: Illustration of a watershed with the longest hydraulic path.

$$t_c = 0.00526 L^{0.8} \left(\frac{1000}{CN} - 9 \right)^{0.7} S_w^{-0.5} \quad \text{Eq.1}$$

Where $\mathbf{t_c}$ is the time of concentration (min), which is equivalent to the time of travel, **L** is the watershed length (ft), **Sw** is the average watershed slope (ft/ft) and **CN** is the curve number (-).

The curve number, **CN**, is the parameter that represents the potential maximum retention of rainfall. The Curve Number depends on the soil type (Group A, B, C, or D), land use and moisture conditions. Examples of suggested Curve Numbers for use with SCS hydrology is given in Table 1. However, users can calculate an appropriate value for **CN** based on the watershed characterisation. For additional information, see Urban Hydrology for Small Watersheds, Technical Release 55, United States Department of Agriculture, June 1986 and McCuen, 1998.

Table 1: Curve Numbers for different types of Hydrologic Soil Group (McCuen, 1998).



Land Use Description	Average % impervious[b]	A	B	C	D
		Hydrologic Soil Group			
Fully developed urban areas[a] (vegetation established)					
Lawns, open spaces, parks, golf courses, cemeteries, etc.					
Good condition; grass cover on 75% or more of the area		39	61	74	80
Fair condition; grass cover on 50% to 75% of the area		49	69	79	84
Poor condition; grass cover on 50% or less of the area		68	79	86	89
Paved parking lots, roofs, driveways, etc.		98	98	98	98
Streets and roads					
Paved with curbs and storm sewers		98	98	98	98
Gravel		76	85	89	91
Dirt		72	82	87	89
Paved with open ditches		83	89	92	93
Commercial and business areas	85	89	92	94	95
Industrial districts	72	81	88	91	93
Row houses, town houses, and residential with lots sizes 1/8 acre or less	65	77	85	90	92
Residential: average lot size					
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acre	12	46	65	77	82
Developing urban areas[c] (no vegetation established)					
Newly graded area		77	86	91	94
Western desert urban areas					
Natural desert landscaping (pervious area only)[f]		63	77	85	88
Artificial desert landscaping		96	96	96	96

Land Use Description	Treatment or Practice[d]	Hydrologic Condition	A	B	C	D
			Curve Numbers for Hydrologic Soil Group			
Cultivated agricultural land						
Fallow	Straight row or bare soil		77	86	91	94
	Conservation tillage	Poor	76	85	90	93
	Conservation tillage	Good	74	83	88	90
Row crops	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Conservation tillage	Poor	71	80	87	90
	Conservation tillage	Good	64	75	82	85
	Contoured	Poor	70	79	84	88
	Contoured	Good	65	75	82	86
	Contoured and	Poor	69	78	83	87
	conservation tillage	Good	64	74	81	85

The time of concentration formula is an empirical formula that is based on a number of assumptions and therefore, will, in most cases, produce a smaller IPZ-3 than if more advanced modelling was available. However, this method is a good starting method to estimate the time of travel within the watershed in the absence of an advanced numerical model. The formula is intended for use on watersheds where overland flow dominates and was developed for non-urban watersheds of 4000 acres or less. This does not mean it can not be used to determine a time of travel in a more urban watershed, but does mean that the numbers may be lower than expected in these types of watershed. Time of travel calculated using this formula is based on the following assumptions: average slope of the watershed, one type of land use and soil and an approximated watershed length.

If neither the alternative (1) nor the alternative (2) can be used, the time of travel (ToT) for a watershed can be the same time of travel of another watershed if both watersheds have similar characterisations.

2.1 Option 1: Contaminant Transport Approach:

If the SPC is concerned about specific activities that are being carried out upstream of the surface water intake, this approach can be used to determine the transport of contaminant(s) to the intake. If the contaminant reaches the intake, the IPZ-3 boundary can be delineated including the area of that activity. With this approach, the SPC would need to determine a concentration threshold to decide whether a contaminant released at the location of the activity in question has reached the intake or not. If not, i.e. the SPC decides the concentration of the contaminant is too low for it to be considered reaching the intake, then the location of that activity may not be included in the delineation of an IPZ-3. An understanding of contaminant transport from a number of activities can then be used to determine the extent of the IPZ-3.

As a second step, if the contaminant reaches the intake and results in the deterioration of the water quality (as per Rule 130), then this activity would be identified as a significant drinking water threat. The IPZ-3 delineation will include the contributing area of the activity(ies) that cause(s) an issue at the surface water intake.

Methods that can be used to delineate IPZ-3:
a- Numerical models (1D, 2D or 3D)
b- Analytical approach (explained below in section 3.4). This approach does not need a time of travel to be determined.

<u>Required inputs</u> to apply option (1): flood discharge, estimated time of travel, and mass of the contaminant, either continuous or instant. The estimated TOT may be used as the simulation time if a numerical model is used.

2.2 Option 2: Boundary Approach:

This option can be used if in the opinion of the SPC there are no activities of concern upstream of the intake. This approach determines the boundary of IPZ-3 within the water body without analysing specific activity(ies). This approach requires that a time of travel (ToT) is determined as mentioned above. The assumption would be that whatever is released within the chosen ToT would reach the intake (under specific storm event conditions).

Methods that can be used to delineate IPZ-3:
a- Particle Tracking
b- Numerical Model (1D)
c- Manning equation

Required inputs to apply the option (2): flood discharge and estimated time of travel, which may be used as the simulation time if a numerical model is used.

2.3 Option 3: Combined Approach:
This approach is a combination of option (1) and (2). As a first step, option (2) is used to delineate the IPZ-3. As a second step, if the SPC is concerned about specific activities that are located inside or outside the IPZ-3, option (1) would then be used to determine whether the IPZ-3 needs to be expanded or reduced, by determining whether the contaminant from a specific activity reaches the intake or not. As in option 1, the SPC would need to determine a concentration threshold to decide whether a contaminant has reached the intake or not. If yes, modify the delineated IPZ-3 to include (or exclude) the contributing area of that activity. As a third step, the SPC can then determine whether the activity causes an issue or not (as per Rule 130).

Methods that can be used to delineate IPZ-3 in option (3) are a combination of methods mentioned in option (1) and option (2).

3- Supporting Methods

There are several physical processes controlling the transport of contaminants in river systems: mixing; molecular diffusion; turbulent diffusion; dispersion; advection; dilution (decay function); and sorption. The mixing process is affected by the spatial variation of velocity on the macroscopic scale according to the Fick’s law 1855.

If an activity discharges into a stream, the initial mixing of a contaminant is determined by the momentum and buoyancy forces of the discharge. As the contaminant is diluted, those forces disappear and the transport of the contaminant is dominated by ambient water velocity variation in the stream. Then, the contaminant plume is spread along the stream by dispersion and advection. Typical flow velocities of rivers range from 0.1 m/s to 1.5 m/s corresponding to channel slopes of 0.02% to 1% (Chin, 2006).

Numerical models are one of the tools that can be used to delineate the IPZ-3. Simple analytical approaches or particle tracking are other options to estimate the concentration of contaminants in the water bodies. Particle tracking is one of the more recently developed tools that provide information on the distance from an intake that particles can be transported through by knowing the flow velocities and concentration of the particles. This document presents an overview of the numerical models but focuses more on an analytical approach that can help users to calculate the distance contaminants are transported in a water system.

3.1 Numerical Codes

Several numerical codes are now available to simulate water quality in rivers and streams. Most codes typically provide numerical solutions to the advection-dispersion equation or some other forms of the law of mass conservation. The numerical solutions are produced at discrete locations and times for complex boundary conditions, and spatially and temporally disturbed contaminant transport. The numerical codes used in practical engineering are mostly 1D and 2D. 3D numerical codes are sometimes used but generally more costly. Numerical codes are commonly used to facilitate the analysis of fate and transport process of contaminants in river systems and include QUAL2E, HSPS, WASP6, SED2D, MIKE family, DELFT family, TELEMAC system, and HEC-6. It is up to the user to select the appropriate numerical model to simulate the contaminant transport based on the capabilities and limitations of each model and the local condition.

3.2 Particle Tracking Method

Particle tracking is a technique that is linked to hydrodynamic numerical models. The particle tracking method describes the effects of molecular and turbulent diffusion on the dispersion of constituents with time and can determine path lines in spatially variable parameter domains. When calculations are computed in reverse time, it is called Reverse Particle Tracking (RPT) and when computed in forward time it is call Forward Particle Tracking (FRT). The particle tracking method identifies an area from points of withdrawal that are likely to contribute flow to the intake within a specific time period. To use the particle tracking method, the location of an intake should be determined in both x and y directions if two-dimensional approach is used and in x, y and z directions if a three-dimensional approach is used. The number of hypothetical particles for tracking analyses should be specified as well as the time of travel (ToT) to determine the distance of the traveling particles. The diffusion rate of particles is controlled by flow velocities and longitudinal and transverse diffusions. This method determines the distance traveled in the water body, and as a second step the transport pathways, setbacks or regulation limit need to be added to delineate the IPZ-3.

3.3 Manning Equation

The Manning Equation is the most commonly used equation to analyze open channel flows. It is a semi-empirical equation for simulating water flows in channels and culverts where the water is open to the atmosphere, i.e. not flowing under pressure. The distance from the intake can be determined as follows:

$$\mathbf{D = V.T} \qquad \mathbf{, V = \frac{1}{n} R^{2/3} S^{1/2}} \ \textbf{(Part a)} \quad \textbf{or} \quad \mathbf{V = \frac{Q}{A}} \ \textbf{(Part b)} \quad \text{Eq. 2}$$

Where **D** is the distance from an intake in the water body (m), **T** is the estimated time of travel as explained (s), **n** is the Manning coefficient (friction coefficient), which varies from 0.001 to 0.03 based on type of stream bed material and flow, **R** is the hydraulic radius (m) which in most cases is equivalent to the water depth of river, and **S** is the energy slope which is equivalent to the stream slope.

If the inflow discharge of a flood event is known, then the flow velocity can be determined through equation 2, part b. If the water depth at the flood event is known but not the discharge, then equation 1, part a can be used to calculate the flow velocity.

Then the distance, **D**, from the surface water intake can be determined. This approach determines the distance traveled in the water body, and as a second step the transport pathways, setbacks or regulation limit need to be added to delineate the IPZ-3.

3.4 Analytical Approach

The analytical approach provides a mechanism that can be used if the contaminant mass and type entering a water body are known. The analytical approach can be used for point source discharges such as industrial or municipal discharges, stormwater discharges, or spills, and considers the physical properties of the contaminants only. Spills in rivers or streams can be a result of major collisions on transportation routes or failures at large storage sites. Spills can be thought of as large masses of contaminants that are released in a very short period of time.

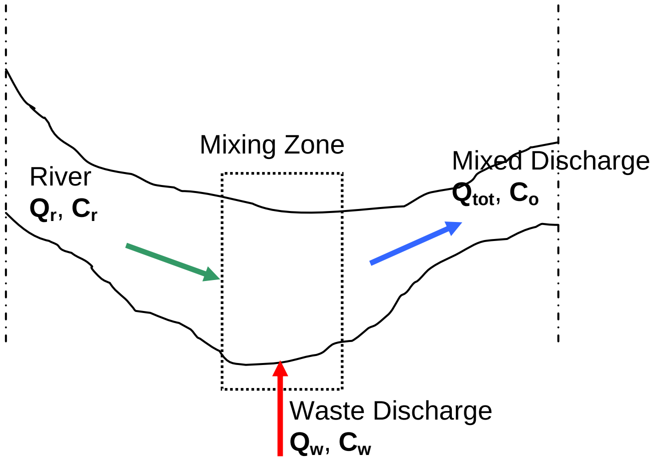
Non-point sources of contaminants, such as runoff from rural or agricultural areas and urban runoff are not considered in this approach. The main goal is to determine the concentration of a contaminant at the surface water intake according to option (1). There are two concepts that can be used to calculate the concentration of a contaminant: 1) without dispersion and 2) with dispersion.

3.4.1 No dispersion

If full mixing, decay and no dispersion are considered, equation 4 calculates the concentration at a certain distance. To do that, first determine the mean concentration of a contaminant after mixing; see figure 4, with the water body of the stream through equation 3:

$$\mathbf{Q_r C_r + Q_w C_w = Q_{tot} C_o \Rightarrow C_o = \frac{Q_r C_r + Q_w C_w}{Q_r + Q_w}} \quad \text{Eq.3}$$

Fig.4:
Initial mixing of waste discharge with stream discharge.



For simplicity, it can be assumed that the discharge of a contaminant is well mixed across the cross section.

$$\mathbf{C(x,t) = C_o e^{-\lambda \frac{XA}{Q}}} \quad \text{Eq.4}$$

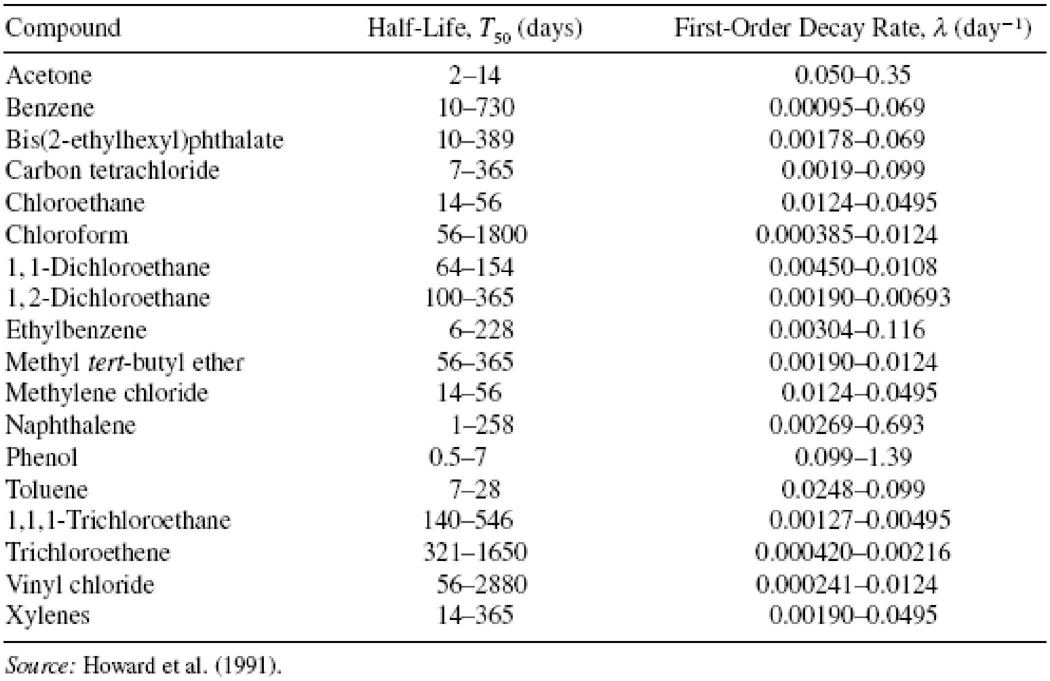
Where **C** is the concentration of the contaminant at the surface water intake (kg/m^3), **X** is the distance between the point discharge from an activity projected on the stream flow and the surface water intake along the stream line (m), λ is the decay (s^{-1}), **A** is the wet cross sectional area of the stream (m^2) and **Q** is the discharge that has been determined to represent the extreme event (m^3/s).

The coefficient, λ, can be expressed in terms of the *half-life*, $\mathbf{T_{50}}$, which is the time required for 50% of the initial mass to decay as follows, equation 5:

$$\mathbf{T_{50}} = \frac{\mathbf{\ln 2}}{\lambda} \quad \text{Eq.5}$$

The half-life time depends on the type of chemical or contaminant released. An example of the half-life time of several organic compounds in soils has been compiled by Howard *et al.,* 1991, see Table 2. Users will need to determine the correct value for the contaminant(s) in question.

Table 2: First order decay rates of selected organic compounds in Soil.



Compound	Half-Life, T_{50} (days)	First-Order Decay Rate, λ (day^{-1})
Acetone	2–14	0.050–0.35
Benzene	10–730	0.00095–0.069
Bis(2-ethylhexyl)phthalate	10–389	0.00178–0.069
Carbon tetrachloride	7–365	0.0019–0.099
Chloroethane	14–56	0.0124–0.0495
Chloroform	56–1800	0.000385–0.0124
1,1-Dichloroethane	64–154	0.00450–0.0108
1,2-Dichloroethane	100–365	0.00190–0.00693
Ethylbenzene	6–228	0.00304–0.116
Methyl *tert*-butyl ether	56–365	0.00190–0.0124
Methylene chloride	14–56	0.0124–0.0495
Naphthalene	1–258	0.00269–0.693
Phenol	0.5–7	0.099–1.39
Toluene	7–28	0.0248–0.099
1,1,1-Trichloroethane	140–546	0.00127–0.00495
Trichloroethene	321–1650	0.000420–0.00216
Vinyl chloride	56–2880	0.000241–0.0124
Xylenes	14–365	0.00190–0.0495

Source: Howard et al. (1991).

3.4.2 With dispersion

If full mixing, decay, longitudinal dispersion, mass of contaminant released are considered, the following can be applied:

The governing equation for longitudinal dispersion that is well mixed over the cross sections of rivers and streams is given in equation 6. This equation considers dispersion and first order decay and assumes that a mass of contaminant, **M**, is instantaneously mixed over the cross section of the stream at time **t=0**.

$$\mathbf{C(x,t)} = \frac{\mathbf{Me^{-\lambda t}}}{\mathbf{A\sqrt{4\pi K_L t}}}\,\mathbf{exp}\left[-\frac{\mathbf{(x-Vt)^2}}{\mathbf{4K_L t}}\right] \quad \text{Eq.6}$$

Where **C** is the concentration of contaminant (kg/m^3) at a point, **M** is the mass of contaminant released from the facility (kg), **V** is the average flow velocity (m/s), $\mathbf{K_L}$ is the longitudinal dispersion (m^2/s), λ is the coefficient that includes dilution (decay); dissolved oxygen concentration; water temperature etc. (s^{-1}), and **A** is the cross-sectional area of the stream (m^2). If the contaminant is assumed to be conservative, then the decay coefficient is equal to zero. The exponential term in equation 6 is equal to 1 if the flow is uniform and steady. This term appears only when the water body is stagnant, i.e., **V=0**.

In equation 6: the flow velocity can be calculated from the determined flow discharge that represents the extreme event discharge, **Q**, and average cross-sectional area of the stream, **A**. The time, **t**, can be calculated by knowing the average flow velocity, **V**, in the stream and the distance between the surface water intake and the projected location of the activity on the stream. The mass of contaminant should be specified based on available data of the activity.

One of the first approaches to estimate the dispersion coefficient in river systems, $\mathbf{K_L}$, is mentioned in Elder 1959 which states that $\mathbf{K_L = 5.93u_*\bar{d}}$ where $\bar{\mathbf{d}}$ is the mean depth of stream (m) and $\mathbf{u_*}$ is the shear velocity of flow (m/s). However, several new approaches have been developed to estimate the $\mathbf{K_L}$, and a summary of them is given in Table 3. To apply the equations shown in Table 3, the stream width must be larger than the mean water depth (**w** >> **d**) where longitudinal dispersion is dominated by transverse variations in the mean velocity and the dispersion caused by vertical variations in mean velocity is relatively small. Typical values of $\mathbf{K_L}$ are 0.05m^2/s to 0.3m^2/s for small streams (Genereux, 1991) and as high as 1000m^2/s for larger rivers (Wanner et al., 1989).

Table 3: Estimates of the Longitudinal Dispersion Coefficient in Rivers, Chin 2006.

Formula	Reference
$\frac{K_L}{\bar{d}u_*} = 0.011\left(\frac{w}{\bar{d}}\right)^2\left(\frac{V}{u_*}\right)^2$	Fischer et al. (1979)
$\frac{K_L}{\bar{d}u_*} = 0.18\left(\frac{w}{\bar{d}}\right)^2\left(\frac{V}{u_*}\right)^{0.5}$	Liu (1977)
$\frac{K_L}{\bar{d}u_*} = 0.6\left(\frac{w}{\bar{d}}\right)^2$	Koussis and Rodríguez-Mirasol (1998)
$\frac{K_L}{\bar{d}u_*} = 2.0\left(\frac{w}{\bar{d}}\right)^{1.5}$	Iwasa and Aya (1991)
$\frac{K_L}{\bar{d}u_*} = 5.915\left(\frac{w}{\bar{d}}\right)^{0.620}\left(\frac{V}{u_*}\right)^{1.428}$	Seo and Cheong (1998)
$\frac{K_L}{\bar{d}u_*} = 0.01875\left[0.145 + \frac{1}{3520}\frac{V}{u_*}\left(\frac{w}{\bar{d}}\right)^{1.38}\right]^{-1}\left(\frac{w}{\bar{d}}\right)^{5/3}\left(\frac{V}{u_*}\right)^2$	Deng et al. (2001)

The shear flow velocity, $\mathbf{u_*}$, in Table 3 can be determined from equation 7,

$$\mathbf{u_*} = \sqrt{\tau_o / \rho}\,;\ \tau_o = \rho \mathbf{gRS};\ \mathbf{R} = \mathbf{A/P} \quad \text{Eq.7}$$

Where τ_o is the mean shear stress on the wetted perimeter (N/m^2), ρ is the water density (kg/m^3), **g** is the gravity (m/s^2), **R** is the hydraulic radius (m), **P** is the wetted perimeter (m), **A** is the cross section (m^2) and **S** is the energy slope (-). To apply this equation the average water depth in the stream should be known. For simplicity, the energy slope can be assumed to be equal to the stream slope. The wetted perimeter, **P**, is the sum of all wet lengths along the cross section, see figure 5:

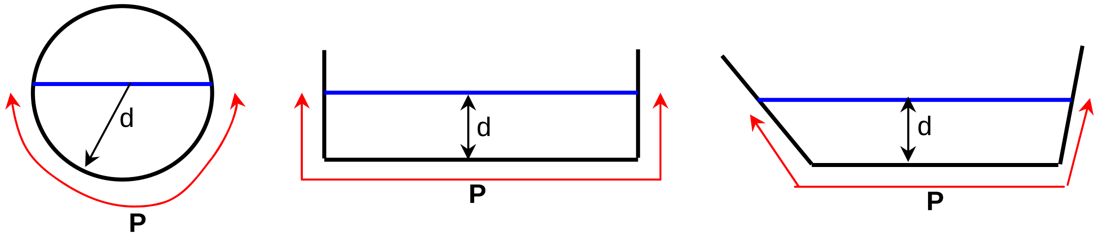


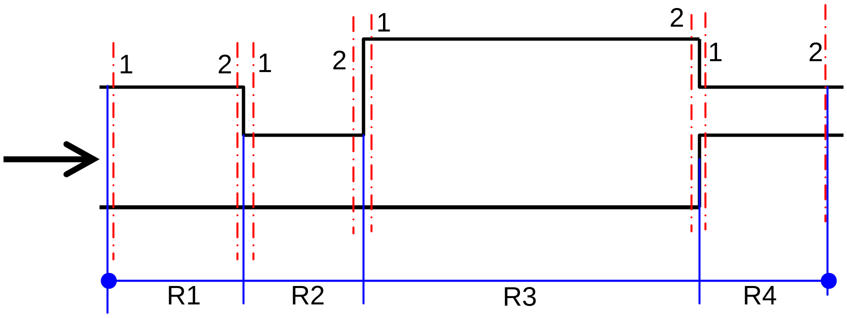
Fig. 5: Illustration of wetted perimeter over different cross sections of streams.

If the cross section of a river or stream changes significantly along the distance, the above approach can be used with some adjustment for each cross-section change as follows: Assume there is a longitudinal section of a river as shown in figure 6, the section consists of four reaches and each reach has a different width and small changes in water depth. Each reach has two cross sections 1 and 2 that represent the beginning and end of each reach.

The goal is to calculate the contaminant concentration at section 2 of reach 4, i.e. C_{2-4}. Continuity is valid which means that the amount of flow through each reach is the same, i.e. no losses in the total volume of water passing. To calculate the contaminant concentration C_{2-4}, follow the steps below.

1- Calculate V_{1-1}, A_{1-1}, C_{1-1}, M is known;
2- Calculate C_{1-2} ;
3- Use $C_{1-2} = C_{2-1}$, then calculate M_{2-2} and C_{2-2} ;
4- Use $C_{2-2} = C_{3-1}$; then calculate C_{3-2} and etc.

Fig. 6: Illustration of varied longitudinal section of river.



River or stream calculations can be done either manually by assuming one or two reaches for the entire stream length or by using a spreadsheet calculation (as shown below) or any other tool that users find appropriate.

4- Examples

This section provides two examples that illustrate the method and analytical solution shown above.

Example 1:
Let us assume a wastewater treatment plant discharges its effluent into a small stream with a water depth of 0.8m and a width of 6.0m and a flow velocity of 0.2m/s, figure 7. The wastewater treatment plant discharges 0.04m^3/s of chemical A with a concentration of 18mg/l into the stream. The concentration of chemical A in the stream upstream of the wastewater treatment plant is 0.22mg/l. Assume no dispersion and full instantaneous mixing with a dilution coefficient of 1.2d^{-1}. What is the concentration of chemical A 3km downstream of the wastewater treatment plant? At what distance downstream from the wastewater treatment plant will the concentration of chemical A in the stream be 0.22mg/l?

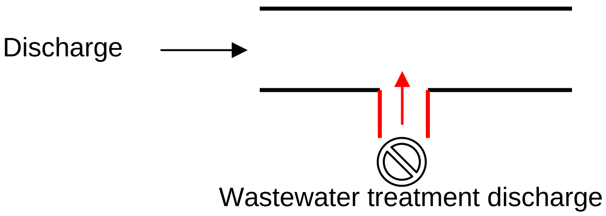


Fig. 7: Illustration of example 1.

Solution:
Q stream = 0.8*6.0*0.2 = 0.96m^3/s

Velocity after the WWT= (0.96+0.04)/(0.8*6) = 0.21m/s

C downstream of the WWT, Eq. 3 = (0.96*0.22 + 0.04*18)/ (0.96+0.04) = 0.9312mg/l

C at 3000 m, Eq.5 = $0.9312 * e^{(-[1.2*3000/(3600*24*0.21)]} = 0.7636$mg/l

X at C=0.22 mg/l, Eq.5 => $0.22 = 0.9312 * e^{(-[1.2*t/(3600*24)]} \rightarrow t = 149874.3$s, V=0.21m/s

Then X= 21,706m from the discharge position.

Example 2:
Let us assume an intake as shown in figure 8. In this figure, the distance of the boundaries of IPZ-1, 2, and 3 from the intake is $\mathbf{D_1}$, $\mathbf{D_2}$, and $\mathbf{D_3}$, respectively and the flow direction is from left to right.

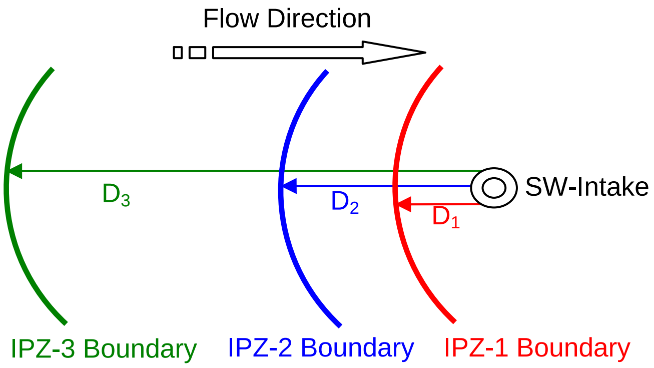


Fig. 8: Illustration of intake protection zone distances, example 2.

Assume a spill of a specific contaminant of 10,000kg occurred at a point upstream from the intake. The river has a width **w** = 75m and an average water depth **d** = 1.5m, a discharge of **Q** = 90m^3/s and an energy slope of 0.0004. Assume the first order decay rate of this contaminant is 5.E-5s^{-1}. Calculate the concentration of the contaminant at a distance 40km from the spill location with decay and without decay.

Solution:
A spreadsheet is used to calculate the maximum concentration at a distance of 40km from the intake. Figure 9 shows the distance **X** that represents $\mathbf{D_3}$ for the delineation of **IPZ-3**. Based on the type of contaminant of concern, the parameters shown in figure 9 may change. The spreadsheet can now be used to calculate the maximum concentration that reaches the intake. The user will need to determine the concentration at the intake that could be used as a threshold to decide whether the contaminant has reached the intake or not.

GIVEN										
Mass M(kg)	10000									
River width w (m)	75									
River depth d (m)	1.5									
Discharge Q (m^3/s)	90									
Energy Slope S (-)	0.0004									
Decay coefficient l (s^{-1})	5.00E-05									
REQUIRED	**X1**	**X2**	**X3**	**X4**	**X5**	**X6**	**X7**	**X8**	**X9**	**X10**
Distance X (m)	100	1000	5000	10000	15000	20000	25000	30000	35000	40000
CALCULATED										
Hydraulic Piermeter P (m)	78									
Hydraulic Radius (m)	1.44230769									
Shear velocity u_* (m/s)	0.07523042									
Velocity V (m/s)	0.8									
Long. Dispersion K_L (m^2/s)	169.268434									
Max. Con. w/o decay (kg/m^3)	0.17242874	0.0545268	0.024385107	0.01724	0.01408	0.01219	0.01091	0.00996	0.00922	0.00862
Max. Con. with decay (kg/m^3)	0.17135442	0.0512231	0.017840525	0.00923	0.00551	0.00349	0.00229	0.00153	0.00103	0.00071

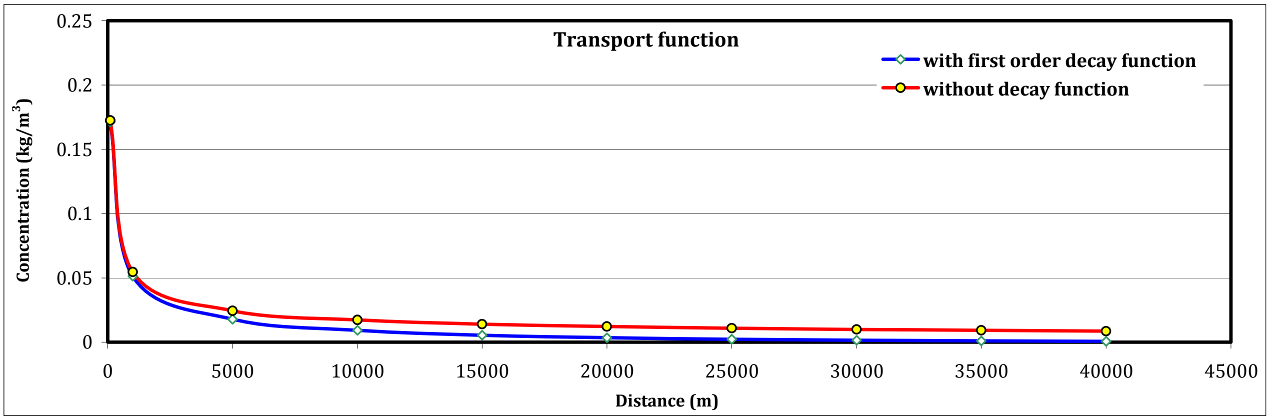


Fig. 9: Illustration to calculate the maximum concentration as a function of distance.

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