Version 2.0 November 1, 2017

Groundwater Protection Model

This document provides guidance to qualified professionals on using the ministry's Groundwater Protection Model (GPM). The GPM is an analytical fate and transport model that simulates the relationship between a substance concentration in soil and the corresponding substance concentration in groundwater at a downgradient point of compliance.

The GPM is applied under the Contaminated Sites Regulation (Regulation) for the purposes of:

- Deriving a site-specific numerical soil standard (SSS) under Protocol 2 "Site-Specific Numerical Soil Standards". The GPM runs in backward calculation mode to calculate a substance concentration in soil (the SSS) based on the applicable water use standard at a downgradient point of compliance
- Completing a screening level risk assessment (SLRA) under Protocol 13 "Screening Level Risk Assessment". The GPM runs in forward calculation mode to calculate the substance concentration in groundwater at a downgradient point of compliance based on an input substance concentration in soil or substance concentration in soil leachate.

Background

The GPM was developed for calculating the matrix numerical soil standards protective of groundwater for the substances listed in Schedule 3.1 Part 1 of the Regulation.

Details of the model development can be found in Protocol 28, 2016 Standards Derivation Methods, Chapter 4. Derivation of Soil to Groundwater Protection Matrix Soil Quality Standards.

Install the GPM

The GPM runs in Microsoft Excel with macros written in Visual Basic for Applications. The model is downloaded through the following link:

Groundwater Protection Model

It is recommended to save the Excel file to the user's own computer before executing the GPM.

How to run the GPM

Guidance on how to run the GPM is found in Appendix 1.

GPM Framework

The GPM is formulated on a conceptual site model of a contaminated site, see Figure 1.

The model assumes a contaminant source of prescribed dimensions in the unsaturated zone which generates leachate by partitioning. The leachate is transported through the unsaturated zone assuming one-dimensional steady-state flow with sorption and biological degradation (organic substances only). At the groundwater

table, leachate mixes with groundwater based on a simple water balance model. Finally, solute is transported through the saturated zone to a point of compliance assuming two-dimensional steady-state flow with dispersion (all substances) and sorption and biodegradation (organic substances only).

The governing equations for the four model components are included in Appendix 2:

- soil leachate partitioning
- unsaturated fate and transport
- leachate/groundwater mixing
- saturated fate and transport

Details on the model development and model assumptions are described in Protocol 28, Chapter 4.

Model parameters

The GPM model parameters are divided into the following categories:

- Source dimensions
- Infiltration
- Hydrogeology
- Substance

Model parameters for source dimensions, infiltration and hydrogeology can be modified by the user from default values as listed in Appendix 3. Substance physical/chemical parameters cannot be modified in the GPM. Values applied in the model are listed in the GPM and are described in detail in Protocol 28, Chapter 4.

References

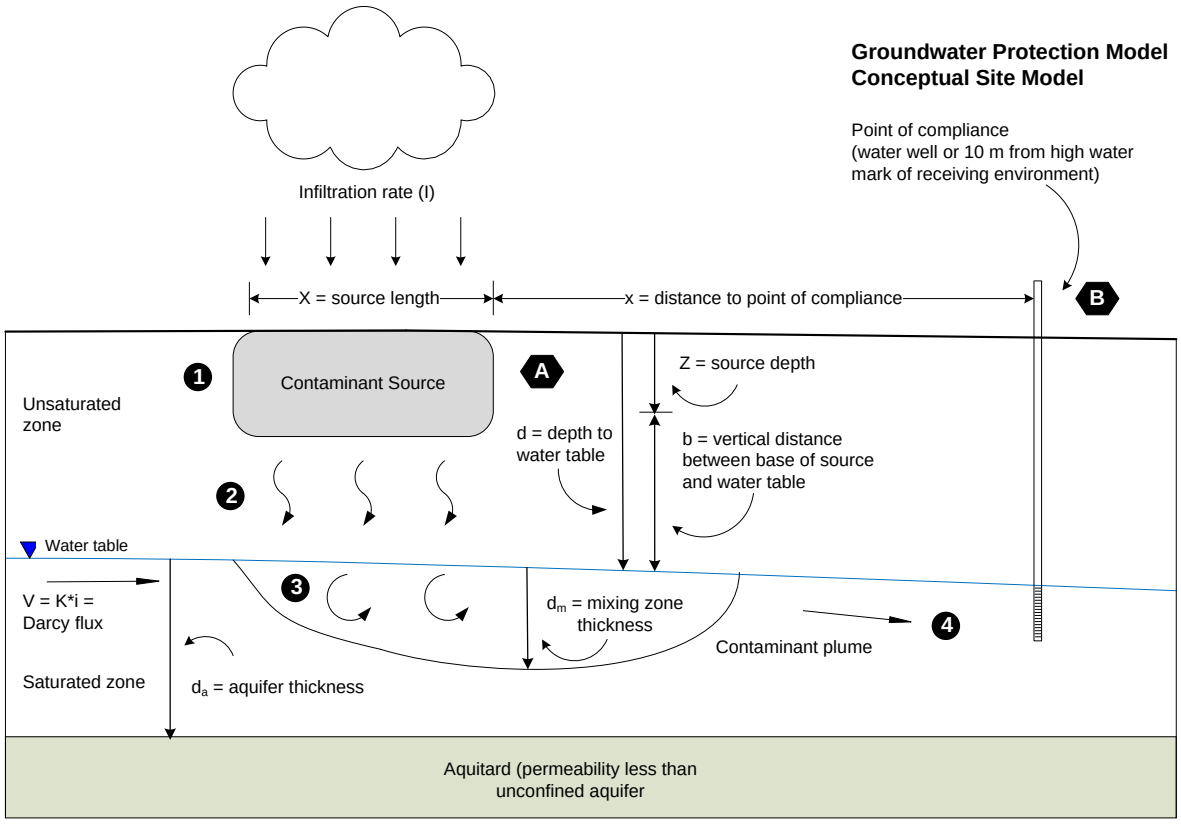
1. United States Environmental Protection Agency. (1996). Soil Screening Guidance. https://www.epa.gov/superfund/superfund-soil-screening-guidance
2. Kool, J.B, Huyakorn, P.S., Sudicky, E.A., Saleem, Z.A. (1994). A Composite Modeling Approach for Subsurface Transport of Degrading Contaminants from Land-Disposal Sites. Journal of Contaminant Hydrology, 17. 1994
3. Domenico, P.A. (1987). An Analytical Model for Multidimensional Transport of a Decaying Contaminant Species. Journal of Hydrology, 91. 1987.

For more information, contact the Environmental Emergencies and Land Remediation Branch at site@gov.bc.ca.

Revision history

Approved Date	Effective Date	Document Version	Notes
November 1, 2017	November 1, 2017	2.0	Updated for Stage 10/11 Amendment to the CSR
2009	2009	1.0	

Figure 1



LEGEND

1. Leachate concentration due to partitioning
2. Unsaturated zone contaminant fate and transport
3. Mixing of leachate and groundwater flux at water table
4. Saturated zone contaminant fate and transport

A — Soil concentration at source (C_s)

B — Water use standard at point of compliance (C_x)

Schematic only.
Not to scale.

Appendix 1

How to run the Groundwater Protection Model

The ministry's Groundwater Protection Model (GPM) is a Microsoft Excel (Excel) based analytical groundwater fate and transport model. The GPM is applied when:

- Calculating site-specific numerical soil standards (SSSs) under Protocol 2 "Site-Specific Numerical Soil Standards"; or
- Completing screening level risk assessment (SLRA) under Protocol 13 "Screening Level Risk Assessment".

This appendix provides practical guidance on how to run the GPM. A detailed description of the model framework, equations and parameters are found in Protocol 28 "2016 Standards Derivation Methods", Chapter 4, Derivation of Soil to Groundwater Protection Matrix Soil Quality Standards.

Getting started

The GPM is developed in Excel with macros written in Visual Basic for Applications. To run the model, it is recommended to save the Excel file to the user's own computer. The first time the GPM is opened; the macros need to be enabled by pressing the "Enable Content" in the Security Warning at the top of the page.

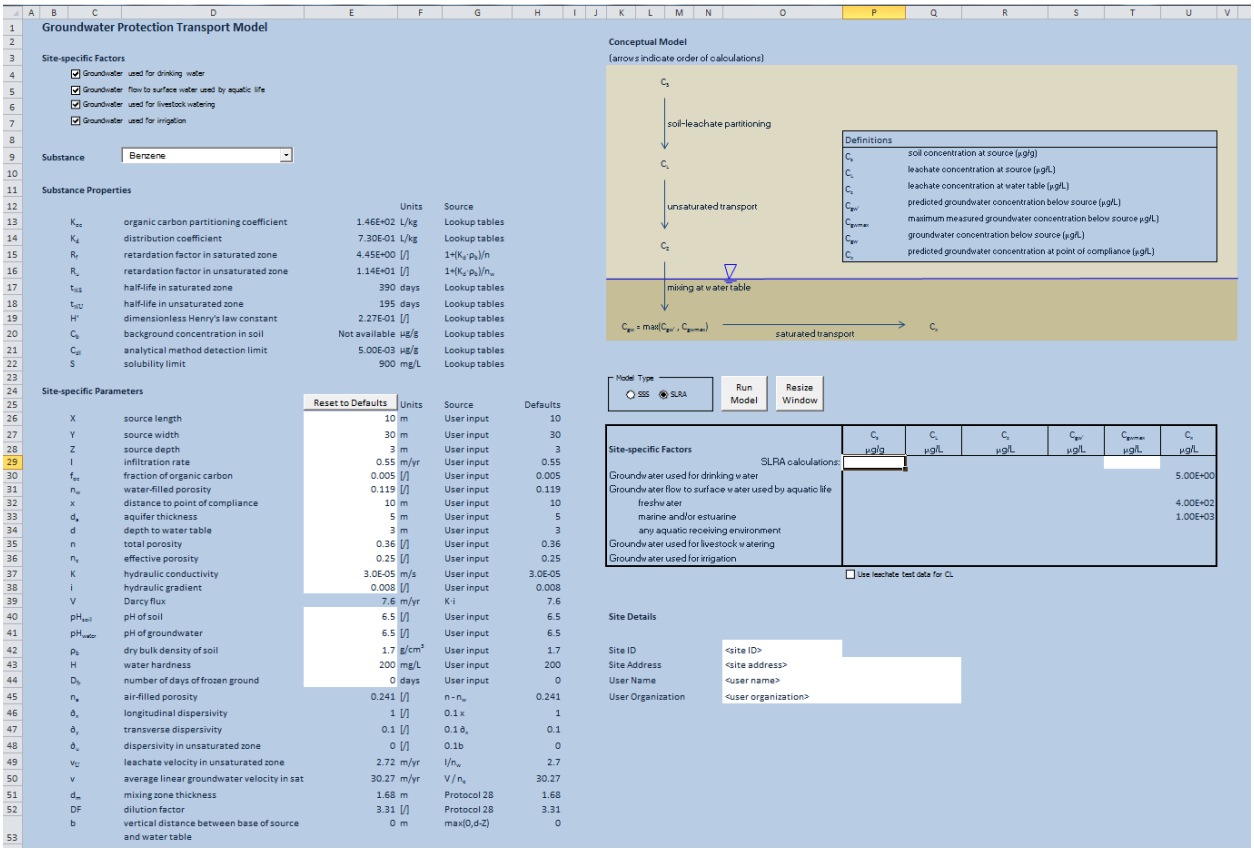
The GPM includes the following six Excel spreadsheets:

Spreadsheet	Function
input	The input sheet is the main model interface, where the user enters model input, starts the model run and views the model results. The user can enter site information for reference including site ID, site address and user name. Model modifications are controlled by choosing model type (SSS or SLRA), substance, applicable water use(s) and site-specific model parameters. The model is run by pressing the "Run Model" button.
defaults	The default sheet provides the default model parameter values and acceptable parameter ranges. The sheet cannot be modified by the user.
substances	The substance sheet provides the chemical/physical properties for all available substances. The Schedule 3.1 Part 1 substances in the Regulation (matrix substances) are marked with "P28" in the "Origin" column of the sheet. The sheet cannot be modified by the user.

kds_kocs	The kds_kocs sheet provides the K_d values for available inorganic substances and K_{oc} value for organic substances. The sheet cannot be modified by the user.
water use standards	The water use standards sheet provides the numerical water use standards for all available substances as prescribed in Schedule 3.2 of the Regulation. The sheet cannot be modified by the user.
soil standards	The soil standards sheet provides the numerical soil standards for all available substances as prescribed in Schedule 3.1 of the Regulation. The sheet cannot be modified by the user.

The user can modify the size of the spreadsheet windows as desired by using the Excel zoom option. The Excel window can be adjusted to fit the entire screen by pressing the "Resize Window" button on the input sheet. Clicking the "Resize Window" button again, will return the window to its previous settings.

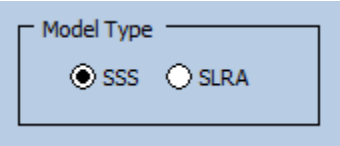
Input sheet



The input sheet is the main model interface where the user controls the model input and starts the model run. The input sheet is divided into the following sections, as described in detail below:

- Site-specific Factors
- Substance
- Substance Properties
- Site-specific Parameters
- Conceptual Model
- Model Type
- Model Output Box
- Site Details

Choose model type



The user can select between the following two model type options:

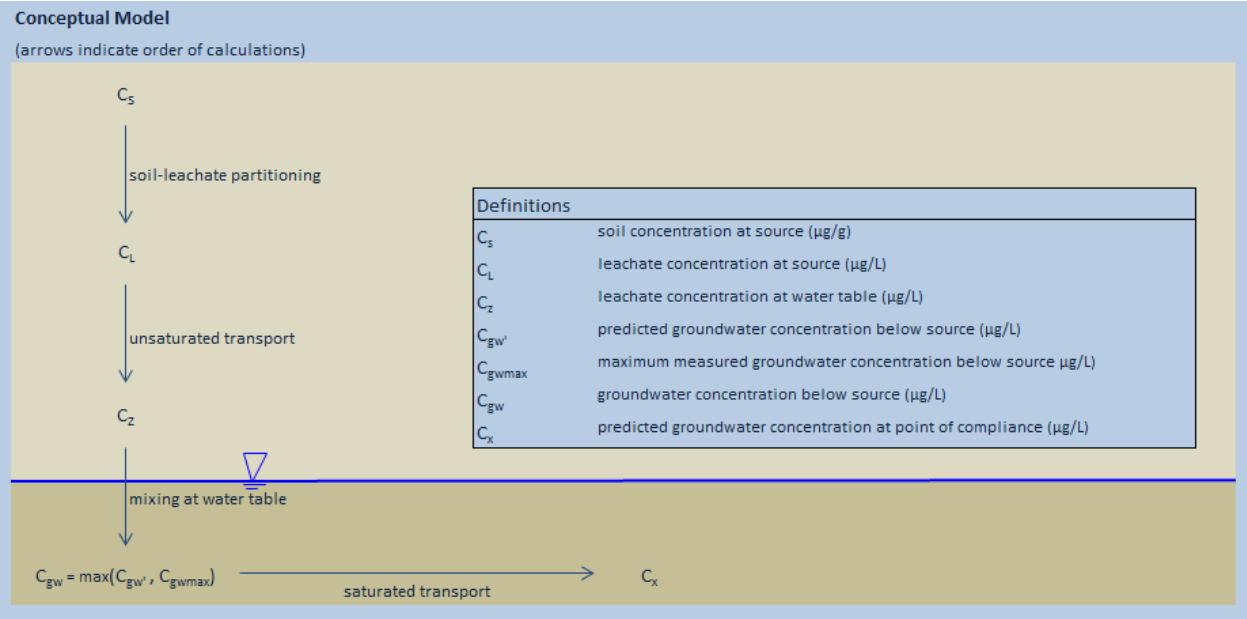
- SSS

  The SSS Model Type is used to derive the site-specific numerical soil standard under Protocol 2. The model runs in backward calculation mode to calculate the substance concentration in soil (the SSS) based on the applicable water use standard at a downgradient point of compliance.

- SLRA

  The SLRA Model Type is used to complete a screening level risk assessment (SLRA) under Protocol 13. The model runs in forward calculation mode to calculate the substance concentration in groundwater at a downgradient point of compliance based on an input substance concentration in soil or substance concentration in soil leachate.

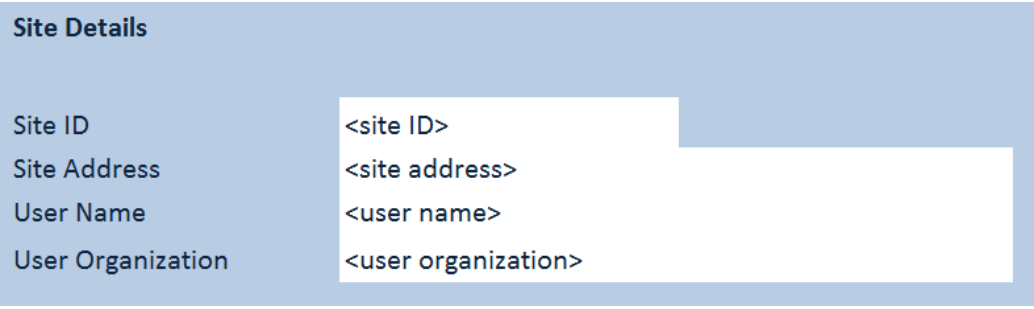
Conceptual Model



The Conceptual Model figure illustrates the four subsurface processes that the model simulates: soil-leachate partitioning, unsaturated fate and transport, leachate mixing at the water table, and saturated fate and transport to a point of compliance. Also, it provides the definitions of the soil and groundwater concentrations used in the model calculations.

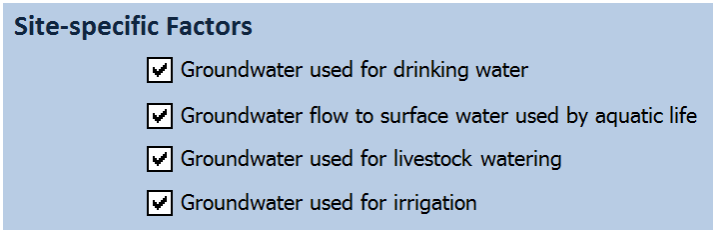
The direction of the arrows illustrates the order in which the model calculates the four processes; i.e. backward calculation mode for the SSS Model Type to derive the soil concentration, C_c, or forward calculation mode for the SLRA Model Type to estimate the groundwater concentration, C_x, at the point of compliance.

Enter site details



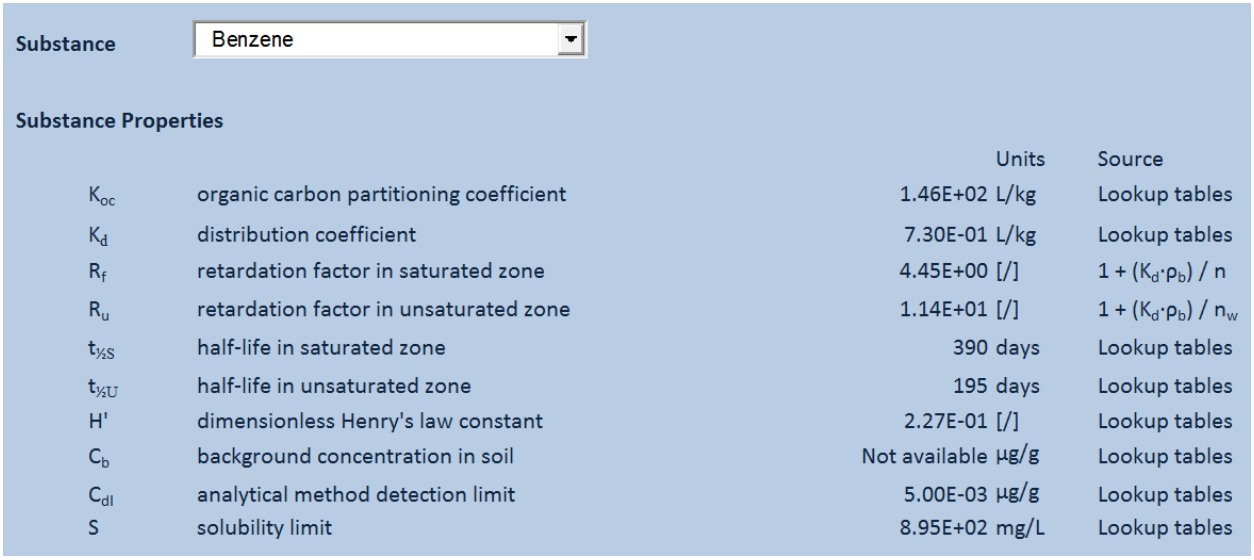
Site details can be entered by the user as desired for later reference.

Choose applicable site-specific factors



Select the site-specific factor(s) protective of groundwater use(s) to include in the model run. For the site-specific factor protective of aquatic life, the user does not specify if the receiving environment is freshwater or marine. Instead, the model will automatically include the applicable numerical aquatic life water use standard(s) for the specific substance.

Choose substance



			Units	Source
K_{oc}	organic carbon partitioning coefficient	1.46E+02	L/kg	Lookup tables
K_d	distribution coefficient	7.30E-01	L/kg	Lookup tables
R_f	retardation factor in saturated zone	4.45E+00	[/]	$1 + (K_d \cdot \rho_b) / n$
R_u	retardation factor in unsaturated zone	1.14E+01	[/]	$1 + (K_d \cdot \rho_b) / n_w$
$t_{½S}$	half-life in saturated zone	390	days	Lookup tables
$t_{½U}$	half-life in unsaturated zone	195	days	Lookup tables
H'	dimensionless Henry's law constant	2.27E-01	[/]	Lookup tables
C_b	background concentration in soil	Not available	µg/g	Lookup tables
C_{dl}	analytical method detection limit	5.00E-03	µg/g	Lookup tables
S	solubility limit	8.95E+02	mg/L	Lookup tables

Select the substance to include in the model run from the drop-down menu. The model can only simulate one substance at a time, so multiple model runs are required if the user wants to include several substances.

The drop-down menu includes both matrix substances listed in Schedule 3.1 Part 1 (substances that can be substituted with a SSS under Protocol 2) and substances available for SLRA under Protocol 13. It is the user's responsibility to ensure that SSSs are derived for substances included in Schedule 3.1 Part 1 only.

The chemical and physical substance properties used by the model for the specific substance are updated in the Substance Properties table. The substance properties are

drawn from the substance sheet and the kds_kocs sheet and cannot be modified by the user.

Enter site-specific parameters

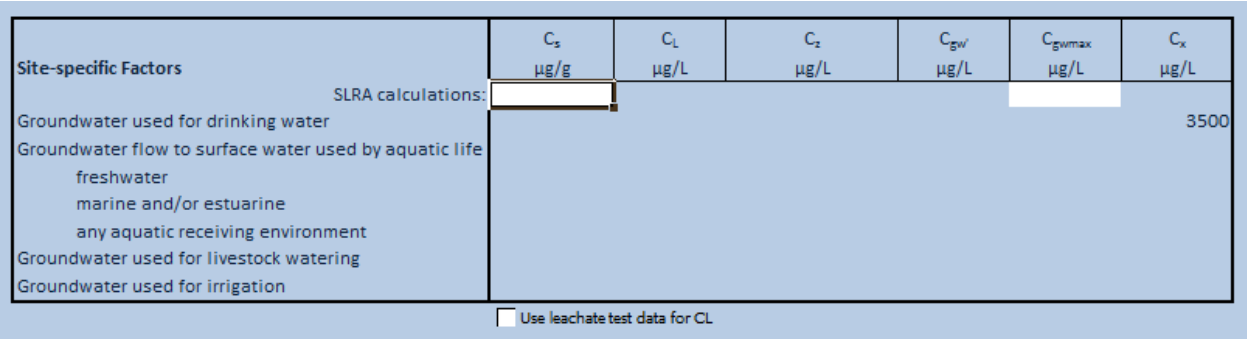
Site-specific Parameters

		Reset to Defaults	Units	Source	Defaults
X	source length	10	m	User input	10
Y	source width	30	m	User input	30
Z	source depth	3	m	User input	3
I	infiltration rate	0.55	m/yr	User input	0.55
f_{oc}	fraction of organic carbon	0.005	[/]	User input	0.005
n_w	water-filled porosity	0.119	[/]	User input	0.119
x	distance to point of compliance	10	m	User input	10
d_a	aquifer thickness	5	m	User input	5
d	depth to water table	3	m	User input	3
n	total porosity	0.36	[/]	User input	0.36
n_e	effective porosity	0.25	[/]	User input	0.25
K	hydraulic conductivity	3.00E-05	m/s	User input	3.00E-05
i	hydraulic gradient	0.008	[/]	User input	0.008
V	Darcy flux	7.57	m/yr	K·i	7.57
pH_{soil}	pH of soil	6.5	[/]	User input	6.5
pH_{water}	pH of groundwater	6.5	[/]	User input	6.5
ρ_b	dry bulk density of soil	1.7	g/cm^3	User input	1.7
H	water hardness	200	mg/L	User input	200
D_{fr}	number of days of frozen ground	0	days	User input	0
n_a	air-filled porosity	0.241	[/]	$n - n_w$	0.241
∂_x	longitudinal dispersivity	1	[/]	0.1 x	1
∂_y	transverse dispersivity	0.1	[/]	0.1 ∂_x	0.1
∂_u	dispersivity in unsaturated zone	0	[/]	0.1 b	0
v_U	leachate velocity in unsaturated zone	2.72	m/yr	I / n_w	2.72
v	average linear groundwater velocity in saturated zone	30.27	m/yr	V / n_e	30.27
d_m	mixing zone thickness	1.68	m	Protocol 28	1.68
DF	dilution factor	3.31	[/]	Protocol 28	3.31
b	vertical distance between base of source and water table	0	m	max (0, d-Z)	0

The user can modify selected model parameters (marked in white cells) from its corresponding default value. If a model parameter is not modified, the default value will apply. Site-specific parameters can be reset to the default values by pressing the "Reset to Defaults" button.

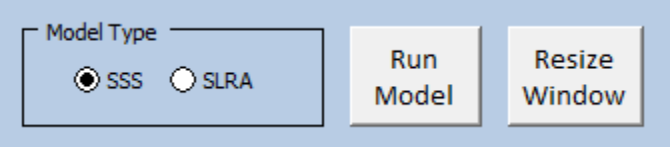
If a parameter is modified outside the allowable range, an error message will pop up and the model run cannot be executed.

Model Output Box



In SLRA mode, the user needs to provide the substance concentration in soil at the source, C_s, and the maximum measured concentration of the substance in the groundwater below the source, C_{gwmax}. If applicable, the user can enter substance concentration data, C_L, from a leachate test by clicking the box "Use leachate test data for CL". The data is entered in the model output box prior to running the model.

Run the model



Execute the model calculations by pressing the "Run Model" button.

Depending on the substance and site-specific parameters, a message box may pop up when running the SSS Model Type, informing the user that a constraint has been actioned in the model. The constraint is either that the substance solubility limit is exceeded (for organics and cyanide) or that the SSS exceeds 100% substance concentration (for inorganics). These messages are not calculation errors, but inform the user that the model calculations have been modified:

Message Box	Substance	Meaning
Calculated leachate concentration > substance solubility limit	P28 organics, cyanide	The simulated leachate concentration is greater than the solubility limit for the substance. The leachate concentration is set equal to the solubility limit.
Calculated SSS soil standard > 100%	P28 inorganics	The calculated SSS is greater than 100% substance concentration. The SSS is set equal to 1E+06 µg/g.

Two other constraints are present in the mixing component of the model, however pop up messages are not included in the model. These include setting the dilution factor (DF) equal to 1 where the source extends into the water table and setting the mixing zone thickness (d_m) equal to the aquifer thickness where the calculated mixing zone thickness exceeds the aquifer thickness. The calculated values for DF and d_m can be viewed in the model interface (input sheet).

Output data

Site-specific Factors	C_x µg/L	C_{gw} µg/L	C_z µg/L	C_L µg/L	C_s µg/g	C_c µg/g
Groundwater used for drinking water	5.00E+00	1.20E+01	3.97E+01	3.97E+01	3.30E-02	3.50E-02
Groundwater flow to surface water used by aquatic life						
freshwater	4.00E+02	9.61E+02	3.18E+03	3.18E+03	2.64E+00	2.50E+00
marine and/or estuarine	1.00E+03	2.40E+03	7.94E+03	7.94E+03	6.61E+00	6.50E+00
any aquatic receiving environment						
Groundwater used for livestock watering						
Groundwater used for irrigation						

Model output is populated in the model output box when running the model for each of the applicable site-specific factors. Model output includes the calculated concentrations for each of the four model components.

For the SSS Model Type, be aware that site-specific soil standards can be calculated for selected substances that do not have a matrix numerical soil standard protective of a specific groundwater use (for example, tetrachloroethylene and trichloroethylene for the site-specific factor protective of drinking water and trichloroethylene for the site-specific factor protective of livestock watering). It is the responsibility of the user to ensure that SSS(s) are calculated for substances that have an applicable site-specific factor only.

For model documentation, the input sheet is saved to a pdf file (by using the “Save As” function in Excel).

Expire date

The model includes an expiry date. If actioned, the following message is displayed "This version of the model expired on <expiryDate>. Contact the Ministry of Environment for a more current version." An updated model will be posted to the ministry website prior to the expiry date

Appendix 2

Soil leachate partitioning

From EPA SSG [1]:

$$C_s = \frac{C_L \left[K_d + \left(\frac{n_w + H' n_a}{\rho_b} \right) \right]}{1000}$$

$$n_a = n - n_w$$

C_s = soil concentration at source (µg/g)
C_L = leachate concentration at source (µg/L)
K_d = distribution coefficient (L/kg)
n = total porosity (default value 0.36)
n_w = water filled porosity (default value 0.119)
n_a = air filled porosity (default value 0.241)
ρ_b = dry bulk density of soil (default value 1.7 g/cm^3)
H' = dimensionless Henry's law constant
1000 = conversion factor (1000 µg/mg)

Unsaturated fate and transport of leachate

Unsaturated zone transport as modified from Kool *et al.*, 1994 [2]:

$$C_L = \frac{C_z}{\exp\left[\frac{b}{2\partial_u}\left(1-\left(1+\frac{4\lambda_u \partial_u R_u}{v_u}\right)^{1/2}\right)\right]}$$

$$b = d - Z$$

$$\partial_u = 0.1b$$

$$\lambda_u = \frac{\ln 2}{t_{1/2u}}\left(1-\frac{D_{fr}}{365}\right) \text{ where } \ln 2 = 0.6931$$

$$R_u = 1 + \frac{\rho_b}{n_w}K_d$$

$$v_u = \frac{I}{n_w}$$

C_L = leachate concentration at source (µg/L)
C_z = leachate concentration at water table (µg/L)
b = vertical distance between base of source and water table (m)
d = depth to water table (m)
Z = source depth (m)
∂_u = dispersivity in unsaturated zone (m)
λ_u = biodegradation rate in unsaturated zone ($days^{-1}$*365 days/yr)
$t_{1/2u}$ = half-life in unsaturated zone (days)
D_{fr} = number of days of frozen ground
R_u = retardation factor in unsaturated zone
ρ_b = dry bulk density of soil (default value 1.7 g/cm^3)
K_d = distribution coefficient (L/kg)
n_w = water filled porosity (default value 0.119)
v_u = leachate velocity in unsaturated zone (m/yr)

Leachate/groundwater mixing

Water balance from EPA SSG [1]:

$$C_z = C_{gw} * DF$$

$$DF = 1 + \left(\frac{d_m V}{X I}\right)$$

$$d_m = r + s = 0.1X + d_a\left[1 - \exp\left(-\frac{XI}{Vd_a}\right)\right]$$

$$r = 0.1X$$

$$s = d_a\left[1 - \exp\left(-\frac{XI}{Vd_a}\right)\right]$$

$$I = P - (RO + EV)$$

C_z = leachate concentration at water table (µg/L)
C_{gw} = groundwater concentration below source (µg/L)
DF = dilution factor
X = source length (m)
d_m = mixing zone thickness (m)
V = Darcy flux or specific discharge (m/yr)
r = depth of mixing due to vertical dispersivity (m)
s = depth of mixing due to downward velocity of infiltrating water (m)
d_a = aquifer thickness (m)
I = infiltration rate (m/yr)
P = precipitation rate (m/yr)
RO+EV = runoff plus evapotranspiration rate (m/yr)

Note: $DF = 1$ if source extends into water table
Note: d_m constrained to $\leq d_a$

Saturated fate and transport of solute

2D saturated transient analytical transport solution from Domenico, 1987 [3]:

$$C(x,y,t) = \frac{C_{gw}}{4} \exp\left\{ \frac{x}{2\,\partial_x} \left[1 - \left(1 + \frac{4\lambda_s\,\partial_x}{v'} \right)^{1/2} \right] \right\} \operatorname{erfc}\left[\frac{x - v't\left(1 + \frac{4\lambda_s\,\partial_x}{v'} \right)^{1/2}}{2(\partial_x v' t)^{1/2}} \right]$$
$$* \left\{ \operatorname{erf}\left[\frac{\left(y + \frac{Y}{2} \right)}{2\left(\partial_y x\right)^{1/2}} \right] - \operatorname{erf}\left[\frac{\left(y - \frac{Y}{2} \right)}{2\left(\partial_y x\right)^{1/2}} \right] \right\}$$

$\partial_x = 0.1x$ and $\partial_y = 0.1\,\partial_x$

$\lambda_s = \frac{\ln 2}{t_{1/2s}}$ where $\ln 2 = 0.6931$

$R_f = 1 + \frac{\rho_b}{n} K_d$ where $K_d = K_{oc} f_{oc}$

$V = K\,i$

$v = \frac{V}{n_e} = \frac{K\,i}{n_e}$

$v' = \frac{v}{R_f}$

At steady-state conditions (t=∞), consolidating terms, and for maximum groundwater concentrations along the plume centreline (y=0), C(x,y,t) reduces to:

$$C_x = C_{gw} \exp\left\{ \frac{x}{2\,\partial_x} \left[1 - \left(1 + \frac{4\lambda_s\,\partial_x}{v'} \right)^{1/2} \right] \right\} \operatorname{erf}\left[\frac{Y}{4\left(\partial_y x\right)^{1/2}} \right]$$

Solving for Cgw:

$$C_{gw} = \frac{C_x}{\exp\left\{\frac{x}{2\,\partial_x}\left[1-\left(1+\frac{4\lambda_s\,\partial_x}{v'}\right)^{1/2}\right]\right\}\operatorname{erf}\left[\frac{Y}{4\left(\partial_y x\right)^{1/2}}\right]}$$

or

$$C_{gw} = \frac{C_x}{\exp\left\{\frac{x}{2\,\partial_x}\left[1-\left(1+\frac{4\lambda_s\,\partial_x R_f}{v}\right)^{1/2}\right]\right\}\operatorname{erf}\left[\frac{Y}{4\left(\partial_y x\right)^{1/2}}\right]}$$

C_{gw} = groundwater concentration below source (µg/L)
C_x = water use standard at point of compliance (µg/L)
x = distance to point of compliance (default value 10 m)
∂_x = longitudinal dispersivity (m)
∂_y = transverse dispersivity (m)
λ_s = biodegradation rate in saturated zone ($days^{-1}$*365 days/yr)
$t_{1/2s}$ = half-life in saturated zone (days)
R_f = retardation factor in saturated zone
ρ_b = dry bulk density of soil (default value 1.7 g/cm^3)
n = total porosity (default value 0.36)
K_d = distribution coefficient (L/kg)
K_{oc} = organic carbon partitioning coefficient (L/kg)
f_{oc} = fraction of organic carbon (default value 0.5%)
v' = retarded average linear groundwater velocity in saturated zone (m/yr)
v = average linear groundwater velocity in saturated zone (m/yr)
V = Darcy flux or specific discharge (m/yr)
n_e = effective porosity (default value 0.25)
K = hydraulic conductivity (m/s*3.154E-07 s/yr)
i = hydraulic gradient
Y = source width (m)

Appendix 3

Model parameters

Category	Parameter	Symbol	Unit	Default value
Source Dimensions	Source length	X	m	10
	Source width	Y	m	30
	Source depth	Z	m	3
Meteorology	Precipitation rate	P	mm/yr	1,000
	Runoff + evapotranspiration rate	RO+EV	mm/yr	450
	Infiltration rate	I	mm/yr	550
	Number of days of frozen ground	D_{fr}	-	0
Hydrogeology	Total porosity	n	-	0.36
	Water-filled porosity	n_w	-	0.119
	Air-filled porosity	n_a	-	0.241
	Effective porosity	n_e	-	0.25
	Dry bulk density of soil	ρ_b	g/cm^3	1.7
	Fraction of organic carbon	f_{oc}	-	0.005
	Hydraulic conductivity	K	m/s	3E-05
	Hydraulic gradient	i	m/m	0.008
	Depth to water table	d	m	3
	Aquifer thickness	d_a	m	5
	pH of soil	pH_{soil}	-	6.5
	pH of groundwater	pH_{water}	-	6.5
	Water hardness	H	mg/L as $CaCO_3$	200
	Distance to point of compliance	x	m	10
Substance	Half-life in unsaturated zone	$t_{1/2u}$	days	Substance dependent
	Half-life in saturated zone	$t_{1/2s}$	days	Substance dependent
	Organic carbon partitioning coefficient	K_{oc}	L/kg	Substance dependent
	Distribution coefficient	K_d	L/kg	Substance dependent
	Dimensionless Henry's law constant	H'	-	Substance dependent
	Solubility limit	S	µg/L	Substance dependent