MILLENNIUM
EMS Solutions Ltd.

#148, 2257 Premier Way
Sherwood Park, AB T8H 2M8
tel: 780.496.9048
fax: 780.496.9049

Suite 202, 701 64 Avenue SE
Calgary, AB T2H 2C3
tel: 403.592.6180
fax: 403.283.2647

#102, 11312 98 Avenue
Grande Prairie, AB T8V 8H4
tel: 780.357.5500
fax: 780.357.5501

Suite 218, 852 Fort Street
Victoria, BC V8W 1H8

#105, 116 Research Drive
Saskatoon, SK S7N 3R3
tel: 306.518.2442

toll free: 888.722.2563
www.mems.ca

Regulatory Approval of Risk Tools Shallow Groundwater Guidelines to Protect Underlying DUA

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Prepared for:
Petroleum Technology Alliance Canada

Prepared by:
Millennium EMS Solutions Ltd.
Suite 202, 701 64 Avenue SE
Calgary, Alberta
T2H 2C3

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1.0 INTRODUCTION

The Alberta Tier 1 *Soil and Groundwater Remediation Guidelines* (AEP, 2019a) for protection of Domestic Use Aquifer (DUA) are based on a groundwater model which assumes that shallow groundwater is a DUA. There is a process within the Tier 2 guidelines (AEP, 2019b) for the exclusion of the DUA pathway when there is a 5 m or greater isolating layer between the base of contamination and the top of any underlying DUA. However, in many cases the shallow groundwater does not qualify as a DUA but the requirements for excluding the pathway are not met (*e.g.,* hydraulic conductivity does not meet the isolating layer criteria).

During the initial phase of this project (MEMS, 2018), a multi-layer groundwater model was proposed based on a modification of the existing Tier 1 groundwater model, adjusted to account for vertical transport through clean saturated (instead of unsaturated) soils and dilution within a deeper DUA. The proposed model was intended to align hydrogeological assessment with risk assessment particularly for use when the DUA is a critical pathway and shallow groundwater is not within a DUA, but the pathway cannot be unconditionally eliminated (*i.e.,* insufficient data to demonstrate adequate isolating unit, isolating unit does not meet elimination requirements, or a specific substance is not eligible for elimination).

The model was presented to Alberta Environment and Parks (AEP) in 2019. During this meeting, it was proposed by AEP that modelling be used as the scientific basis for a guidance document that would provide a basis for developing guidelines for shallow groundwater protective of an underlying DUA. The proposed approach was to develop generic conservative dilution factors that could be applied between shallow groundwater and DUA concentrations, and to use these to make recommendations for corresponding shallow groundwater guidelines. A sensitivity analysis was proposed to demonstrate that the approach was robust and to identify the conditions under which it was applicable.

This report uses a numerical modelling approach to investigate whether a conservative generic "dilution factor" DF can be developed to calculate conservative groundwater guidelines for shallow non-DUA groundwater protective of an underlying DUA. The dilution factors developed using the numerical modelling approach are compared to dilution factors implied by use of the subsoil salinity tool (SST) under similar circumstances.

In this report, the Alberta regulatory framework is used as a starting point, but approaches used in other Canadian jurisdictions are also explored for comparison purposes.

2.0 REGULATORY DEFINITIONS OF DRINKING WATER AQUIFER

Different jurisdictions have various ways of defining groundwater units that have the hydrogeological properties to support domestic water supply. The following sections explore the definition of a domestic use aquifer and the possibility for excluding that exposure pathway within the Alberta, British Columbia and Ontario guidelines.

2.1 Alberta

2.1.1 Definition

The Alberta Tier 1 guidelines document (AEP, 2019a) defines a DUA as follows:

- a bulk hydraulic conductivity of 1 x 10^{-6} m/s or greater; and
- a sufficient thickness to support a sustained yield of 0.76 L/min or greater; or
- is currently being used for domestic purposes; or
- is an aquifer determined by Alberta Environment to be a DUA.

2.1.2 Exclusion

The protection of DUA pathway can be excluded at a Tier 2 level when the following requirements are met (AEP, 2019b):

1. at least 5 metres of massive, undisturbed, unfractured fine-grained material meeting appropriate guidelines with a bulk hydraulic conductivity that is less than or equal to 1 x 10^{-7} m/s; or
2. an equivalent thickness of natural, undisturbed geologic material that is more than 5 meters thick and is supported by technical information regarding the lithology;
3. if a shallow large diameter well (or bored well) has been installed in a geologic unit that otherwise would not meet the definition of a DUA; and
4. the entire geological unit is not considered a DUA, but the well must be treated as a point of compliance for the DUA pathway.

2.1.3 Subsoil Salinity Tool

The Subsoil Salinity Tool (SST) is built on a conceptual model where shallow groundwater may not be a DUA. The SST models diffusion and dispersion as a chloride plume leaches downward towards a DUA and reduction in breakthrough concentrations due to lateral groundwater flow. The conceptual model is similar to that proposed by MEMS (2018), except those additional processes including 3 dimensional dispersions are also included in the SST, while the MEMS (2018) model conservatively only considered 1 dimensional dispersion. However, the SST does not consider biodegradation since it is based on a conservative solute (chloride).

2.2 British Columbia

2.2.1 Definition

Protocol 21 defines the aquifer properties of a potential drinking water source as follows (MECCS, 2017):

1. Saturated geological units with yields greater than or equal to 1.3 L/min.
2. Saturated unconsolidated geological units with hydraulic conductivities greater than or equal to 1 x 10^{-6} m/s or greater.
3. Bedrock units show a poorer correlation between yield and hydraulic conductivity. Therefore, hydraulic conductivity alone cannot be used to rule out drinking water use in bedrock.

2.2.2 Confining Unit

Protocol 21 defines a natural confining unit as unconsolidated geological units that serve as protection for an underlying aquifer from shallow groundwater contamination. There are two primary confining layers, Type A and Type B. The properties of these two confining layers are outlined below:

2.2.2.1 Type A

A Type A natural confining barrier is a geological unit or part of geological unit that:

1. has a bulk hydraulic conductivity less than 1 x 10^{-7} m/s;
2. has a minimum thickness of 5 metres;
3. is reasonably uniform in composition and is unfractured;
4. is continuous across the extent and predicted migration pathway of contaminant plumes; and
5. is demonstrated free of contamination based on substance concentrations in soil or water that are:
   - less than or equal to the commercial land use soil standards listed in Schedule 3.1 Part 2 and 3 of the Regulation;
   - less than or equal to the commercial land use soil standards for the site-specific factor of groundwater used for drinking water, irrigation water or livestock water listed in Schedule 3.1 Part 1 of the Regulation, depending on the applicable water use of the deeper aquifer; or

  - less than or equal to the drinking, irrigation or livestock water standards in Schedule 3.2 of the Regulation, depending on the applicable water use of the deeper aquifer, where no soil standards.

2.2.2.2 Type B

A Type B natural confining barrier is a geological unit or part of geological unit that:

- has a bulk hydraulic conductivity between 1 x 10^{-7} m/s and 1 x 10^{-6} m/s;
- has a ratio of thickness to hydraulic conductivity greater than 5 x 10^{-7} m/s;
- is reasonably uniform in composition and is unfractured;
- is continuous across the extent and predicted migration pathway of contaminant plumes; and
- is demonstrated free of contamination based on substance concentrations in soil and water that are less than or equal to the applicable regulatory standards.

2.3 Ontario

Ontario's approach to handling ingestion of water is somewhat different. Separate standards are provided for "potable" and "non-potable" water scenarios, but the primary factor in determining which standards apply is the presence of municipal water supplies.

The calculation of guidelines for the protection of potable water in Ontario includes well-bore dilution and source attenuation, resulting in higher guidelines than Alberta Tier 2 for benzene, toluene, ethylbenzene and xylenes (BTEX) (MOE, 2011).

2.4 Summary

The primary factors determining if a unit can support potential drinking water used in both Alberta and British Columbia are its intrinsic hydrogeological properties, namely the hydraulic conductivity and yield. In addition, a confining unit beneath a contaminated zone that is deemed sufficient to protect an underlying DUA is generally 5 m of a low hydraulic conductivity material.

Both jurisdictions provide a clear description of key hydrogeological parameters and site characteristics required to protect the drinking water pathway.

Figure 1 illustrates the conceptual site model with a source of contamination in a shallow groundwater unit which is not a DUA, and an underlying groundwater unit that is a DUA.

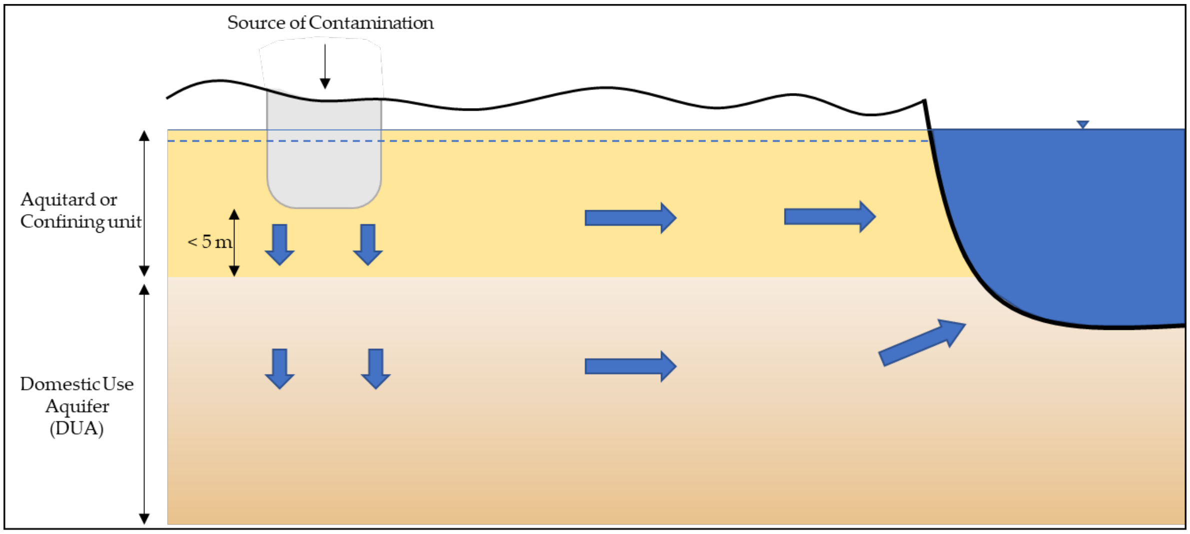

Figure 1 **Conceptual Site Model**

3.0 HYDROGEOLOGICAL BASIS FOR GROUNDWATER DILUTION

The primary purpose of this report is to build the case for a generic dilution factor between contaminant concentrations in shallow non-DUA groundwater and those in an underlying DUA. This is explored in the following sections of the report. However, before getting into these quantitative calculations, it is important to understand the conceptual site model that is being considered, the hydrogeological basis for this dilution, and the relationship between this dilution factor and groundwater guideline calculated for shallow groundwater.

3.1 Conceptual Site Model

As shown in Figure 1, the conceptual site model considered in this document is one in which a DUA is present but is not the shallowest groundwater layer. So, 3 layers are assumed to be present, a vadose zone, underlain by a shallow groundwater zone that does not have the properties of a DUA, underlain by a deeper groundwater zone that does have the properties of a DUA. The contaminant source area is within the shallow groundwater zone. The contaminant source area may or may not extend right to the base of the shallow groundwater zone but does not extend down into the underlying DUA. It is assumed that there is a downward component of hydrogeological flow in the shallow groundwater unit, and that the groundwater flow in the DUA unit is predominantly lateral. As will be elaborated in Section 4, Alberta Tier 1 default values are used as a starting point for assumptions about the dimensions of the source area and the thickness of units.

Note that in this context, the term "source area" is being used in the sense of "the area from which contaminant is migrating" as in the "source size" referred to in Section 5 and Table C-3 of Appendix C of the Tier 1 guidelines document. This is different from the requirement for Sources to be removed or controlled referred to in Section 2.3.1 of the Tier 1 guidelines document.

3.2 Hydrogeological Basis for Dilution

Two processes can drive a decrease in contaminant groundwater concentration between the base of the source are and the DUA:

1. If the contaminant degrades in the subsurface and if there is a vertical separation between the base of the source area and the top of the DUA, there will be a decrease in contaminant concentration related to the degradation of the contaminant during the time required for transport down from the base of the source area to the top of the DUA.
2. There will be dilution due to mixing where the downward migrating groundwater from the shallow groundwater unit enters the DUA. In general, the lower the downward groundwater flow rate in the shallow groundwater unit and the higher the lateral groundwater flow rate in the DUA, the greater will be the dilution.

These two processes are considered in the Tier 1 and Tier 2 guidelines documents where they are referred to as DF2 and DF3. DF2 will typically only be significant for contaminants that degrade, while DF3 applies to all contaminants that are mobile in groundwater.

3.3 Implications for Calculating Shallow Groundwater Guidelines

The combination of the dilution factors for these two processes represents the ratio of the contaminant concentration in shallow groundwater to the expected contaminant concentration in underlying DUA groundwater.

$$DF = DF2 * DF3$$

Definitions:

DF	Overall dilution factor between shallow groundwater concentrations and underlying DUA concentrations.
DF2	Dilution factor relating to the decrease in contaminant concentration between the base of the source area and the top of the DUA.
DF3	Dilution factor relating to mixing where shallow groundwater enters the DUA.

The groundwater guideline applicable in the DUA is the applicable drinking water guideline for the chemical being considered (Table C11 in the Alberta Tier 1 Guidelines document, AEP, 2019a). The overall dilution factor DF can be used to calculate a conservative guideline for shallow groundwater from the drinking water guideline applicable in the DUA.

$$GWG_{shallow} = DF * GWG_{DUA}$$

Definitions:

$GWG_{shallow}$	Groundwater guideline for shallow groundwater protective of underlying DUA.
DF	Overall dilution factor, see above.
GWG_{DUA}	Groundwater guideline applicable to DUA groundwater (normally the drinking water guideline).

Thus, determining a generic, conservative dilution factor between shallow groundwater concentrations and concentrations in an underlying DUA allows a conservative, generic groundwater guideline to be calculated for shallow, non-DUA groundwater protective of the DUA exposure pathway.

4.0 GENERIC DILUTION FACTOR BASED ON NUMERICAL MODELLING

A numerical groundwater model was used to provide a basis for the overall dilution factor (DF) that would act in a range of different situations, starting with the set of default parameter values from the Alberta Tier 1 guidelines and varying key parameters in a process of sensitivity analysis. The overall goal of this process is to determine a generic dilution factor that will be conservative for a range of typical conditions and identify the conditions where a more site-specific approach would be required.

Numerical models are appropriate for this exercise as they are constructed from a domain of cells and operate by iteratively calculating the properties of one cell from the properties of neighboring cells using fundamental hydrogeological relationships (Darcy’s law, basic contaminant transport equations).

A 2-dimensional model was constructed in Modflow to represent the conceptual model described in Section 3 using Tier 1 default parameter values. The numerical model domain is illustrated in Figure 2. Key parameter values were then adjusted in a process of sensitivity analysis. Chloride is used as an example of a conservative contaminant and is used as a surrogate for other conservative contaminants. Benzene is used as an example of a degrading contaminant that is also retarded and is used as a surrogate for other BTEX components because benzene degrades at a similar or slower rate than other BTEX compounds. The overall dilution factor (DF) was calculated from each model scenario as the ratio between the source area groundwater concentration (arbitrarily set at 1,000 mg/L for chloride and 1 mg/L for benzene) and the maximum concentration in the top row of cells in the DUA at any future time. The time of that maximum was also noted.

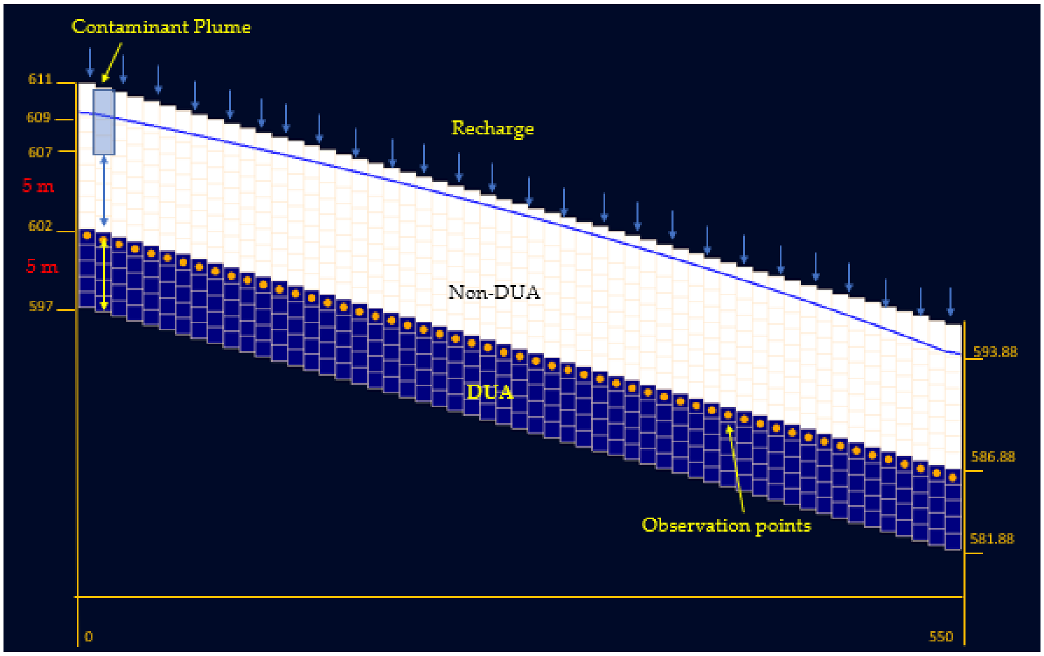

Figure 2 **Numerical Model Domain**

4.1 Base Case Model

As indicated above, a Base Case model was set up using default Alberta Tier 1 parameters for fine-grained soils together with other consistent and appropriate values. In summary, the base case model assumes a source zone with dimensions 10 m x 10 m x 3 m thick in non-DUA shallow groundwater extending to the base of the shallow groundwater, but not into the immediately underlying DUA. Two source zones are considered separately. A benzene source zone is assumed to have a groundwater concentration of 1 mg/L, and a chloride source zone is assumed to have a groundwater concentration of 1.000 mg/L. The purpose of the base case model exercise is to calculate the ratio between the source zone concentration and the maximum modelled future concentration at any location in the DUA. This is expressed as the dilution factor (DF).

Note that no attempt is made to construct a Base Case model for Alberta Tier 1 coarse-grained soils since the Tier 1 default properties for coarse-grained soils would imply that shallow groundwater is a DUA and invalidate the Conceptual Site Model assumed in this document.

The Base Case model parameters are summarized in Table 1 below. Chemical-specific parameters are summarized in Table 2.

Table 1 Base Case Parameter Values (Numerical Model)

Parameter	Value	Notes
Hydraulic conductivity of DUA (K_{DUA})	1 x 10^{-6} m/s	Tier 1 default value for fine-grained soil
DUA thickness	5 m	Assumed
DUA porosity	0.36	Tier 1 default value, assumes coarse-grained soil since fine-grained soil would not have the hydraulic properties to support a DUA.
Hydraulic conductivity of non-DUA ($K_{non\text{-}DUA}$)	8 x 10^{-7} m/s	Not used in Tier 1 model. This value was selected as being the upper end of the range for a non-DUA. Higher values are conservative.
Non-DUA thickness	7 m	Assumed. Allows sufficient space in the model for a 3 m thickness of contaminated unit as the source-DUA separation increases.
Non-DUA porosity	0.47	Tier 1 default value for fine-grained soil
Recharge	12 mm/year	Tier 1 default value for fine-grained soil
Contaminant source dimension	10 m x 10 m x 3 m thick	Tier 1 default values
Lateral gradient	0.028	Tier 1 default value
Length of model domain	550 m	Allows sufficient space for lateral plume migration.
Longitudinal dispersivity	50 m	Consistent with Tier 1 assumptions
Lateral dispersivity	5 m	Consistent with Tier 1 assumptions
Model run time	500 years	Consistent with Tier 1 assumptions

Table 2 Chemical Specific Parameter Values

	Value	
Parameter	**Chloride**	**Benzene**
Contaminant Source Concentration	1,000 mg/L	1 mg/L
Organic carbon-water partition coefficient (K_{oc})	0 ml/g (not retarded)	81 ml/g
Degradation half-life	Infinite (does not degrade)	1 year

4.1.1 Base Case Model Results

The results of running the base case model were as follows:

- For chloride, the maximum modelled future concentration in the DUA was 129 mg/L and occurred at the top of the DUA after 8 months (see breakthrough curves in Appendix A). This corresponds to a DF value of 7.75 (1,000 mg/L/129 mg/L).
- For benzene, the maximum modelled future concentration in the DUA was 0.0675 mg/L and occurred at the top of the DUA after 6 months (see breakthrough curves in Appendix A). This corresponds to a DF value of 14.8 (1 mg/L/0.0675 mg/L).

In both cases, the lateral location of the maximum concentration was immediately below the source area.

4.2 Sensitivity Analysis

A sensitivity analysis was conducted on the chloride and benzene models by varying selected key input parameters through a realistic range of values. The parameters selected for sensitivity analysis together with the rationale for their selection and the values selected are discussed it the following sections.

4.2.1 Scenario 1 – Vary the Separation Distance (b)

In this scenario, the separation distance between the base of the source area and the top of the DUA is varied. This parameter is referred to as “b” in the Tier 2 guideline document (AEP, 2019b). This parameter value is selected for sensitivity analysis as the Tier 2 calculation for DF2 is particularly sensitive to this parameter for contaminants that degrade. The values selected for sensitivity analysis are 0 m (base case) and 0.1 m, 0.3 m, 1 m and 3 m.

4.2.2 Scenario 2 – Vary the Source Length (X)

In this scenario, the source length is varied. This parameter is referred to as "X" in the Tier 1 and Tier 2 guideline documents (AEP, 2019a,b). This parameter value is selected for sensitivity analysis as the Tier 2 calculation for DF3 is sensitive to this parameter for all contaminants as increasing this parameter increases the length of the mixing zone. The source length is measured in the direction of groundwater flow. The values selected for sensitivity analysis are 10 m (base case), 30 m and 100 m. Source lengths greater than 100 m are possible, but at such sites it is assumed that there would be multiple triggers for a more site-specific approach.

4.2.3 Scenario 3 – Vary the Hydraulic Conductivity of Shallow Groundwater (K1)

In this scenario, the hydraulic conductivity of the non-DUA shallow groundwater is varied. There is no value for this parameter in the Tier 1 guidelines document since the Tier 1 model considers only one groundwater layer (the DUA). In the Tier 1 model, the hydraulic conductivity of the DUA is referred to as "K". In this document, the hydraulic conductivities of the shallow and DUA groundwater layers are referred to as "K1" and "K2", respectively.

This parameter value is selected for sensitivity analysis based on the conceptual site model described in Section 3.1. The hydraulic conductivity of the shallow groundwater controls the downward flux of contaminant in the shallow groundwater unit, and therefore affects the mixing/dilution that occurs at the interface between shallow groundwater and the underlying DUA. The values selected for sensitivity analysis are 8×10^{-7} m/s (base case), 1×10^{-7} m/s and 1×10^{-8} m/s. This represents a reasonable range of the hydraulic conductivity typically measured in clay till shallow groundwater units. Values much higher than the base case would result in shallow groundwater being a DUA which would invalidate the conceptual site model being considered.

4.2.4 Scenario 4 – Vary the Hydraulic Conductivity of the DUA (K2)

In this scenario, the hydraulic conductivity of the DUA ("K2") is varied. This parameter value is selected for sensitivity analysis as the Tier 2 calculation for DF3 is sensitive to this parameter for all contaminants as increasing this parameter increases the dilution in the mixing zone. The values selected for sensitivity analysis are 1×10^{-6} m/s (base case), and 1×10^{-5} m/s. This represents a reasonable range of the hydraulic conductivity typically measured in units that meet the definition of a DUA. Higher values of K2 are possible but would result in higher DUA flow rates and therefore greater dilution factors. Accordingly, the DF values calculated with the selected range of values for K2 are conservative for higher values of K2.

4.2.5 Parameters Not Selected for Sensitivity Analysis

The Tier 1 and Tier 2 models, as well as the numerical model developed in this document use other parameters which were not varied in the sensitivity analysis. The rationale for not including some of these other parameters is provided below.

Source width ("Y" in the Tier 1 guidelines document) is not included here for sensitivity analysis as it has no effect on the calculation of either DF2 or DF3 (AEP, 2019a,b). In addition, it has no meaning in the 2-D model being run.

Vertical hydraulic gradient is relevant to the conceptual site model and the DF values calculated. However, it is not explicitly included in the Tier 1 or Tier 2 guideline calculations and is not an input parameter of the numerical model, but rather is a result of the other model inputs and boundary conditions. Accordingly, no attempt was made to include vertical hydraulic gradient in the sensitivity analysis.

Lateral hydraulic gradient was not varied in the sensitivity analysis. Changing the lateral hydraulic gradient in the DUA unit would affect the dilution factor, however, the dilution factor is a function of the Darcy Velocity in the DUA, which is a product of the lateral hydraulic gradient and K2. Varying K2 varies the Darcy Velocity in the DUA and therefore covers off the effect of changing the lateral hydraulic gradient.

The source zone thickness (Z) was not included in the sensitivity analysis as it has no effect on the Tier 1 or Tier 2 calculations for either DF2 or DF3 (except to calculate "b" which was included in Scenario 1).

Recharge was left at the Tier 1 default value and not varied in the sensitivity analysis. Making a reliable measurement of recharge is not straightforward and is not typically done at environmental sites. Attempting to use site-specific values for recharge has generally been discouraged by Alberta regulators.

4.3 Results of Sensitivity Analysis

The scenarios were assessed by observing breakthrough curves at each of the observational points along the top of the DUA. The peak DUA concentration and the time to achieve the peak concentration were recorded for each scenario. In addition, the DF value for each scenario was calculated (source concentration/peak DUA concentration). Breakthrough curves for the location of peak concentration for all scenarios are included in Appendix A. In all cases, the lateral location of the observation point with the maximum future peak concentration was either beneath the source area or at most 10 m downgradient of the downgradient edge of the source area. A summary of results for the chloride and benzene models are provided in Tables 3 and 4 below, respectively.

Table 3 Sensitivity Analysis Results – Chloride (Numerical Model)

Scenario #	Scenario	Peak Concentration (mg/L)	Time to Peak Concentration (years)	Dilution Factor (DF)
0	Base Case	129	0.67	7.8
1	Vary b:			
	1a: b = 0.1 m	112	0.75	8.9
	1b: b = 0.3 m	86.3	1.2	12
	1c: b = 1 m	29.2	7	34
	1d: b = 3 m	19.3	11	52
2	Vary X:			
	2a: X = 30 m	264	1.2	3.8
	2b: X = 100 m	375	2.6	2.7
3	Vary K1:			
	3a: K1 = 1 x 10^{-7} m/s	145	2.3	6.9
	3b: K1 = 1 x 10^{-8} m/s	159	3.1	6.3
4	Vary K2:			
	4a: K2 = 1 x 10^{-5} m/s	114	0.17	8.8

Notes: b is the separation distance between the base of the source area and the top of the DUA; X is the source length; and K1 and K2 are the hydraulic conductivity of the shallow groundwater and underlying DUA units, respectively. The peak concentration is the highest concentration measured at the top of the DUA at any downgradient distance and any future time. The time to peak concentration is the time required to achieve that peak. The dilution factor is the ratio of the source zone concentration to the peak concentration.

Table 4 Sensitivity Analysis Results – Benzene (Numerical Model)

Scenario #	Scenario	Peak Concentration (mg/L)	Time to Peak Concentration (years)	Dilution Factor (DF)
0	Base Case	0.0675	0.5	15
1	Vary b:			
	1a: b = 0.1 m	0.0505	0.58	20
	1b: b = 0.3 m	0.0280	1.1	36
	1c: b = 1 m	0.00545	1.9	180
	1d: b = 3 m	0.000129	3.9	7,800
2	Vary X:			
	2a: X = 30 m	0.0959	0.75	10
	2b: X = 100 m	0.103	0.83	9.7
3	Vary K1:			
	3a: K1 = 1 x 10^{-7} m/s	0.0366	0.92	27
	3b: K1 = 1 x 10^{-8} m/s	0.0725	0.92	14
4	Vary K2:			
	4a: K2 = 1 x 10^{-5} m/s	0.0416	0.25	24

Notes: b is the separation distance between the base of the source area and the top of the DUA; X is the source length; and K1 and K2 are the hydraulic conductivity of the shallow groundwater and underlying DUA units, respectively. The peak concentration is the highest concentration measured at the top of the DUA at any downgradient distance and any future time. The time to peak concentration is the time required to achieve that peak. The dilution factor is the ratio of the source zone concentration to the peak concentration.

4.4 Summary and Implications

4.4.1 Chloride and Conservative Non-Degrading Chemicals

Based on the sensitivity analysis results for chloride summarized in Table 3, the base case scenario using Tier 1 default parameters results in a dilution factor of 7.8. So long as the source length does not exceed 10 m, the dilution factor (DF) is always greater than 5 regardless of varying other parameter values in the sensitivity analysis. A source length greater than 10 m would create a Tier 1 excluding condition (Tier 1 Guideline document Section 5.1.6). This means that a conservative minimum generic dilution factor of 5 can be applied between concentrations in shallow groundwater and those in an underlying DUA for chloride or any other conservative, non-degrading chemical so long as Tier 1 guidelines are applicable. This means that a Tier 1 level groundwater guideline of 5x the drinking water guideline can be applied to shallow groundwater to be protective of drinking water in an underlying DUA whenever Tier 1 guidelines are applicable. However, if any Tier 1 excluding conditions are present, a site-specific Tier 2 approach would be required.

4.4.2 Benzene and Other Chemicals with Degradation Half-Life <= 1 Year

Based on the sensitivity analysis results for benzene summarized in Table 4, the base case scenario using Tier 1 default parameters results in a dilution factor of 15.

Using a similar approach to that taken for chloride, but with the results for the benzene analysis, a conservative generic minimum dilution factor (DF) of 10 can be applied between concentrations in shallow groundwater and those in an underlying DUA for benzene so long as Tier 1 guidelines are applicable (source length does not exceed 10 m and no other Tier 1 excluding conditions are violated). This dilution factor would also be applicable to any other chemicals with a degradation half life equal to or shorter than that of benzene. This would include toluene, ethylbenzene, and xylenes, and potentially other degrading organic compounds.

This means that for BTEX compounds, a Tier 1 level groundwater guideline of 10x the drinking water guideline could be applied to shallow groundwater to be protective of drinking water in an underlying DUA whenever Tier 1 guidelines are applicable. However, if any Tier 1 excluding conditions are present, a site-specific Tier 2 approach would be required.

Where a separation of at least 1 m is present, the minimum calculated DF was 180. Since benzene is the most conservative of the petroleum hydrocarbon compounds (BTEX and PHC fractions) with respect to transport, a minimum DF of 100 would be protective for petroleum hydrocarbons and potentially other degradable compounds where a clear and consistent separation of at least 1 m can be established.

5.0 GENERIC DILUTION FACTOR BASED ON SUBSOIL SALINITY TOOL

In this section, shallow groundwater/DUA groundwater dilution factors are calculated for chloride using the subsoil salinity tool (SST Version 3.0) for a base case model and a series of sensitivity analysis equivalent to the scenarios run with the numerical model for chloride in Section 4. The purpose of this is to conduct a reality check on the numerical model results and determine whether the SST is generating dilution factors in a broadly similar range to the DF values generated by the numerical model. The construction of the SST is not equivalent to the way that the numerical modelling exercise is built, and the parameter set is not exactly equivalent, so exact replication of DF values is not expected.

The SST tool generates guidelines for four different exposure pathways, but in this exercise, only the groundwater guidelines protective of DUA were used.

All SST simulations were performed using "Tier 2B" to generate shallow groundwater guidelines for the protection of DUA. Default assumptions were applied except as noted in Table 5 below. For most simulations, the alpine subregion was selected for site location since this maximizes the vertical drainage rate (AEP, 2021) and applies a recharge rate of 12 mm/year, equivalent to the Tier 1 default value for fine-grained soils. The distance to freshwater aquatic life (FAL) receptor and depths were adjusted so that the FAL and rooting zone pathways were not constraining guidelines, while maintaining the desired thickness of impacts and distance between impacts and DUA.

5.1 Base Case Model

A base case model was set up in the SST to try and replicate as closely as possible the base case (chloride) numerical model (Section 4.1) which in turn was based as closely as possible on the Alberta Tier 1 default model and fine-grained soil parameter set. The set of parameters used to run the SST base case is summarized in Table 5 below.

Table 5 Base Case Parameter Values (SST Model)

Parameter	Input Value	Comment
Tier	2B	
Number of subareas	1	
Region; subregion	Subalpine	Gives Tier 1 default of 12 mm/year
Land use	Natural	Dugout pathways not considered
Subsoil lithology for vertical transport	Fine	
Shallow groundwater transport lithology	Fine	
Deep groundwater transport lithology	Fine	
Site-specific vertical gradient	none selected	
Site-specific K related to drainage	none selected	
Source length for entire site	10 m	Tier 1 default value
Source length	10 m	Tier 1 default value
Water table depth	<2 m below ground	
Top of impact	3 m below ground	Source zone is within shallow groundwater
Base of impact	6 m below ground	

Table 5 Base Case Parameter Values (SST Model)

Parameter	Input Value	Comment
Depth to DUA	6 m below ground	DUA present immediately below impact
Shallow groundwater K	1 x 10^{-6} m/s	Tier 1 default value
DUA K	1 x 10^{-6} m/s	Tier 1 default value
Shallow groundwater gradient	0.028	Tier 1 default value
DUA lateral gradient	0.028	Tier 1 default value
Background chloride in groundwater	30 mg/L	Default

5.1.1 Base Case Model Results

The results of running the base case model were as follows:

- Using the parameter set in Table 5 above, a shallow groundwater guideline of 5,400 mg/L was calculated for chloride. Since the DUA/drinking water guideline for chloride is 250 mg/L, this corresponds to a dilution factor (DF) of 22.

5.2 Sensitivity Analysis

A sensitivity analysis was conducted on the SST base case model for the same scenarios as were examined for the numerical, as far as possible given the different ways the two models are constructed.

Three sensitivity analysis scenarios were run, varying the separation distance (b), source length (X) and DUA hydraulic conductivity (K2). SST does not provide the option to vary K1. The rationale for selecting these parameters to vary is the same as indicated in Section 4.2 for the numerical model. Where possible, similar input values were used for sensitivity analysis as those used in Section 4.2, though constraints on SST inputs resulted in some minor changes.

Sensitivity analysis parameters and results are summarized in Table 6 below.

Table 6 Sensitivity Analysis Results – Chloride (SST Model)

Scenario #	Scenario	Shallow Groundwater Guideline (mg/L)	Dilution Factor (DF)
0	Base Case	5,400	22
1	Vary b:		
	1a: b = 1 m	6,900	28
	1b: b = 2 m	8,000	32
2	Vary X:		
	2a: X = 35 m	1,800	7.2
	2b: X = 100 m	860	3.4
3	Vary K2:		
	3a: K2 = 2 x 10^{-6} m/s	10,000	40
	3b: K2 = 5 x 10^{-6} m/s	25,000	100

Notes: b is the separation distance between the base of the source area and the top of the DUA; X is the source length; and K1 and K2 are the hydraulic conductivity of the shallow groundwater and underlying DUA units, respectively. The peak concentration is the highest concentration measured at the top of the DUA at any downgradient distance and any future time. The time to peak concentration is the time required to achieve that peak. The location of the peak concentration is the distance downgradient from the upgradient edge of the source area. The dilution factor is the ratio of the source zone concentration to the peak concentration.

5.3 Summary

Comparing the results of the SST model sensitivity analysis (Table 6) to those for chloride with the numerical model (Table 3) allows the following conclusions to be drawn.

- Both the numerical model analysis and the SST analysis support the use of a generic dilution factor (DF) of 5 that can be applied to the drinking water guideline for conservative solutes such as chloride to calculate a shallow groundwater guideline in cases where the Tier 1 excluding conditions are not violated.
- Dilution factors calculated by the numerical modelling approach are conservative relative to those calculated by the SST, providing additional confidence that using DF values from the numerical model will not result in adverse effects with a significant margin of safety.

6.0 OTHER SCIENTIFIC SUPPORT

6.1 BC Science Advisory Board – Vertical Transport

A report prepared for the BC Science Advisory Board (2006) assessed potential transport in scenarios where there is a shallow, less permeable groundwater unit overlying a deeper more permeable aquifer. Among the conclusions of this report:

- If impacts do not extend close to the base of a shallow groundwater unit, *e.g.*, a shallow source zone in a deep unit, the plume is expected to remain in the upper part of the groundwater unit. Vertical transport into the deeper aquifer is primarily a concern with a thin shallow unit and thick source zone (*i.e.*, impacts are already close to the aquifer).
- Transport to deeper aquifers (aside from DNAPLs) generally depends on a strong downwards vertical gradient.
- If the horizontal flux (*i.e.*, hydraulic conductivity and hydraulic gradient) in the deeper aquifer are relatively high compared to the shallow groundwater unit, then there will be sufficient mixing and dilution to substantially reduce contaminant levels.

As a screening approach, a simple mixing ratio can be calculated as:

$$r = \frac{Q_{shallow}}{Q_{aquifer} + Q_{shallow}}$$

Where r is the mixing ratio and Q is the groundwater flux (a function of hydraulic conductivity, hydraulic gradient and area).

This calculation is considered very conservative since it does not include factors such as biodegradation, retardation, or dispersion, but is potentially useful for screening purposes. The report suggests that a more realistic assessment could be conducted by modelling vertical transport using a simple one-dimensional analytical model followed by a mixing calculation (similar to the approach proposed by MEMS, 2018). For a yet more realistic approach, cross-sectional groundwater flow could be assessed using a numerical model (BC SAB, 2006).

6.2 Stratified Aquifer Flow

In a scientific study conducted by Rumynin V.G et. al (2021), an extensive 2D MODFLOW numerical modelling experiment was developed to better understand flow and solute transport in a stratified aquifer. Specifically, the study looked at vertically non-uniform bedrock aquifers with varying hydraulic conductivities in unconfined aquifers. The models were developed based on depth-dependent hydraulic conductivity increasing either stepwise, exponentially or using the power-law. The resulting flow lines from a double layer aquifer with contrasting hydraulic conductivities illustrates the effect of hydraulic conductivity on groundwater flow lines.

The example in Figure 3 below shows the example of a double layer aquifer with a homogenous aquifer and three examples a double layer aquifer with different contrasting hydraulic conductivities. The example illustrates how the flowlines refract due to the contrasting hydraulic conductivity between the two layers. The higher the contrast in permeability the higher the angle of refraction.

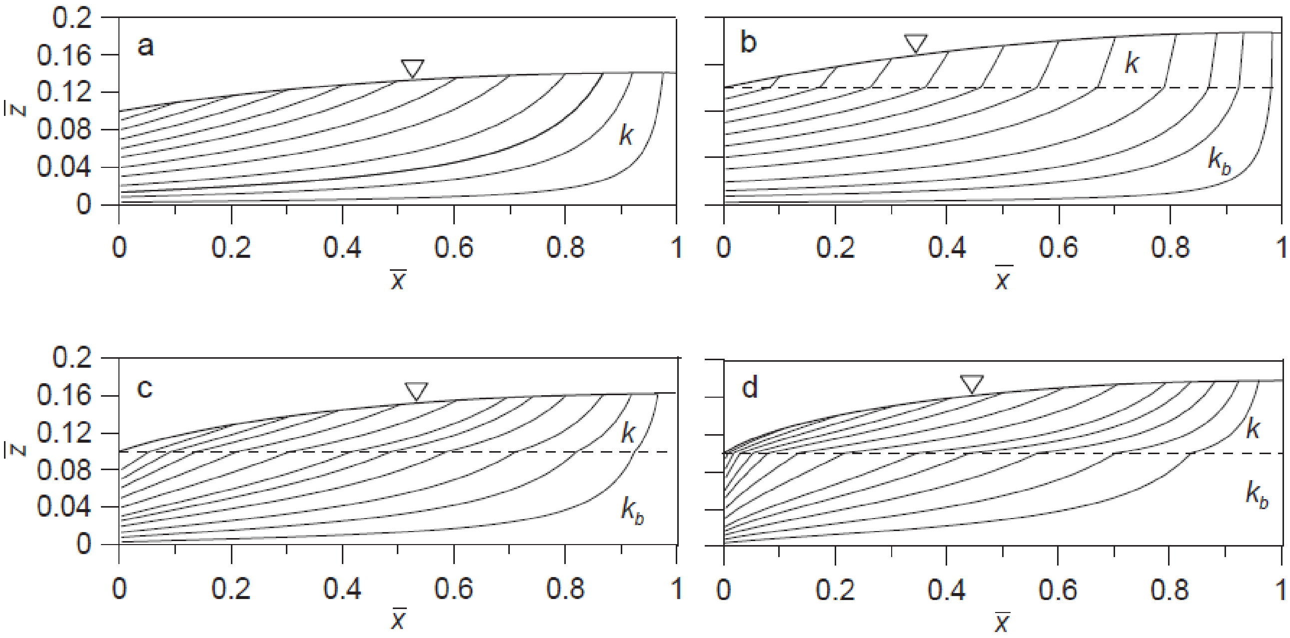

Figure 3 **Flow Lines in Aquifer Cross-Sections**

a) homogenous aquifer and (b,c,d) a two layered unconfined aquifer: (a) k = kb = 100; (b) kb = 100, k = 25; (c) kb = 50, k = 100; (d) kb = 25, k = 100 (V.G. Rumynin *et. al,* 2021).

The change in flow lines illustrate how solute transport is affected based on a change in hydraulic conductivity, similar to the study conducted in Section 4. While hydraulic conductivity is not the only factor that dictates solute transport it is one of the critical parameters in understanding the vertical migration of solute and the resulting risk to receptors.

7.0 ADDITIONAL CONSIDERATIONS

7.1 Fractured Bedrock

The modelling approaches employed in Section 4 are based on transport through unconsolidated soils. Transport through fractures is mechanically different. In particular, transport times may differ for fracture flow as compared to flow through unconsolidated soil. The dilution within the DUA would remain a function of the relative flow between less permeable units and the DUA, but additional site-specific data may be needed to quantify this relationship.

7.2 Continuity and Integrity of Separating Units

Stratigraphy is not perfectly uniform at real-world sites, and therefore an observed separation distance at a single location is not necessarily representative of the entire site. In general, the thicker the separation, the higher the level of confidence that it is reasonably consistent.

At a simple level, the approach used for elimination of the DUA pathway (5 m separation layer identified at 3 or more separate locations) provides strong evidence of separation. However, with sufficient data and a strong conceptual site model, a smaller separation distance can be identified. The absence of an identified DUA (*e.g.,* fine-grained soils are present to the greatest depth investigated) adds confidence in the separation unit.

8.0 APPLICATION

Many sites have been shown to have shallow groundwater contamination within a unit that does not meet the requirements of a potential DUA but for which the protection of DUA pathway cannot be excluded.

This document developed conservative generic dilution factors that can be applied to drinking water guidelines to calculate guidelines for shallow non-DUA groundwater. These shallow non-DUA groundwater guidelines are equivalent to Tier 1 guidelines and are applicable so long as no Tier 1 excluding conditions are triggered for the Site, particularly with respect to source length.

Three different dilution factors are proposed as follows:

- A dilution factor (DF) of 10 is applicable for contaminants that degrade with a half-life of 1 year or less, including the BTEX compounds, trichloromethane, diethylene glycol, triethylene glycol, monoethanolamine, diethanolamine and methanol.
- A dilution factor (DF) of 100 is applicable for petroleum hydrocarbon constituents (BTEX and PHC Fractions), and potentially other degrading compounds that can be demonstrated to degrade over shorter distances than benzene, where a clear separation of at least 1 m can be demonstrated.
- A dilution factor (DF) of 5 is applicable to any other soluble contaminants.

In cases where one or more of the Tier 1 excluding conditions is triggered, a Tier 2 approach will be required, and these generic dilution factors can not be applied.

9.0 LIMITATIONS OF LIABILITY AND CLOSURE

This report was prepared by Millennium EMS Solutions Ltd. (“MEMS”) for the Petroleum Technology Alliance of Canada (“PTAC”) and has been completed in accordance with the terms of reference in the Recipient Agreement dated April 26, 2019, for PTAC Project reference 20-RRRC-09. This report does not necessarily represent the views or opinions of PTAC or the PTAC members.

Transport modelling involves a number of uncertainties and limitations. As a consequence, the use of the results presented herein to develop site management strategies may either be overly protective or may not necessarily provide complete protection to human receptors or prevent damage of property in all circumstances. The results of the modelling as presented herein were determined in accordance with generally accepted protocols and the reported site conditions. Given the assumptions used herein, the assessment provides a conservative estimate of the risks involved. The services performed in the preparation of this report were conducted in a manner consistent with the level of skill and care ordinarily exercised by professional engineers and scientists practising under similar conditions.

While preparing this report, Millennium may use or incorporate Millennium’s proprietary algorithms, methods, compilations, processes, designs, formulas, and/or techniques, and may also employ advanced technologies for simulation, information modeling, generative design, and the development of project documentation (the “Technical Tools”). The Technical Tools may be further used to create data sets and result in simulations or models (collectively, the “Datasets”) that may be included in this report. Both the Technical Tools and the Datasets are by-products of Millennium’s internal processes and shall belong solely to Millennium. No unauthorized use of the Technical Tools or Datasets is permitted.

The results and interpretations included in this report do not represent any specific site. Millennium accepts no responsibility for foreseeable or unforeseeable damages, or direct or indirect damages, if any, suffered by any third party as a result of decisions made or actions taken based on the use of this report, including but not limited to damages relating to delay of project commencement or completion, reduction of property value, and/or fear of, or actual, exposure to or release of toxic or hazardous substances.

10.0 REFERENCES

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APPENDIX A: NUMERICAL MODEL BREAKTHROUGH CURVES

Model Runs	Parameter	Suggested Values/ Changes	Model Number	Peak Concentrations and Arrival Time	Peak Concentration Location (from upgradient edge of the source zone)
New Base Case	b = 0 m, X = 10 m, K1 = 8E-7 m/s and K2 = 1E-6 m/s	-	TSClBase	129 mg/L @ 8 months	0 m (underneath the source)
Scenario 1A	b	3 m	TSClS1Ab	19.3 mg/L @ 11 years	10 m From the edge of the source
Scenario 1B	b	1 m	TSClS1Bb	29.2 mg/L @ 7 years	0 m (underneath the source)
Scenario 1C	b	0.3 m	TSClS1Cb	86.3 mg/L @ 14 months	0 m (underneath the source)
Scenario 1D	b	0.1 m	TSClS1Db	112 mg/L @ 9 months	0 m (underneath the source)
Scenario 2A	X	30 m	TSCl2AX	264 mg/L @ 14 months	0 m (underneath the source)
Scenario 2B	X	100 m	TSCl2BX	375 mg/L @ 2.6 years	0 m (underneath the source)
Scenario 3A	K1	1E-7 m/s	TSCl3AK1	145 mg/L @ 2.3 years	0 m (underneath the source)
Scenario 3B	K1	1E-8 m/s	TSCl3BK1	159 mg/L @ 3.1 years	0 m (underneath the source)
Scenario 4	K2	1E-5 m/s	TSCl4K2	114 mg/L @ 2 months	0 m (underneath the source)

Models are zipped and saved in this folder:

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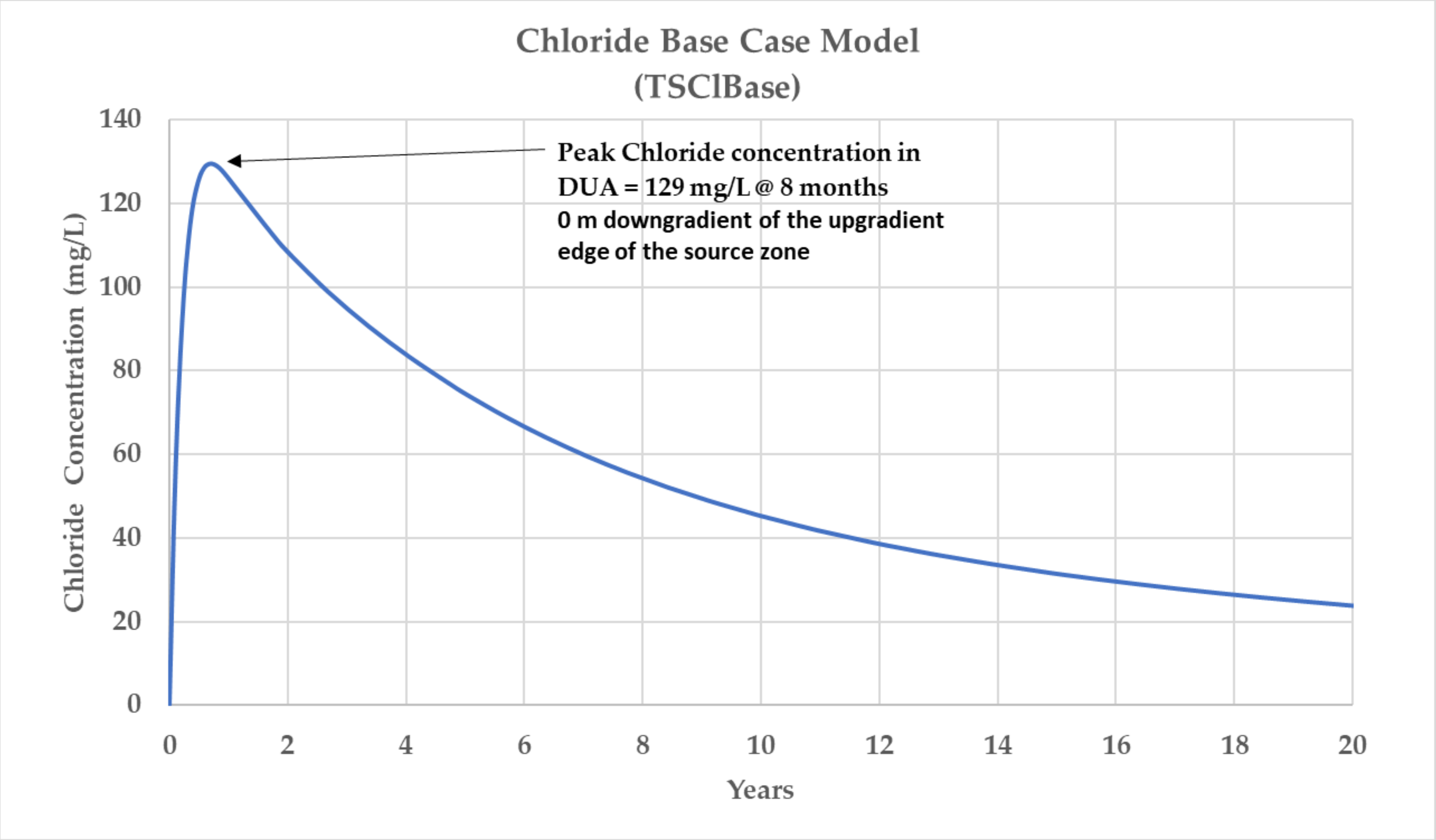
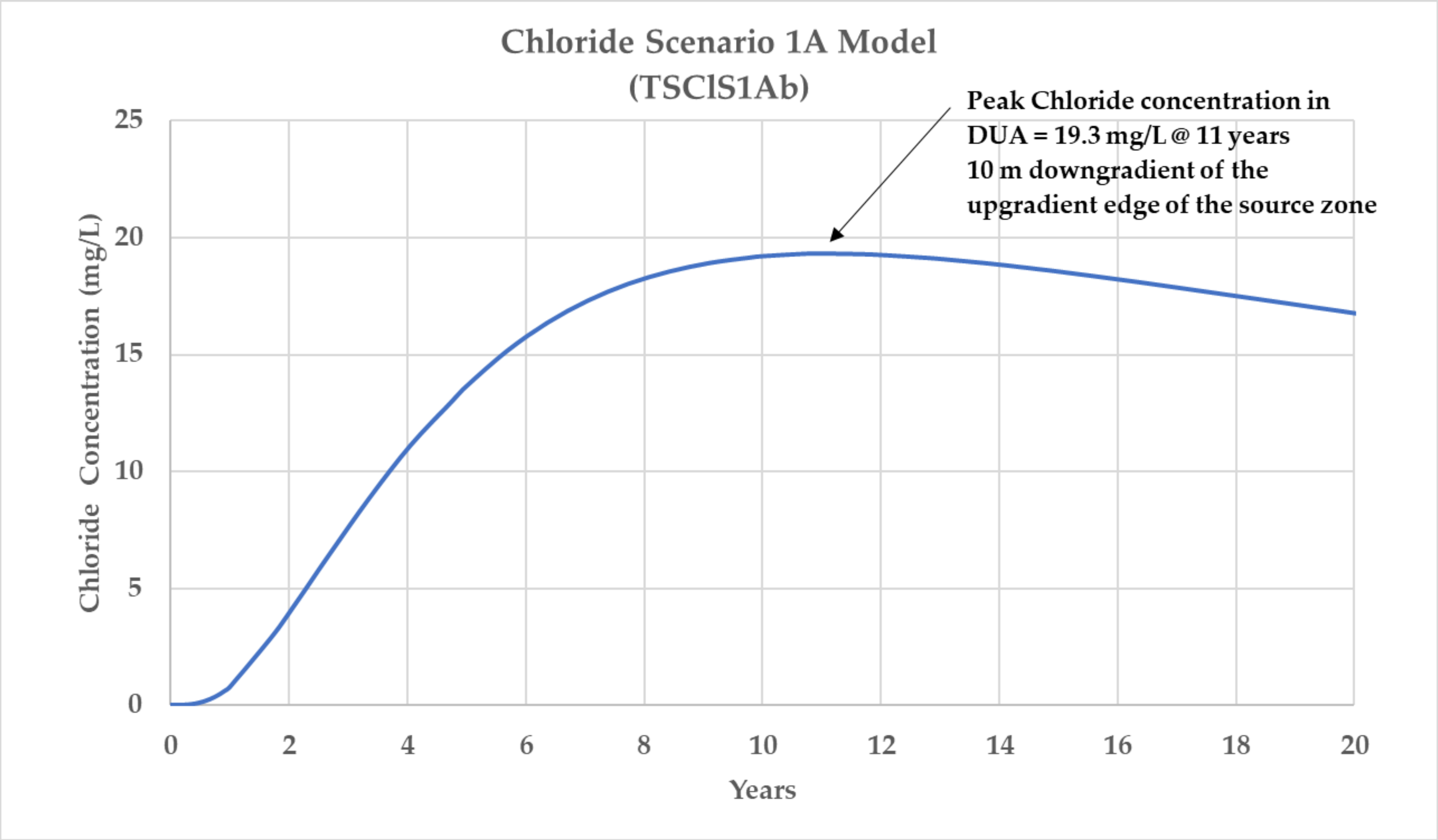
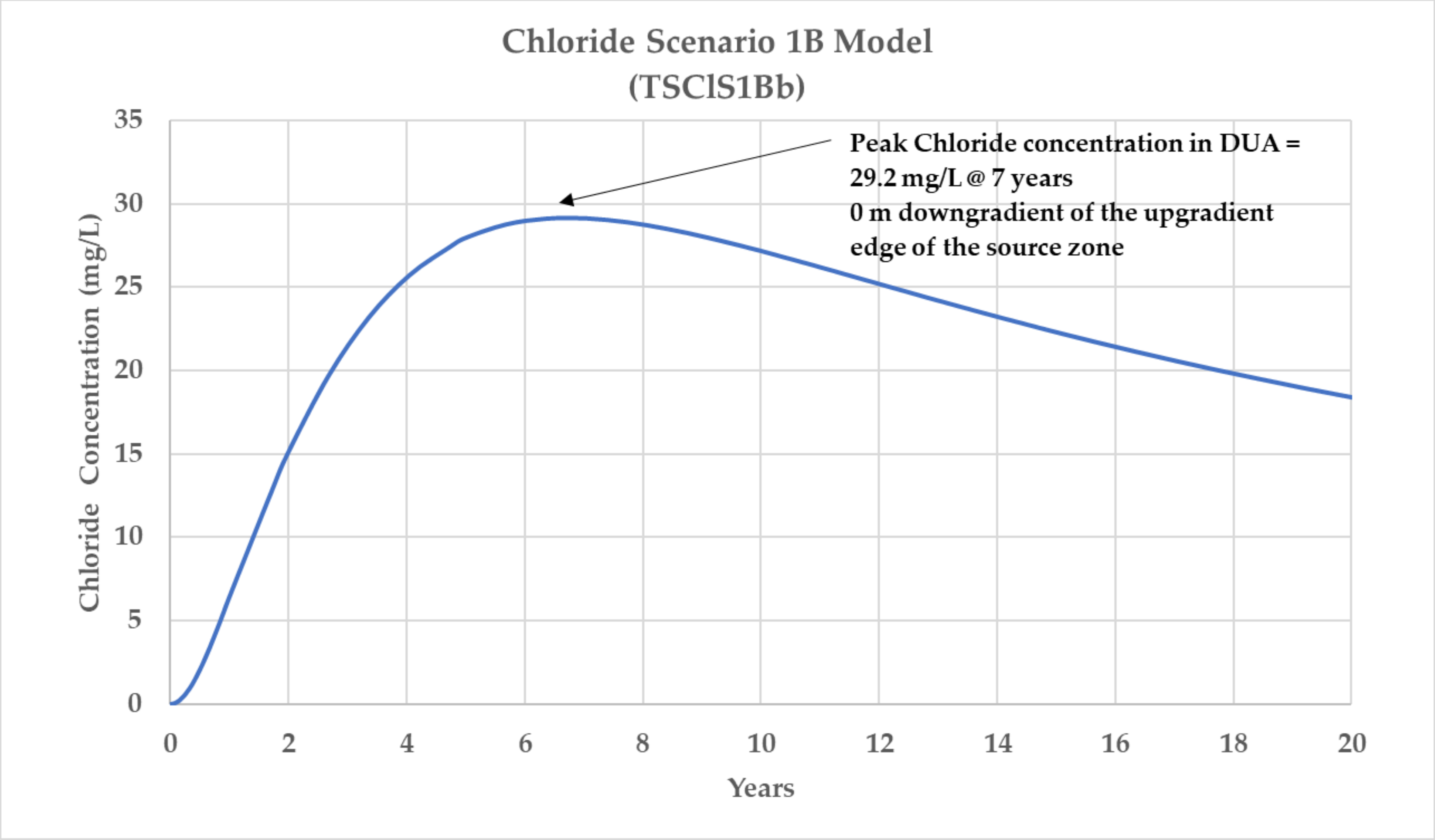


Chloride Base Case Model
(TSClBase)

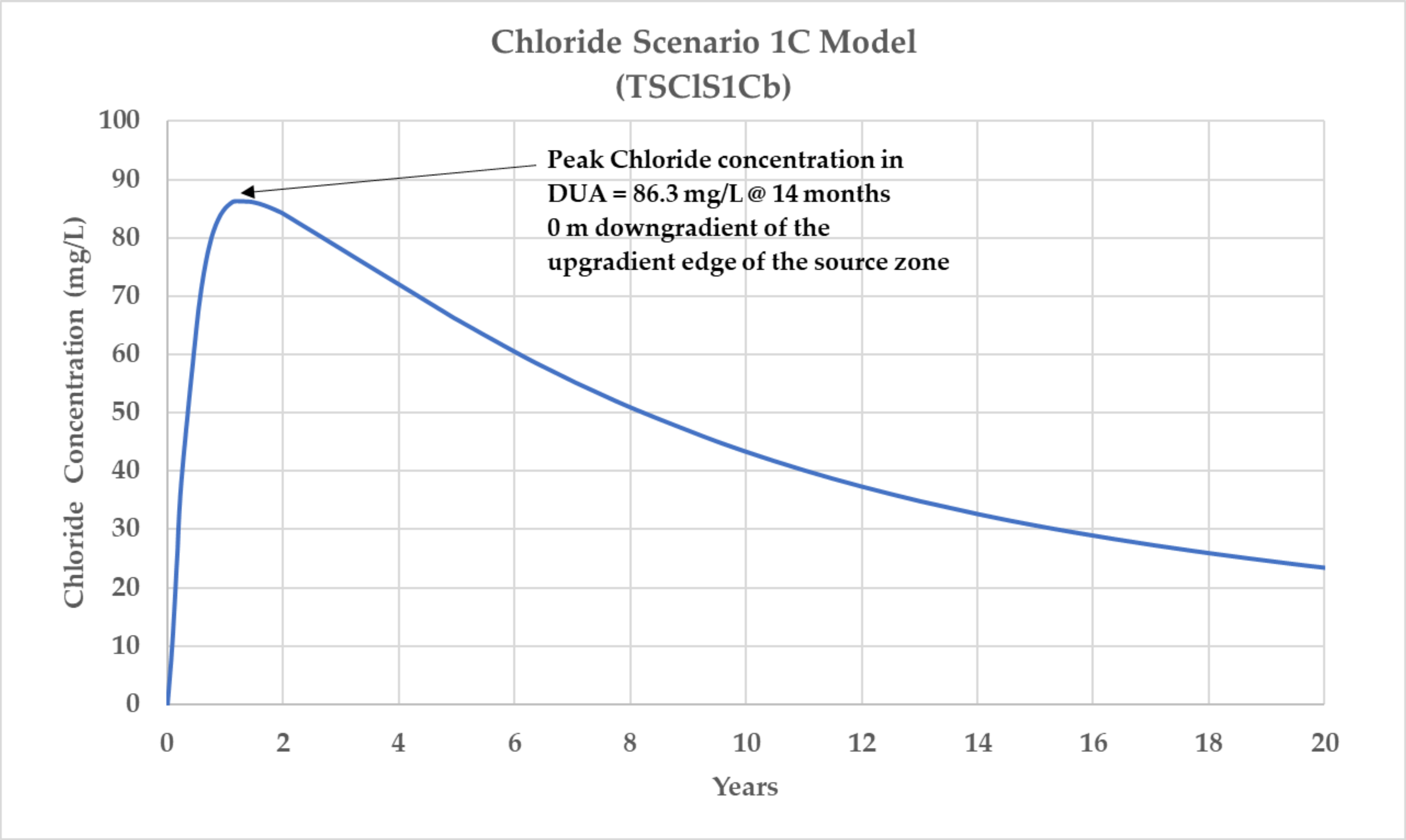
Peak Chloride concentration in
DUA = 129 mg/L @ 8 months
0 m downgradient of the upgradient
edge of the source zone


Chloride Scenario 1A Model
(TSClS1Ab)
Peak Chloride concentration in
DUA = 19.3 mg/L @ 11 years
10 m downgradient of the
upgradient edge of the source zone
Chloride Concentration (mg/L)
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
Years

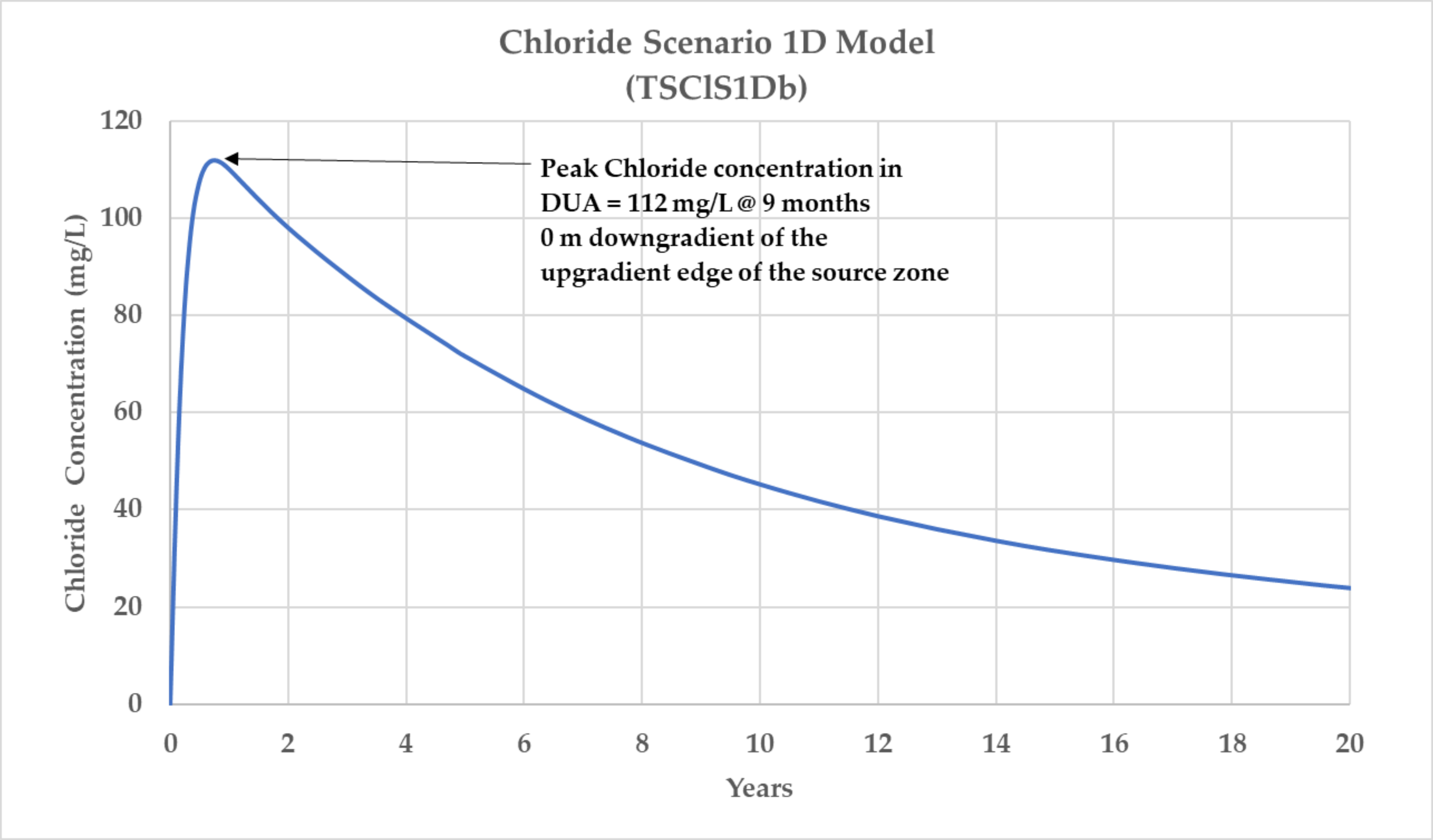


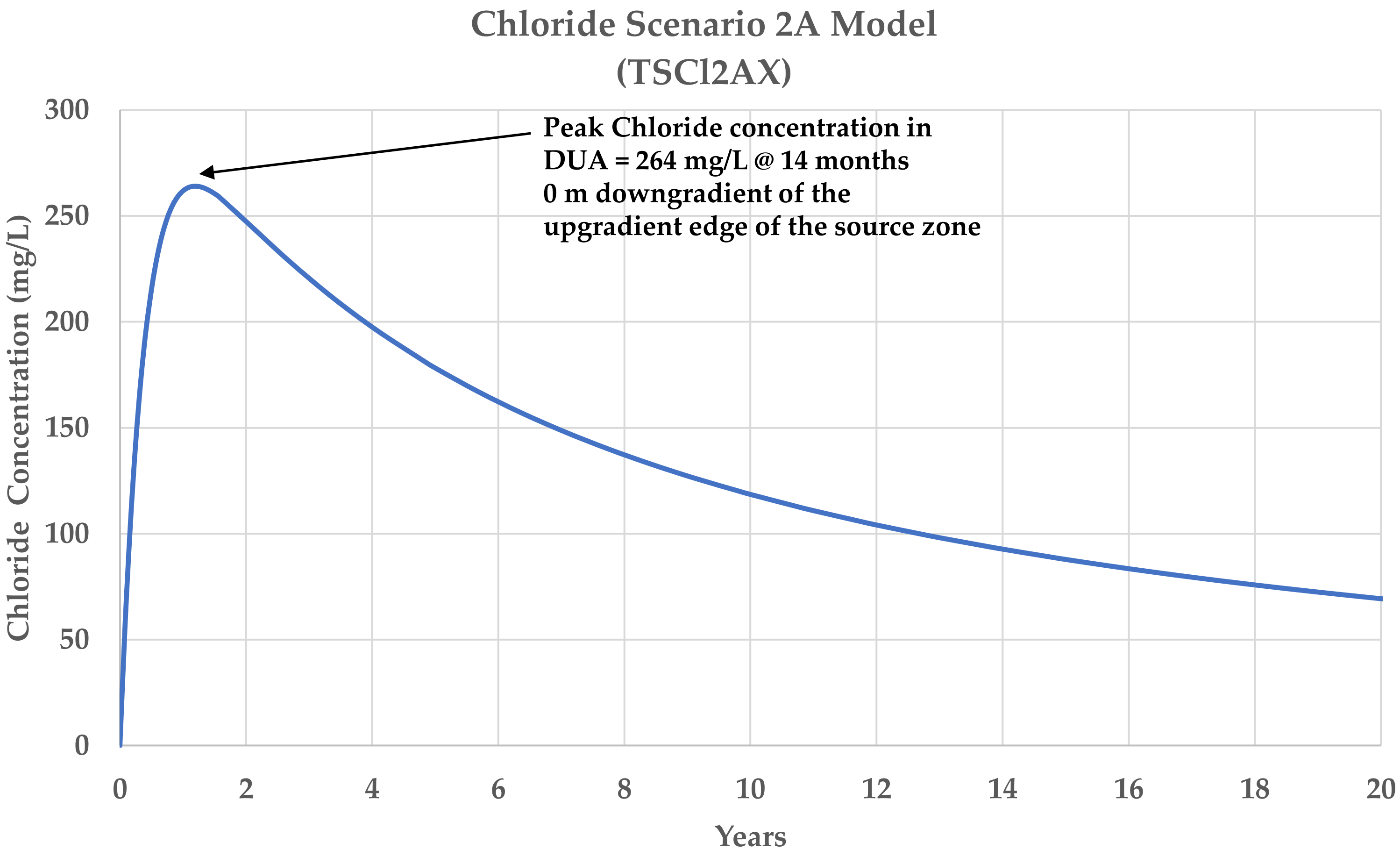
Chloride Scenario 1B Model
(TSClS1Bb)

Peak Chloride concentration in DUA =
29.2 mg/L @ 7 years
0 m downgradient of the upgradient
edge of the source zone



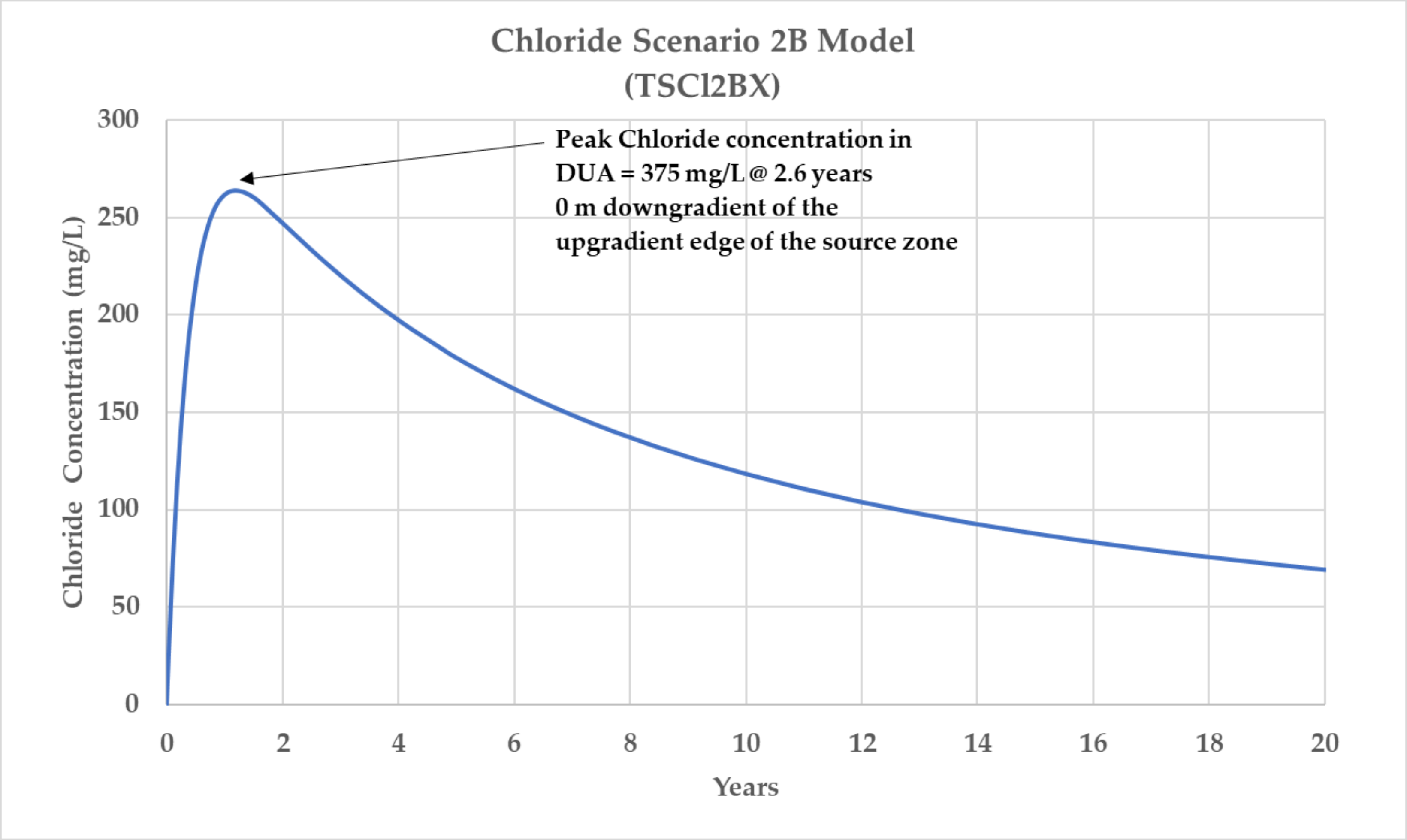
Peak Chloride concentration in
DUA = 86.3 mg/L @ 14 months
0 m downgradient of the
upgradient edge of the source zone


Chloride Scenario 1D Model
(TSClS1Db)
Chloride Concentration (mg/L)
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
Years
Peak Chloride concentration in
DUA = 112 mg/L @ 9 months
0 m downgradient of the
upgradient edge of the source zone

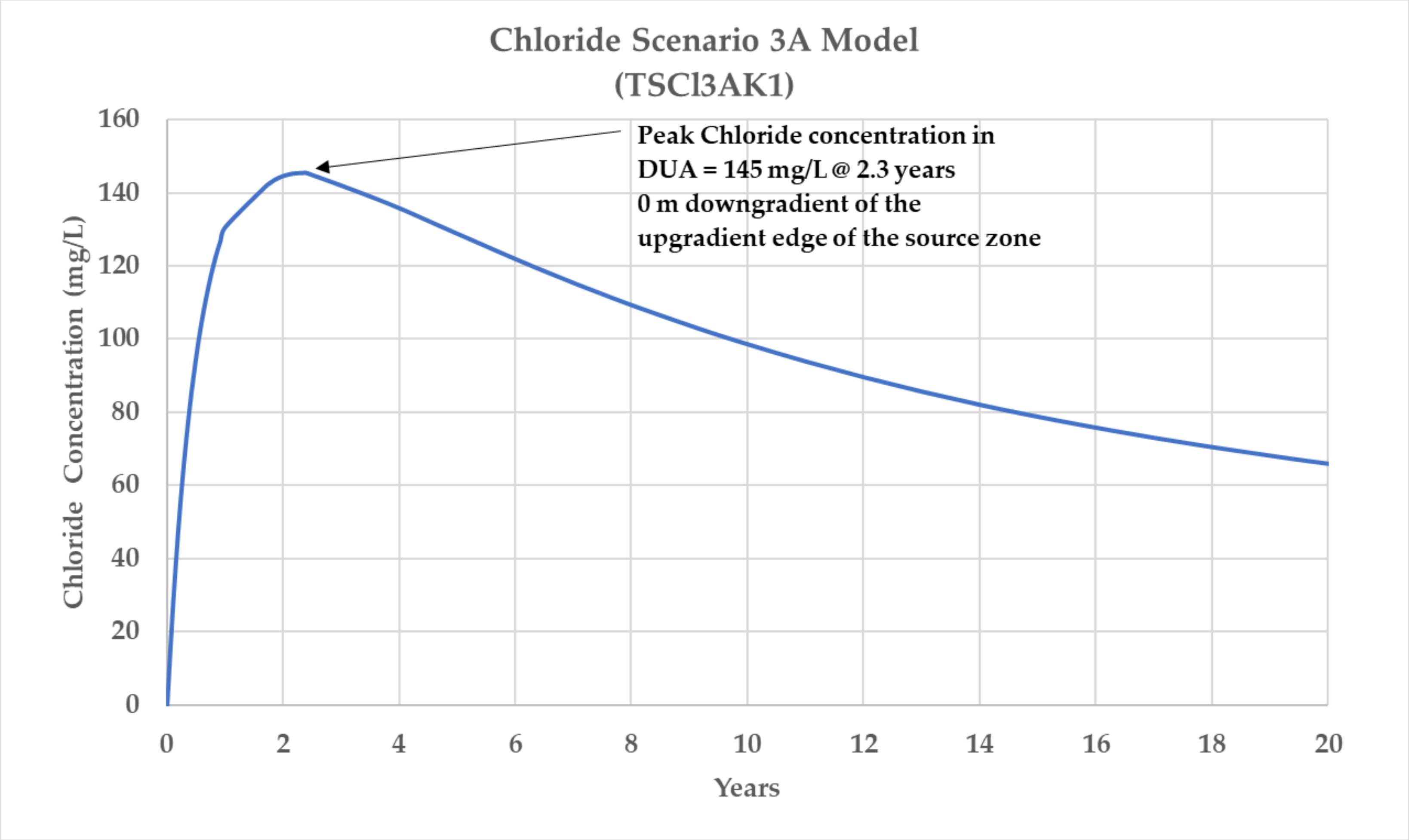


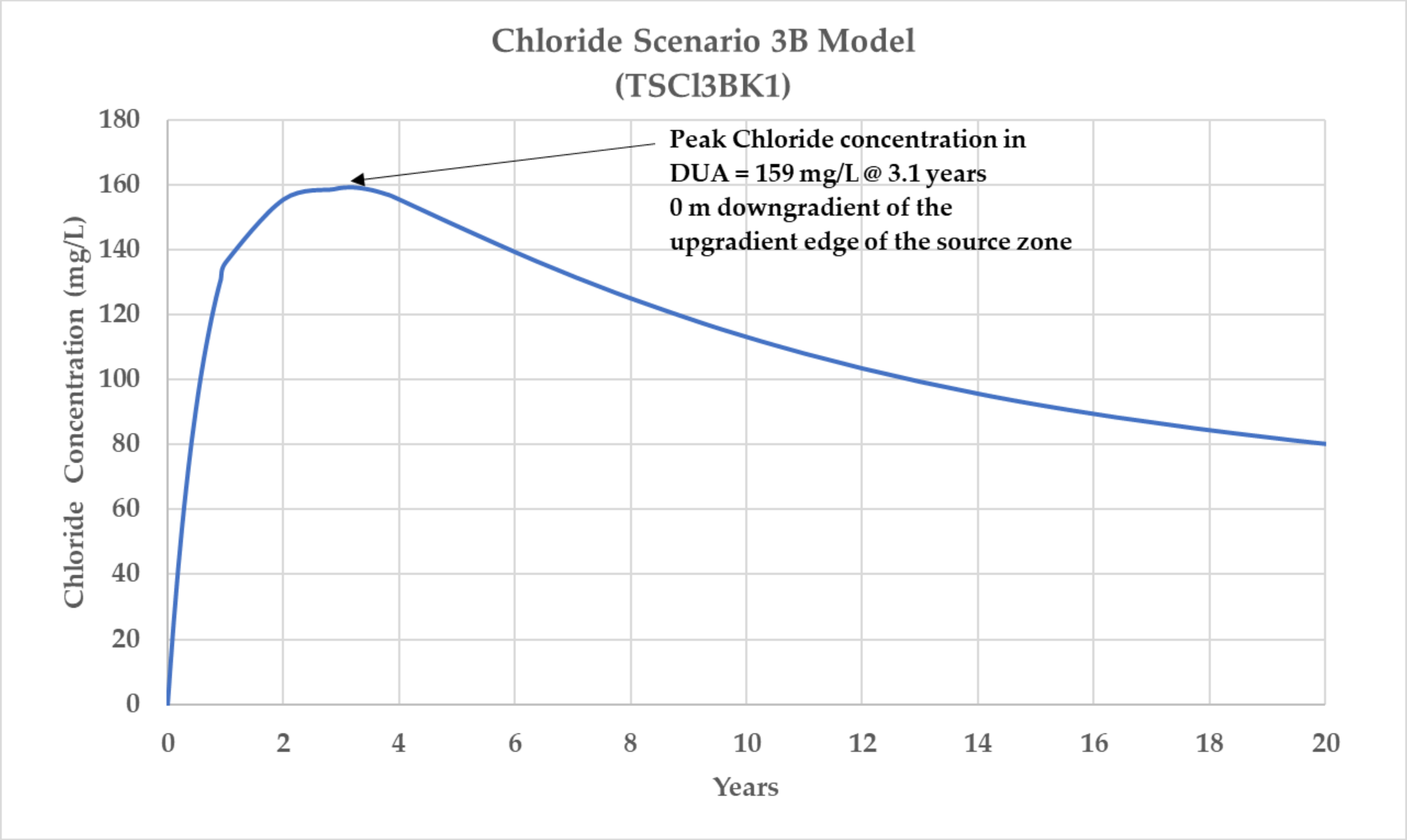
Chloride Scenario 2A Model
(TSCl2AX)

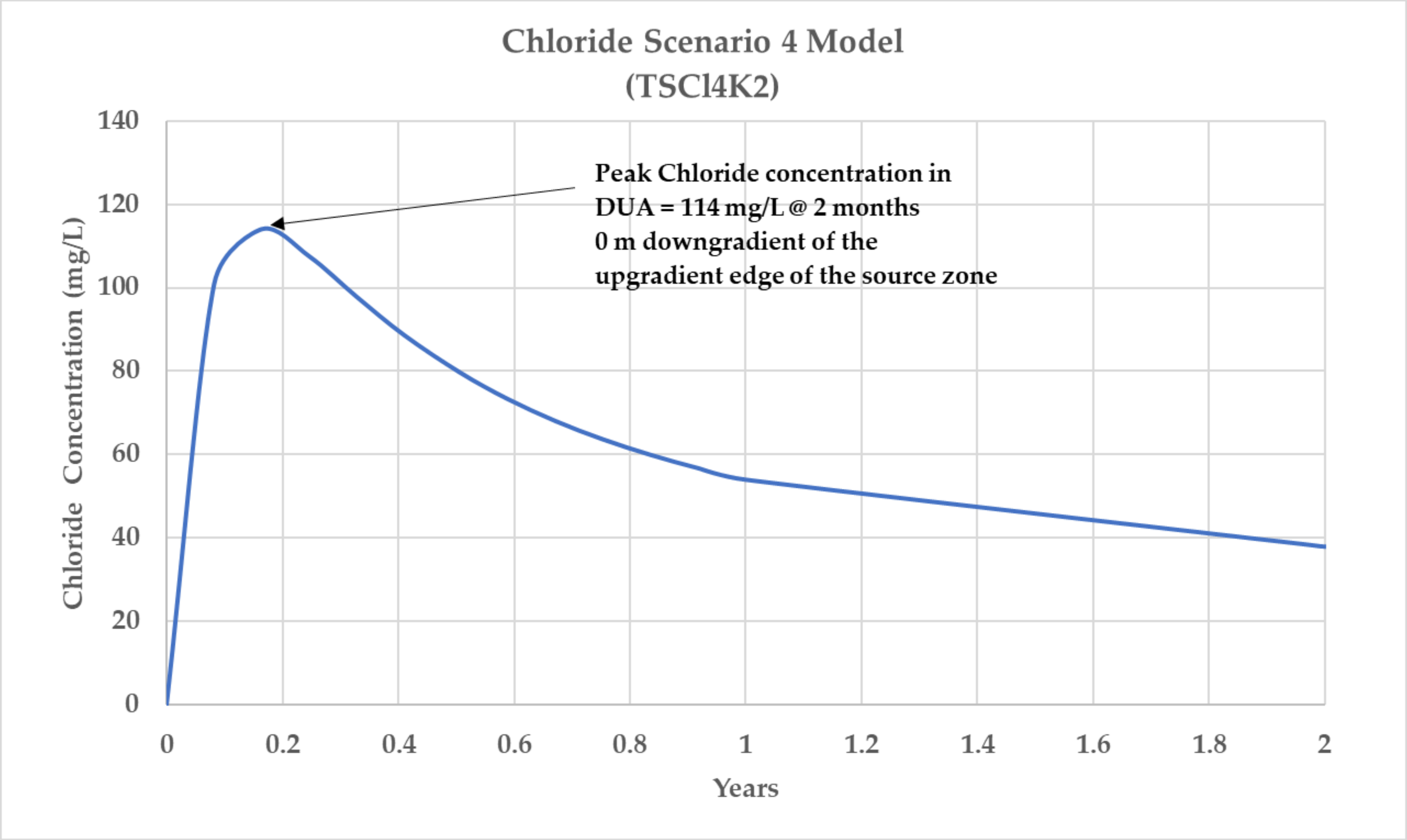
Peak Chloride concentration in
DUA = 264 mg/L @ 14 months
0 m downgradient of the
upgradient edge of the source zone



Peak Chloride concentration in
DUA = 375 mg/L @ 2.6 years
0 m downgradient of the
upgradient edge of the source zone


Chloride Scenario 3A Model
(TSCl3AK1)
Peak Chloride concentration in
DUA = 145 mg/L @ 2.3 years
0 m downgradient of the
upgradient edge of the source zone
Chloride Concentration (mg/L)
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
Years


Chloride Scenario 3B Model
(TSCl3BK1)
Peak Chloride concentration in
DUA = 159 mg/L @ 3.1 years
0 m downgradient of the
upgradient edge of the source zone
Chloride Concentration (mg/L)
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
Years


Chloride Scenario 4 Model
(TSCl4K2)
Chloride Concentration (mg/L)
140
120
100
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Years
Peak Chloride concentration in
DUA = 114 mg/L @ 2 months
0 m downgradient of the
upgradient edge of the source zone

Model Runs	Parameter	Suggested Values/ Changes	Model Number	Peak Concentrations and Arrival Time	Peak Concentration Location
New Base Case	b = 0 m, X = 10 m, K1 = 8E-7 m/s and K2 = 1E-6 m/s	-	TSBEN03bE1	6.75E-02 mg/L @ 6 months	0 m (underneath the source)
Scenario 1A	b	3 m	TSBEN03bA1	1.29E-04 mg/L @ 3.9 years	0 m (underneath the source)
Scenario 1B	b	1 m	TSBEN03bB1	5.45E-03 mg/L @ 1.9 years	0 m From the edge of the source
Scenario 1C	b	0.3 m	TSBEN03bC1	2.80E-02 mg/L @ 1.08 years	0 m (underneath the source)
Scenario 1D	b	0.1 m	TSBEN03bD1	5.05E-02 mg/L @ 8 months	0 m (underneath the source)
Scenario 2A	X	30 m	TSBEN03XA1	9.59E-02 mg/L @ 9 months	0 m (underneath the source)
Scenario 2B	X	100 m	TSBEN03XB1	1.03E-01 mg/L @ 10 months	0 m (underneath the source)
Scenario 3A	K1	1E-7 m/s	TSBENK1A1	3.66E-02 mg/L @ 11 months	0 m (underneath the source)
Scenario 3B	K1	1E-8 m/s	TSBENK1B1	7.25E-02 mg/L @11 months	0 m (underneath the source)
Scenario 4	K2	1E-5 m/s	TSBEN03K21	4.16E-02 mg/L @ 3 months	0 m (underneath the source)

Models are zipped and saved in this folder:

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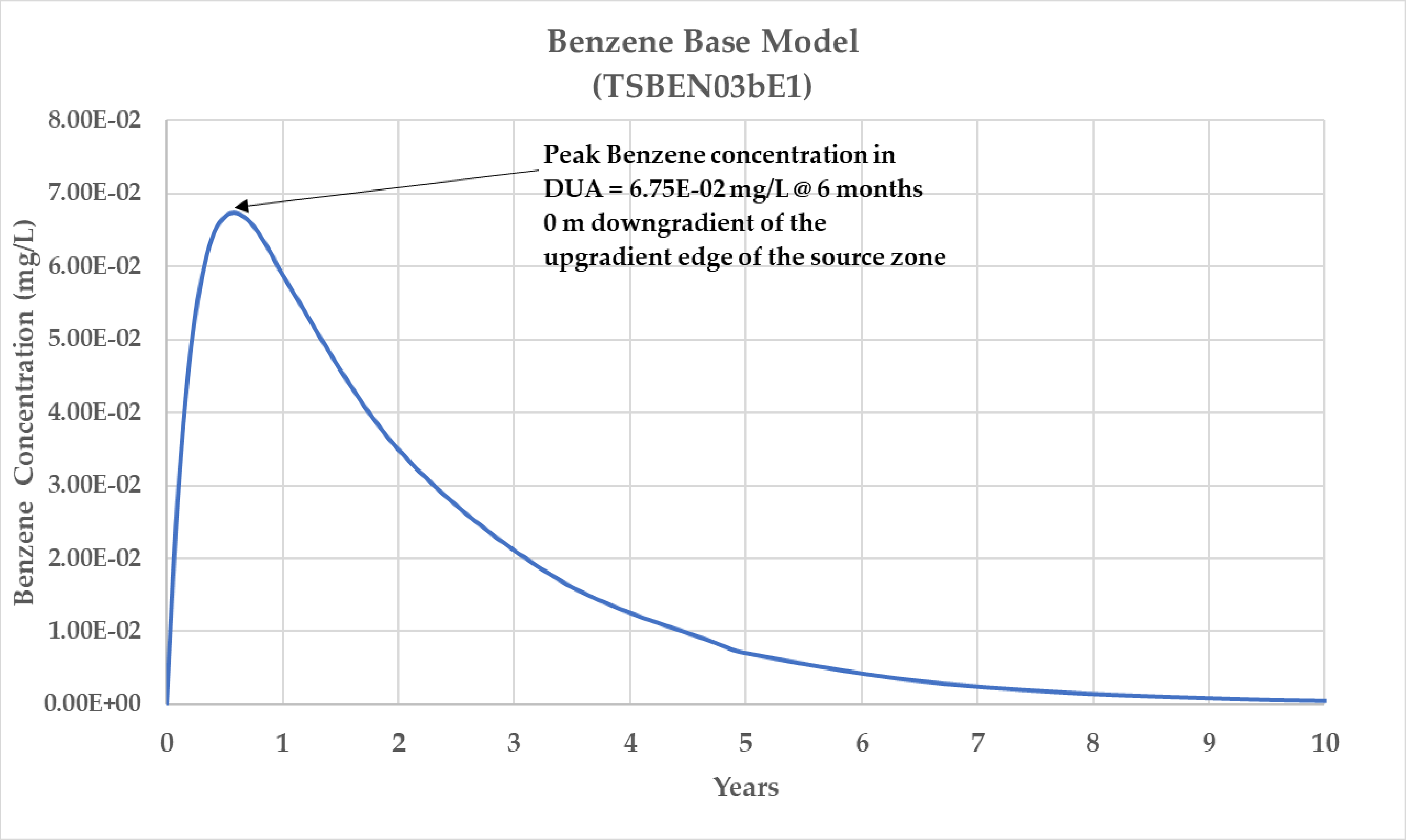
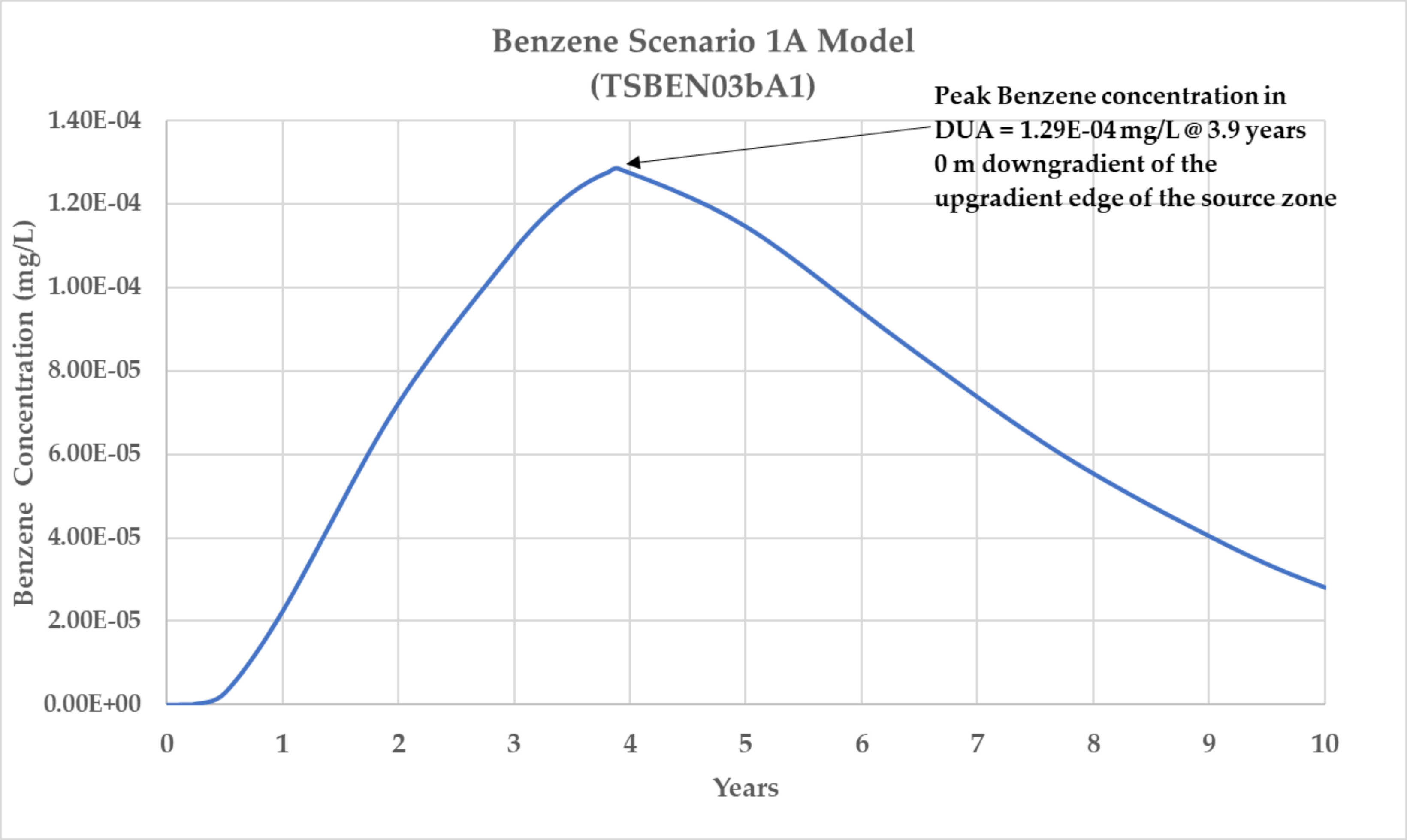
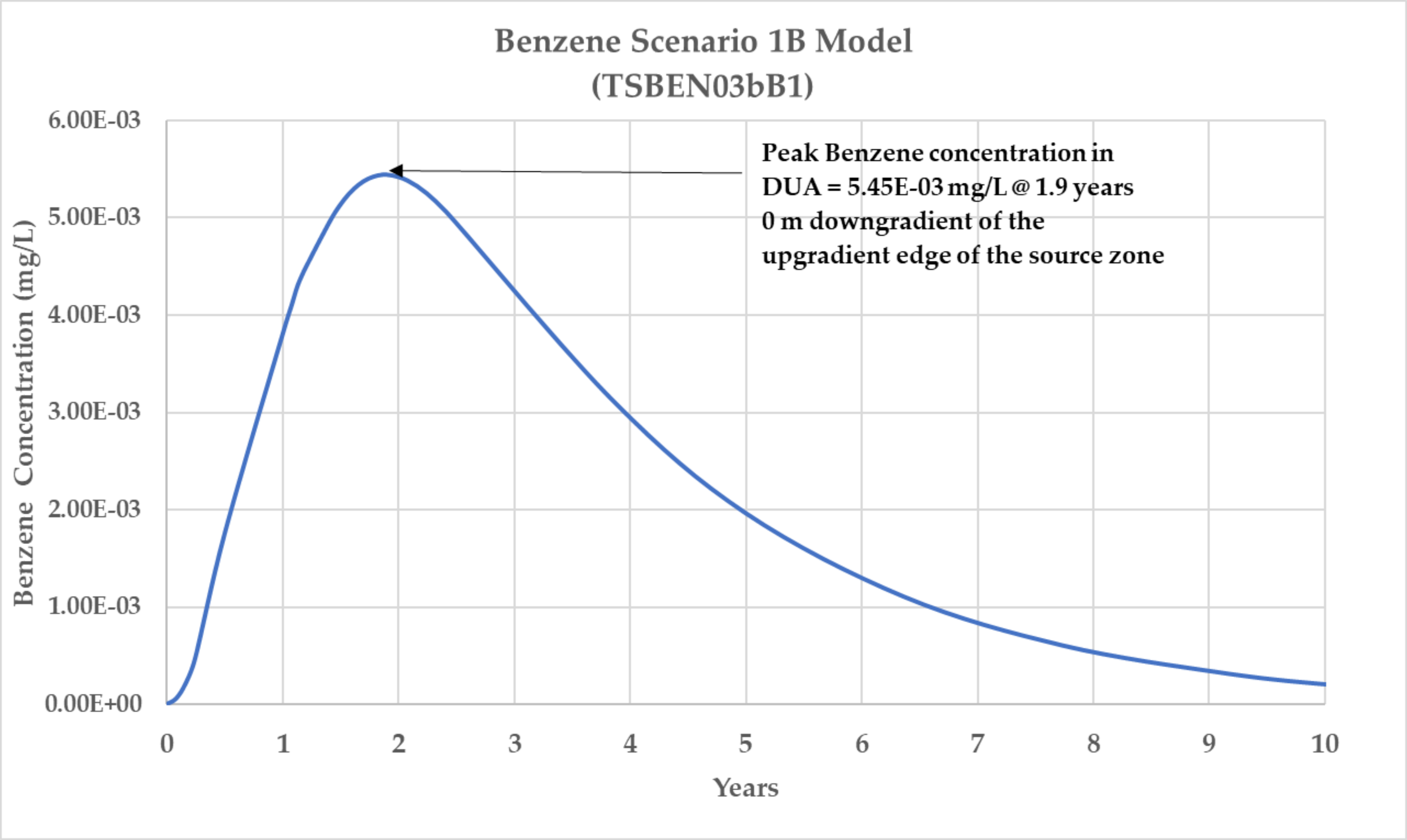
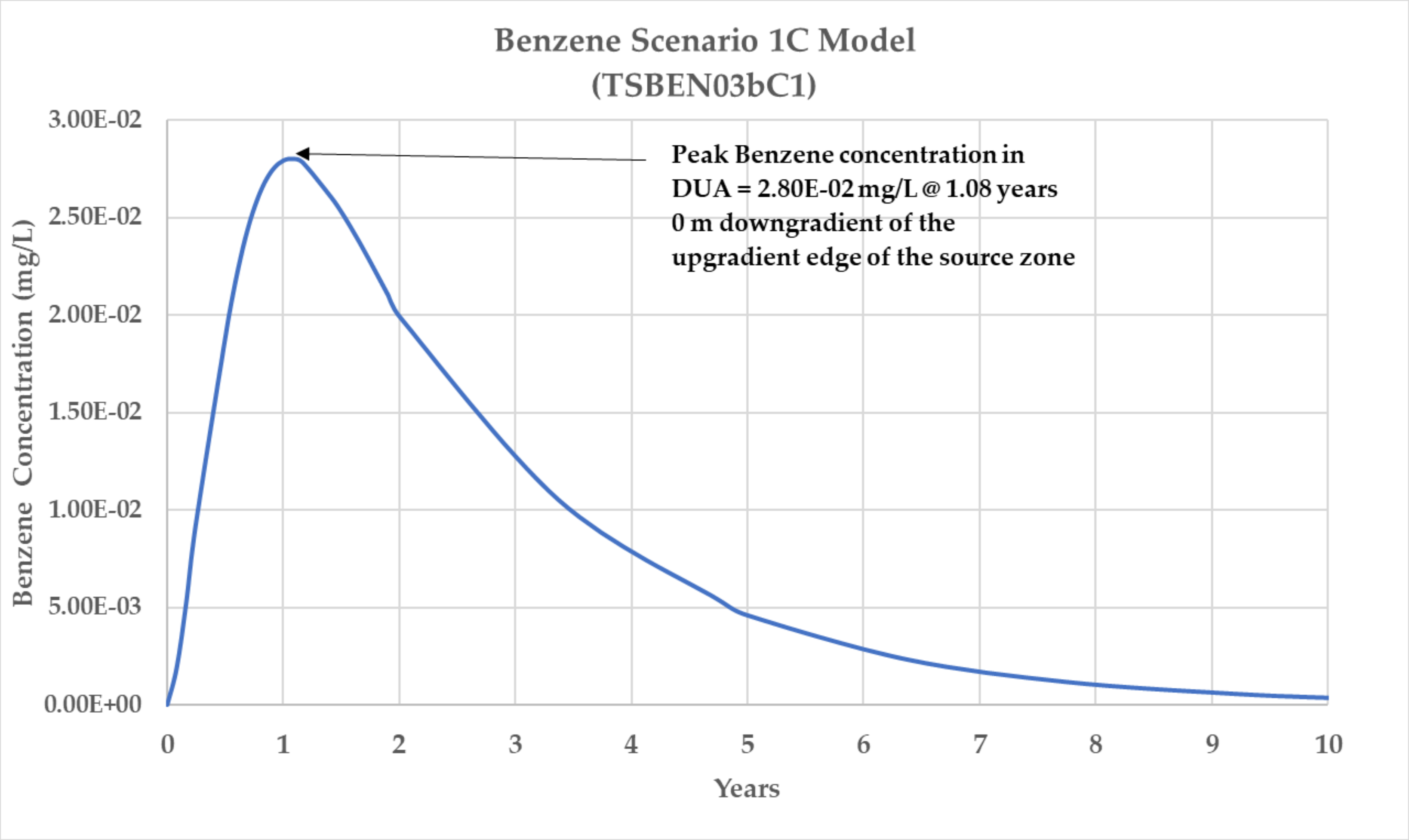
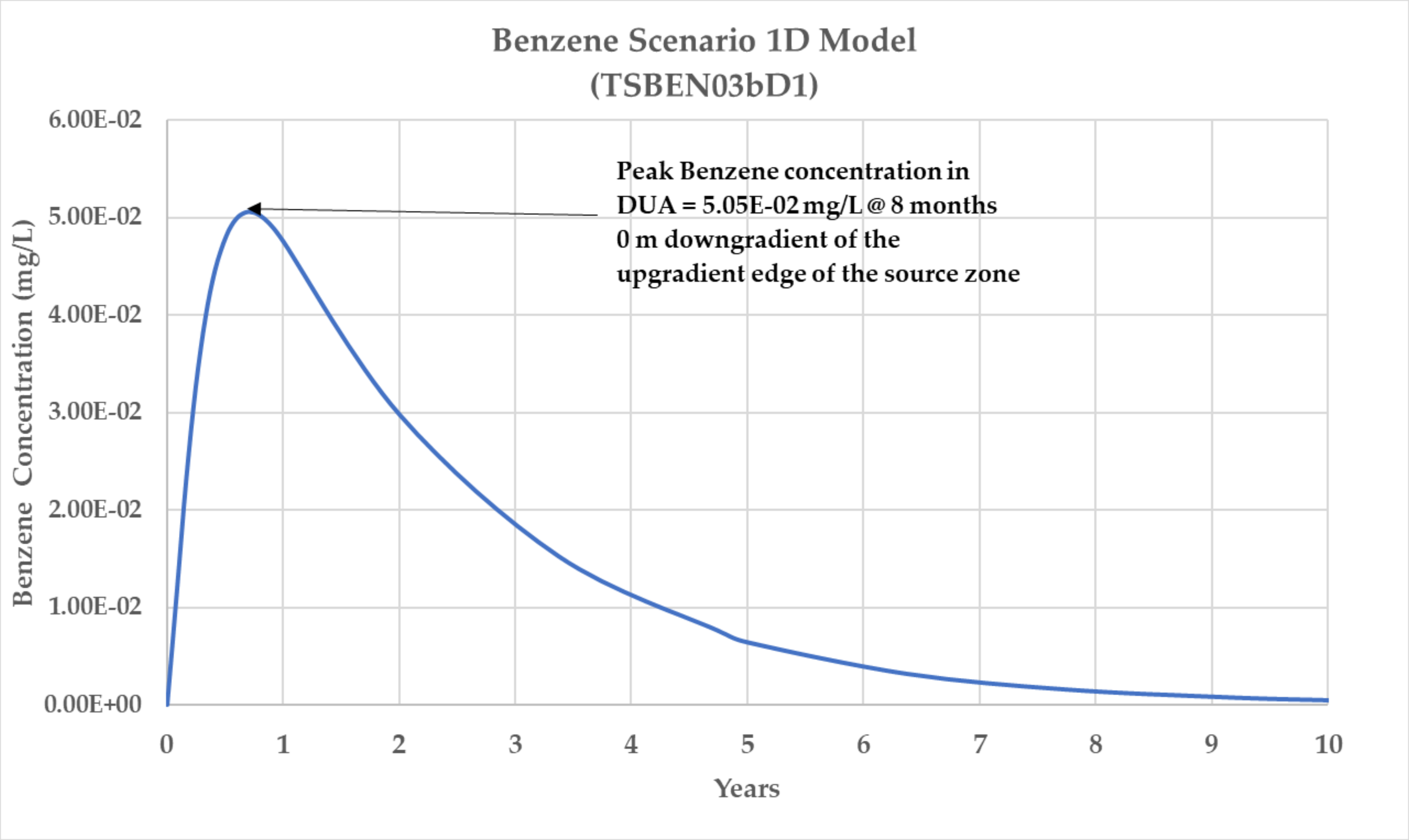
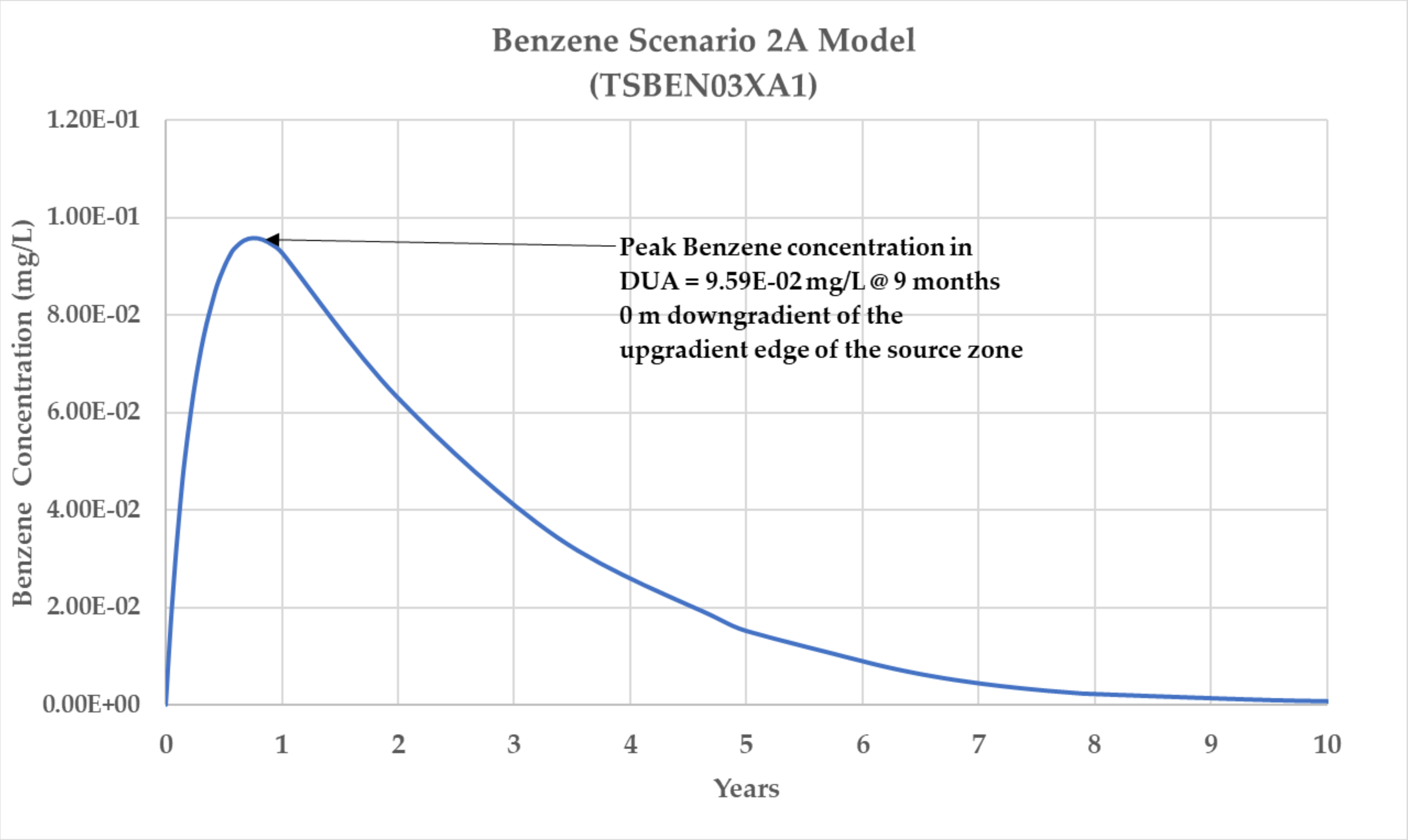

Benzene Base Model
(TSBEN03bE1)
Peak Benzene concentration in
DUA = 6.75E-02 mg/L @ 6 months
0 m downgradient of the
upgradient edge of the source zone
Benzene Concentration (mg/L)
8.00E-02
7.00E-02
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
0
1
2
3
4
5
6
7
8
9
10
Years

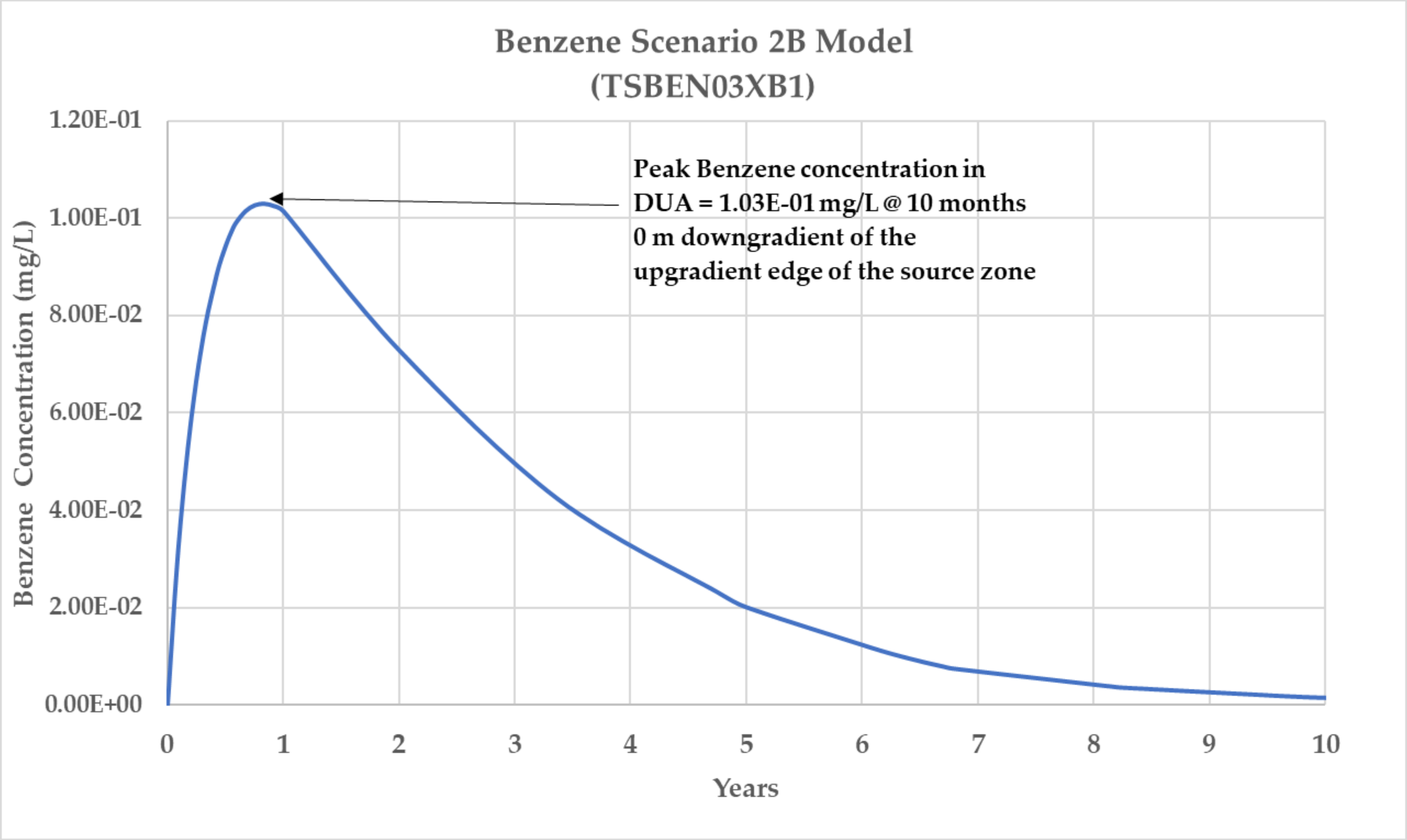

Benzene Scenario 1A Model
(TSBEN03bA1)
Peak Benzene concentration in
DUA = 1.29E-04 mg/L @ 3.9 years
0 m downgradient of the
upgradient edge of the source zone
Benzene Concentration (mg/L)
1.40E-04
1.20E-04
1.00E-04
8.00E-05
6.00E-05
4.00E-05
2.00E-05
0.00E+00
0
1
2
3
4
5
6
7
8
9
10
Years

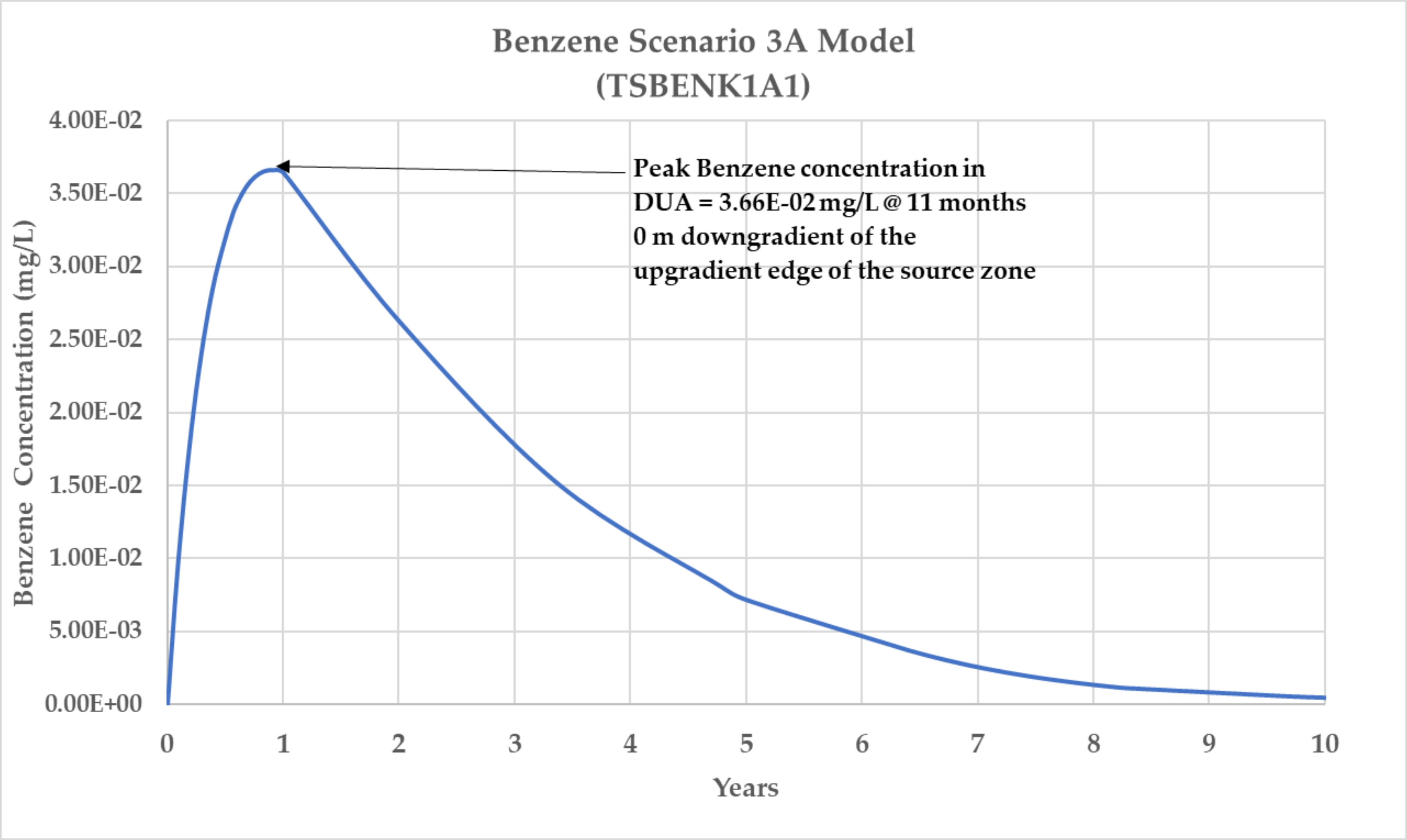

Benzene Scenario 1B Model
(TSBEN03bB1)
6.00E-03
5.00E-03
4.00E-03
3.00E-03
2.00E-03
1.00E-03
0.00E+00
Benzene Concentration (mg/L)
0
1
2
3
4
5
6
7
8
9
10
Years
Peak Benzene concentration in DUA = 5.45E-03 mg/L @ 1.9 years 0 m downgradient of the upgradient edge of the source zone

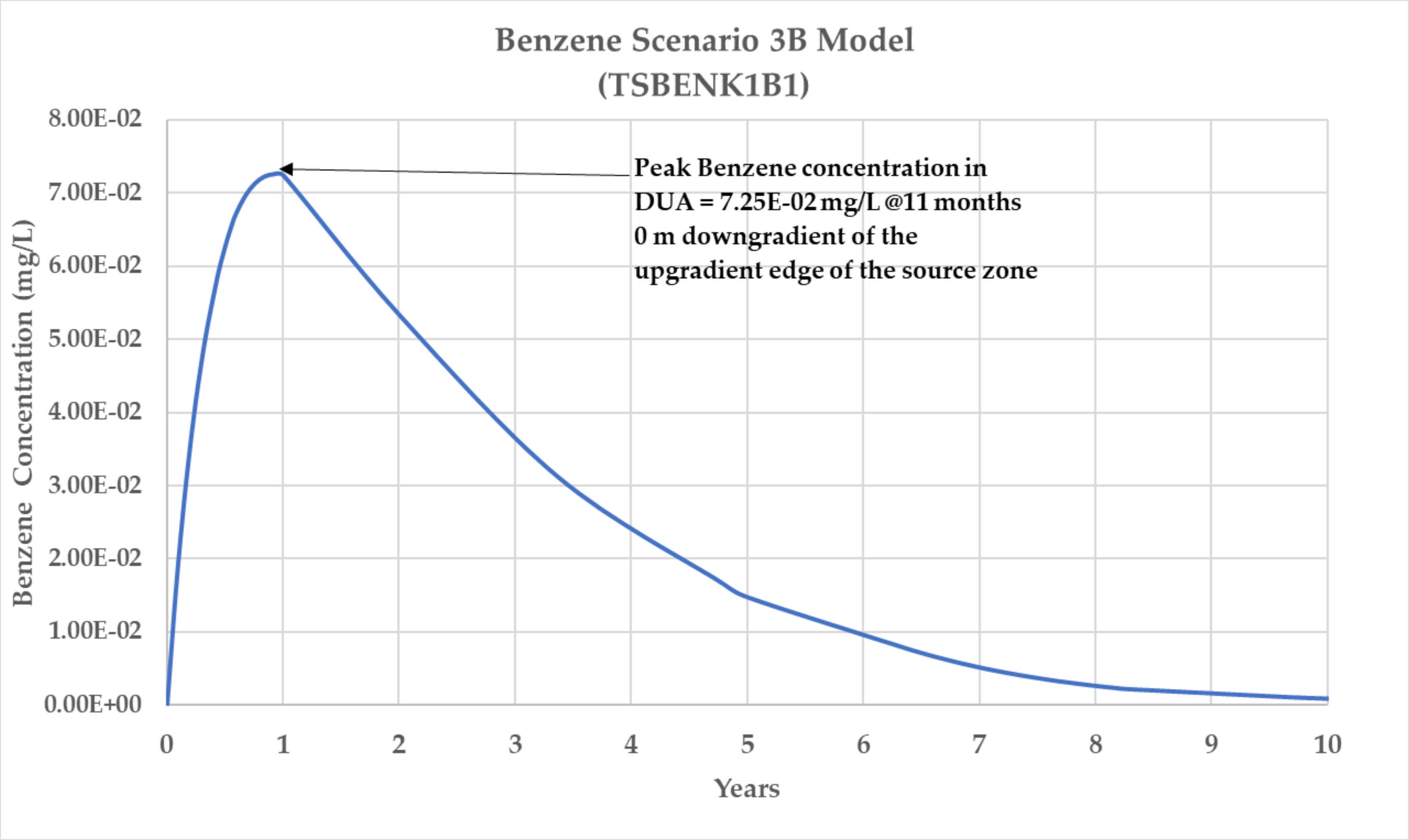

Benzene Scenario 1C Model
(TSBEN03bC1)
Benzene Concentration (mg/L)
3.00E-02
2.50E-02
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
0
1
2
3
4
5
6
7
8
9
10
Years
Peak Benzene concentration in DUA = 2.80E-02 mg/L @ 1.08 years 0 m downgradient of the upgradient edge of the source zone

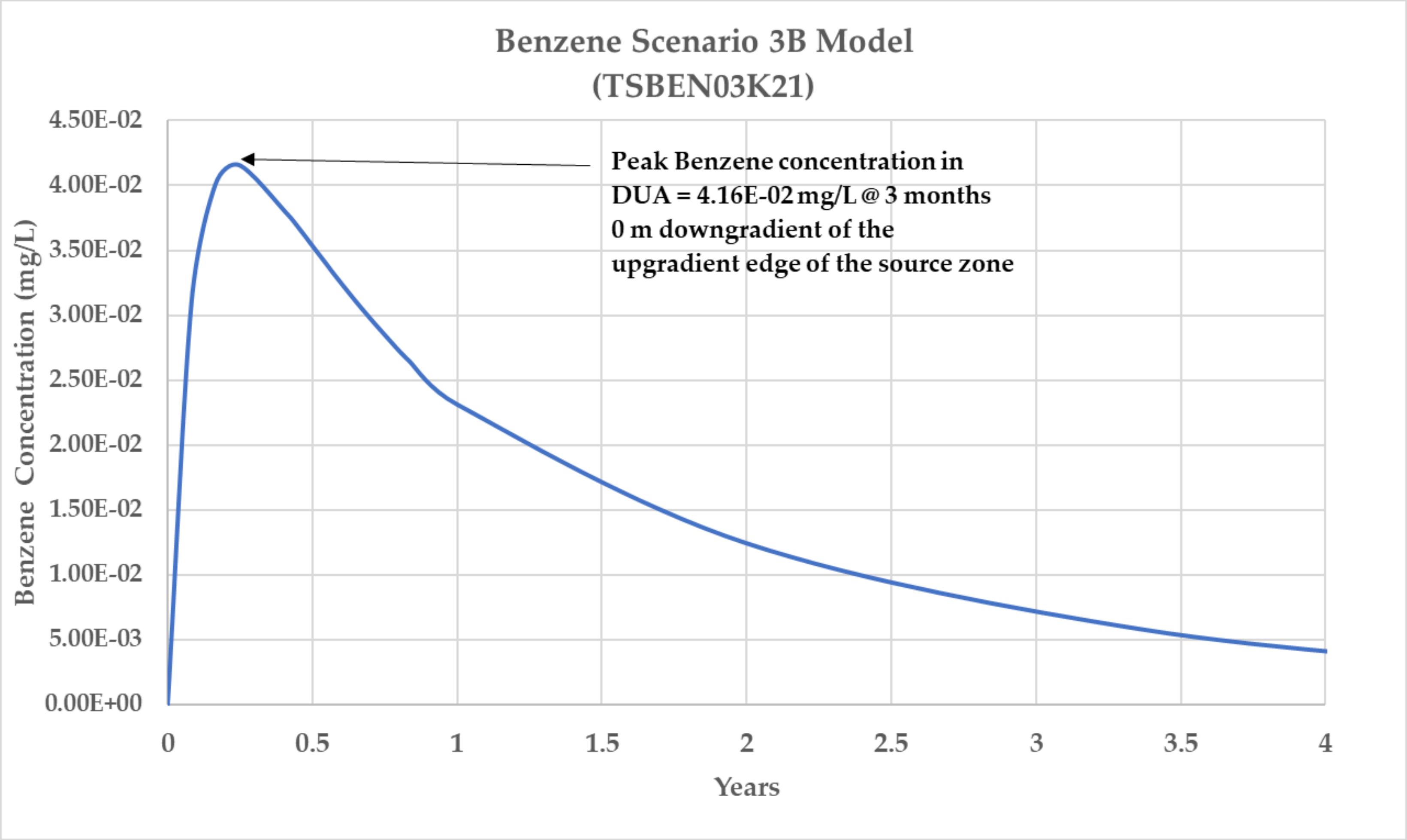

Benzene Scenario 1D Model
(TSBEN03bD1)
Benzene Concentration (mg/L)
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
0
1
2
3
4
5
6
7
8
9
10
Years
Peak Benzene concentration in
DUA = 5.05E-02 mg/L @ 8 months
0 m downgradient of the
upgradient edge of the source zone


Benzene Scenario 2A Model
(TSBEN03XA1)
Benzene Concentration (mg/L)
1.20E-01
1.00E-01
8.00E-02
6.00E-02
4.00E-02
2.00E-02
0.00E+00
0
1
2
3
4
5
6
7
8
9
10
Years
Peak Benzene concentration in
DUA = 9.59E-02 mg/L @ 9 months
0 m downgradient of the
upgradient edge of the source zone


Benzene Scenario 2B Model
(TSBEN03XB1)
1.20E-01
1.00E-01
8.00E-02
6.00E-02
4.00E-02
2.00E-02
0.00E+00
Benzene Concentration (mg/L)
0
1
2
3
4
5
6
7
8
9
10
Years
Peak Benzene concentration in
DUA = 1.03E-01 mg/L @ 10 months
0 m downgradient of the
upgradient edge of the source zone


Benzene Scenario 3A Model
(TSBENK1A1)
Benzene Concentration (mg/L)
4.00E-02
3.50E-02
3.00E-02
2.50E-02
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
0
1
2
3
4
5
6
7
8
9
10
Years
Peak Benzene concentration in DUA = 3.66E-02 mg/L @ 11 months 0 m downgradient of the upgradient edge of the source zone


Benzene Scenario 3B Model
(TSBENK1B1)
Peak Benzene concentration in
DUA = 7.25E-02 mg/L @11 months
0 m downgradient of the
upgradient edge of the source zone
Benzene Concentration (mg/L)
8.00E-02
7.00E-02
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
0
1
2
3
4
5
6
7
8
9
10
Years


Benzene Scenario 3B Model
(TSBEN03K21)
4.50E-02
4.00E-02
3.50E-02
3.00E-02
2.50E-02
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
Benzene Concentration (mg/L)
0
0.5
1
1.5
2
2.5
3
3.5
4
Years
Peak Benzene concentration in DUA = 4.16E-02 mg/L @ 3 months 0 m downgradient of the upgradient edge of the source zone