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September 22, 2017

British Columbia Ministry of Environment and Climate Change Strategy
Land Remediation Section
525 Superior Street
Victoria, BC V8V 1T7

Re: Results of a Sensitivity Analysis for the Omnibus Groundwater Model

1.0 INTRODUCTION AND BACKGROUND

The following recommendations were prepared by Core6 Environmental (Core6) for the British Columbia Ministry of Environment and Climate Change Strategy (BCMOE) with funding provided by BCMOE and the Society of Contaminated Sites Approved Professionals of British Columbia (CSAP). It is recognized that any BCMOE protocols or guidance informed by these recommendations, may differ from those provided herein.

The BC Contaminated Sites Regulation (CSR) Schedule 5 matrix soil standards were originally derived in 1996 using the Contaminated Sites Standards Taskgroup (CSST) model. The model was specifically developed to simulate the transport of various organic and inorganic contaminants of concern (COCs) in groundwater towards various receiving environments, aimed to ultimately protect the four main water uses (i.e., drinking water, aquatic life, irrigation water, livestock water). Recently, the standards have been updated using a refined version of the CSST model, now renamed as the Omnibus model. In November 2017, it will be possible to calculate site-specific soil standards using the Omnibus model under Protocol 2 (P2) of the CSR. In an effort to promote and simplify the use of the P2 model, a sensitivity analysis of the model was completed.

1.1 Objectives

To define and prioritize a list of model input parameters that are considered most sensitive to the calculated site-specific soil standards using the current Omnibus groundwater model, such that they can facilitate use under P2. This will allow a focused assessment on which model parameters should be considered for potential modification or update for use in updated version of the model.

1.2 Scope of Work

The following tasks were completed to meet the objectives of the sensitivity analysis:

- Identify representative or surrogate COCs to represent petroleum hydrocarbons and inorganics to carry through the sensitivity analysis;
- Identify all the potential model input parameters that could be varied in the sensitivity analysis;
- Preparation of graphs to illustrate and quantify the relative sensitivity of the model input parameters

- Ranking of the model input parameters in terms of highest to lowest relative sensitivity; and
- Provision of recommendations for which model input parameters should be updated for use in the upcoming release of the P2 model.

2.0 METHODOLOGY

Prior to initiating the sensitivity analysis, a complete list of model input parameters were defined (i.e., those that could be modified by the user when calculating site-specific soil standards).

Based on discussions with BCMOE and the P2 Technical Working group, benzene was used to represent petroleum hydrocarbons and copper to represent inorganic or metal constituents. Only these two constituents were simulated due to the large number of simulations required during the sensitivity analysis process (see further below). Once the list of model input parameters were defined, the steady-state version of the Omnibus model was used for the sensitivity analysis work.

In an effort to ensure that each model input parameter would be active, the depth to water was set to 6 metres below ground surface (mbgs) compared to the default depth of 3 mbgs. This was done to ensure that the unsaturated transport model would be active, thus activating model input parameters that are used in the unsaturated transport model.

Model simulations were then completed by varying each model input parameter according to a 25%, 50% and 75% increase to determine the result on the predicted site-specific soil standard. Other parameter-specific scaling factors were not evaluated. For example, order of magnitude changes for hydraulic conductivity, or increased distances to receptors; as this would result in an inconsistent scaling of parameters and increased difficulty when discerning and quantifying relative parameter sensitivity.

The base case (i.e., Omnibus default) for a given model input parameter was also simulated such that the base case site-specific soil standard values could be compared to the results that were obtained during three increased steps for that parameter in the sensitivity analysis. Accordingly, four model simulations were completed for each identified model input parameter (17 model input parameters were identified in total), resulting in a total of 68 model simulations. Due to the large amount of data generated with so many simulations, only the site-specific soil standards for protection of the drinking water use (DW) pathway were carried forward during the sensitivity analysis work. Since the DW standards are generally more stringent compared to the other three water uses, the results of the DW pathway were considered sufficient to allow identification of the most sensitive model input parameters.

Subsequent to completion of the model simulations for each of the individual model input parameters, the results were graphed to illustrate their relative sensitivity to base case conditions. And sensitivities were also ranked to identify which model input parameters require greatest consideration for potential modification when used in the P2 model.

3.0 RESULTS AND DISCUSSION

The following model input parameters were considered and simulated as part of the sensitivity analysis.

- Source Length
- Source Width
- Source Depth
- Precipitation
- Runoff Rate & Evapotranspiration
- Fraction of Organic Carbon
- Water Filled Porosity
- Aquifer Thickness
- Depth to Water
- Total Porosity
- Effective Porosity
- Soil pH
- Soil Bulk Density
- Constituent half-life

- Distance to Point of Compliance
- Darcy Flux (includes K and i)
- Distribution Coefficient (Koc / Kd)
- Frozen Days

Results of the sensitivity analysis are present on the attached graphs. A brief summary of the results for each model input parameter in reference to the graphs is summarized in **Table 1** and **Table 2** below.

Table 1. Summary of Sensitivity Analysis Results for Organic Constituents (Benzene)

Model Input Parameter	Soil Conc. at Source Cs (mg/kg)	Comments / Observations
Source Length	4.27 to 4.24	**Little change (1.01X) –** parameter used to calculate dilution factor and mixing zone depth
Source Width	N/A	**No change –** parameter used in the saturated transport model
Source Depth	4.27 to 0.15	**28.5X change –** parameter used in the unsaturated transport model to calculate the unsaturated zone thickness
Precipitation	4.27 to 0.25	**17.1X change –** parameter used in unsaturated transport model to calculate infiltration rate and mixing zone model to calculate dilution factor and mixing zone depth
RO + ET	4.27 to 880	**206X change –** same use as Precipitation
Fraction of Organic Carbon	4.27 to 88.8	**20.8X change –** parameter used in leachate partitioning model, and unsaturated and saturated transport models when calculating retardation factor
Water Filled Porosity	4.27 to 5.46	**Little change (1.3X)** - Used in leachate partitioning model and unsaturated transport model to calculate vertical unsaturated groundwater velocity and retardation factor
Distance to Point of Compliance	4.27 to 5.42	**Little change (1.3X) –** used in saturated transport model. Sensitivity increases substantially with increasing distance.
Aquifer Thickness	4.27 to 4.29	**Very little change –** parameter used in mixing zone calculation when determining mixing zone depth
Depth to Water	0.03 to 12.07	**402X change –** parameter used in the unsaturated transport model to calculate the unsaturated zone thickness
Total Porosity	4.27 to 4.18	**Little change (1.02X)** - Used indirectly to calculate air filled porosity and when calculating retardation factor
Effective Porosity	4.27 to 4.94	**Little change (1.3X) –** parameter used to calculate the groundwater velocity which is used in the saturated transport model and mixing zone model to calculate dilution factor and mixing zone depth
Darcy Flux	4.27 to 4.94	**Little change (1.2X) –** parameter used in the saturated model and mixing zone model to calculate dilution factor and mixing zone depth
Soil pH	N/A	N/A to organic constituents
Bulk Density	4.27 to 50.76	**11.9X change –** parameter used in the leachate partitioning model, unsaturated and saturated transport models when calculating the retardation factor
Half-Life	4.27 to 0.64	**6.7X change –** parameter used in the saturated and unsaturated transport models to simulate solute transport
Distribution Coefficient (Koc)	4.27 to 88.8	**20.8X change –** Used in the leachate partitioning model
Frozen Days	4.27 to 1.92	**2.2X change** - Used in unsaturated transport model to define the Half-Life

Table 2. Summary of Sensitivity Analysis Results for Inorganic Constituents (Copper)

Model Input Parameter	Soil Concentration at Source - Cs (mg/kg)	Comments / Observations
Source Length	31959.9 to 31732.8	**Little change (1.01X) –** parameter used to calculate dilution factor and mixing zone depth
Source Width	31959.9 to 31959.9	**No change –** parameter used in the saturated transport model
Source Depth	31959.9 to 31959.9	**No change –** parameter used in the unsaturated transport model to calculate the unsaturated zone thickness – unsaturated transport model inactive for inorganic contaminants
Precipitation	31959.9 to 2160616	**1.5X change –** parameter used in unsaturated transport model to calculate infiltration rate and mixing zone model to calculate dilution factor and mixing zone depth
RO + ET	31959.9 to 59538	**1.9X change –** same use as Precipitation
Fraction of Organic Carbon	31959.9 to 31959.9	**No change –** parameter used in leachate partitioning model, and unsaturated and saturated transport models when calculating retardation factor – applies only to organics
Water Filled Porosity	31959.9 to 31960	**Little change** - parameter used in leachate partitioning model and unsaturated transport model to calculate vertical unsaturated groundwater velocity and retardation factor
Distance to Point of Compliance	31959.9 to 31959.9	**No change** – Used in saturated transport model. Parameter sensitivity increases more noticeably with increasing distance.
Aquifer Thickness	31959.9 to 32094	**Little change –** parameter used in mixing zone calculation when determining mixing zone depth
Depth to Water	31959.9 to 31959.9	**No change –** parameter used in the unsaturated transport model to calculate the unsaturated zone thickness but not active for inorganic constituents
Total Porosity	31959.9 to 31959.9	**No change** - parameter used indirectly to calculate air filled porosity in the leachate partitioning model
Effective Porosity	31959.9 to 31959.9	**No change –** Used to calculate the groundwater velocity which is used in the saturated model and mixing zone model to calculate dilution factor and mixing zone depth
Darcy Flux	31959.9 to 31732.8	**Little change (1.2X) –** parameter used in the saturated model and mixing zone model to calculate dilution factor and mixing zone depth
Soil pH	31959.9 to 160177	**5.0X change –** parameter used to define the Kd used
Bulk Density	31959.9 to 31959.7	**Little change –** parameter used in the leachate partitioning model, unsaturated and saturated transport models when calculating the retardation factor, but not active for inorganic constituents
Half-Life	N/A	N/A to inorganic constituents
Distribution Coefficient (Koc)	31959.9 to 55929	**1.7X change –** parameter used in the leachate partitioning model
Frozen Days	N/A	N/A to inorganic constituents

Based on the quantified change in the site-specific soil standard according to the changes to the individual model input parameter, the results of the sensitivity analysis were ranked in order from highest to lowest relative sensitivity for the two classes of constituents. **Table 3** summarizes the results of the ranking.

Table 3. Ranking of Model Input Parameter Sensitivities

Sensitivity	Organics	Inorganics
Highest ↓ **Lowest**	Depth to water	Soil pH
	Runoff rate + evapotranspiration	Runoff rate + evapotranspiration
	Source depth	Partitioning coefficient (Kd)
	Fraction of organic carbon (foc) and partitioning coefficient (Koc)	Precipitation
	Precipitation	Darcy flux
	Soil bulk density	
	Half-Life	

As shown in **Tables 1** to **3**, the model input parameters used to estimate the infiltration rate are commonly sensitive to both the organic and inorganic constituents. As such, the precipitation, evapotranspiration and runoff rates will be important model input parameters to define for use in the P2 model. For the organic constituents, the source dimension terms, specifically the source depth was determined to be the most sensitive input parameter when simulating organic COC migration. This is because the source depth is used to define the thickness of the unsaturated zone and therefore the vertical distance over which unsaturated transport can occur. And in general, small increases in unsaturated zone thickness can result in relatively large increases in back calculated site-specific soil standards due to the increased contaminant attenuation that occurs when the unsaturated transport model is active.

The majority of the remaining input parameters are commonly referenced in literature (e.g., soil bulk density, partitioning coefficients Koc/Kd, and half-life) or would be measured on-site (e.g., soil pH and half-life). Recommendations for which model input parameters to adjust or update for future use in the model are provided in the subsection below.

4.0 RECOMMENDATIONS

Based on the results of the sensitivity analysis, and varibability in model input paraters for different constituents (i.e., organic versus inorganic) the following recommendations have been formulated for each of the identified sensitive model input parmeters. The recommendations listed provide details on how to derive/define the input parameter for more simplified use in the P2 model. The recommendations are provided separately for organic constituents **(Table 4)** and inorganic constituents **(Table 5)**.

Table 4. Recommendations for Organic Constituents

Model Input Parameter	Recommended Approach / Use
Depth to water	Site-specific measurements
Runoff rate	Develop lookup table or map as part of calculating the infiltration rate

Model Input Parameter	Recommended Approach / Use
Evapotranspiration	Develop lookup table or map as part of calculating the infiltration rate
Source depth	Develop definition of a source based on constituent type and use site-specific analytical data to define source dimension terms (i.e., length, width, and depth)
Fraction of organic carbon (foc)	Site-specific sample collection for analysis at laboratory or use model default
Partitioning coefficient (Koc)	Use literature/default values used in Omnibus model. Alternative values could be provided based on reputable sources or site-specific values could be derived but P2 submission with require review and approval by MoE.
Precipitation	Develop lookup table or map as part of calculating the infiltration rate
Soil bulk density	Use literature/default values used in Omnibus model or develop lookup table based on soil type
Half-Life	Use literature/default values used in Omnibus model. Alternative values could be provided based on reputable sources or site-specific values could be derived but P2 submission with require review and approval by BCMOE. Consideration to use aerobic degradation rates if it can be demonstrated that aerobic conditions are present.
Frozen Days	The number of frozen days per year should be set to “0” as a default in the model. In regions where there are multiple consecutive days of sub-zero surface temperatures, Environment Canada climate data can be referenced to define the number of frozen days per year.

Table 5. Recommendations for Inorganic Constituents

Model Input Parameter	Recommended Approach / Use
Soil pH	Site-specific soil collection and analysis at laboratory
Runoff rate	Develop lookup table or map as part of calculating the infiltration rate
Evapotranspiration	Develop lookup table or map as part of calculating the infiltration rate
Partitioning coefficient (Kd)	Use literature/default values used in Omnibus model. Alternative values could be provided based on reputable sources or site-specific values could be derived but P2 submission with require review and approval by BCMOE.
Precipitation	Develop lookup table or map as part of calculating the infiltration rate
Darcy flux	Site-specific measurements of K and i in accordance to BCMOE Technical Guidance 8.

The model input parameters that were identified to have little to no sensitivity have also been reviewed, and recommendations for how to utilize these parameters in the P2 model have also been formulated as shown in **Table 6**.

Table 6. Recommendations on Use of Non-Sensitive Model Input Parameters

Model Input Parameter	Recommended Approach / Use
Source Length	Develop definition of a source based on constituent type and use site-specific analytical data to define source dimension terms (i.e. length, width, and depth)
Source Width	Develop definition of a source based on constituent type and use site-specific analytical data to define source dimension terms (i.e. length, width, and depth)
Water Filled Porosity	Use default values used in Omnibus model. Alternatively, site-specific values could be determined if representative samples analyzed at laboratory.
Distance to Point of Compliance	Actual measured distance from downgradient edge of defined source to the point of compliance (high water mark if a water body)
Aquifer Thickness	Site-specific measurements in accordance to BCMOE Technical Guidance 8
Total Porosity	Use default values used in Omnibus model. Alternatively, site-specific values could be determined if representative samples analyzed at laboratory
Effective Porosity	Use default values used in Omnibus model. Alternatively, site-specific values could be determined if representative samples analyzed at laboratory

5.0 CLOSURE

We trust this information is sufficient for your needs and requirements, please do not hesitate to contact the undersigned should you have any questions or concerns.

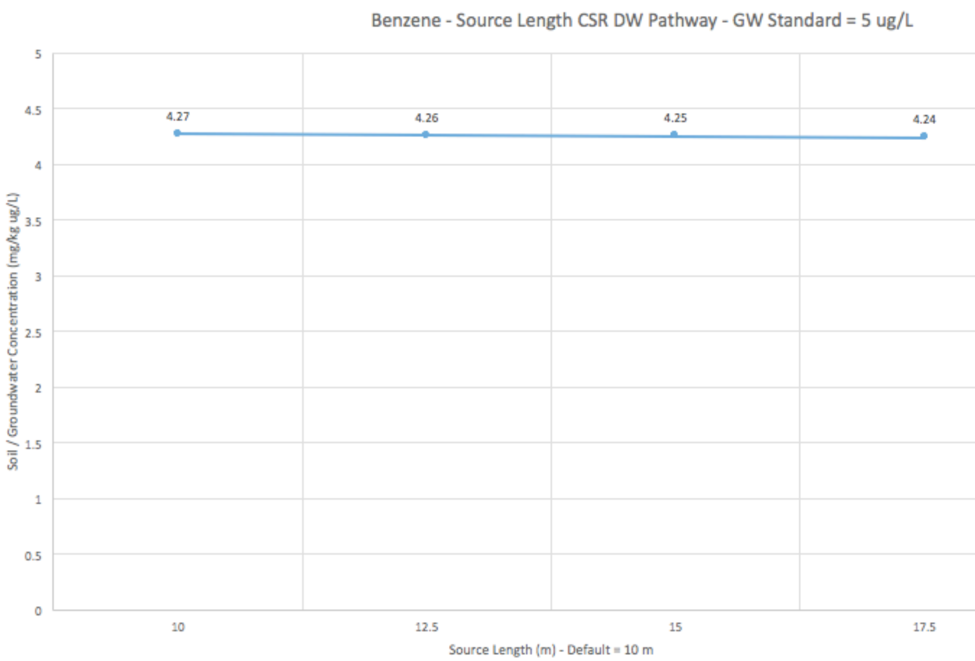
Kind regards,
Core6 Environmental Ltd

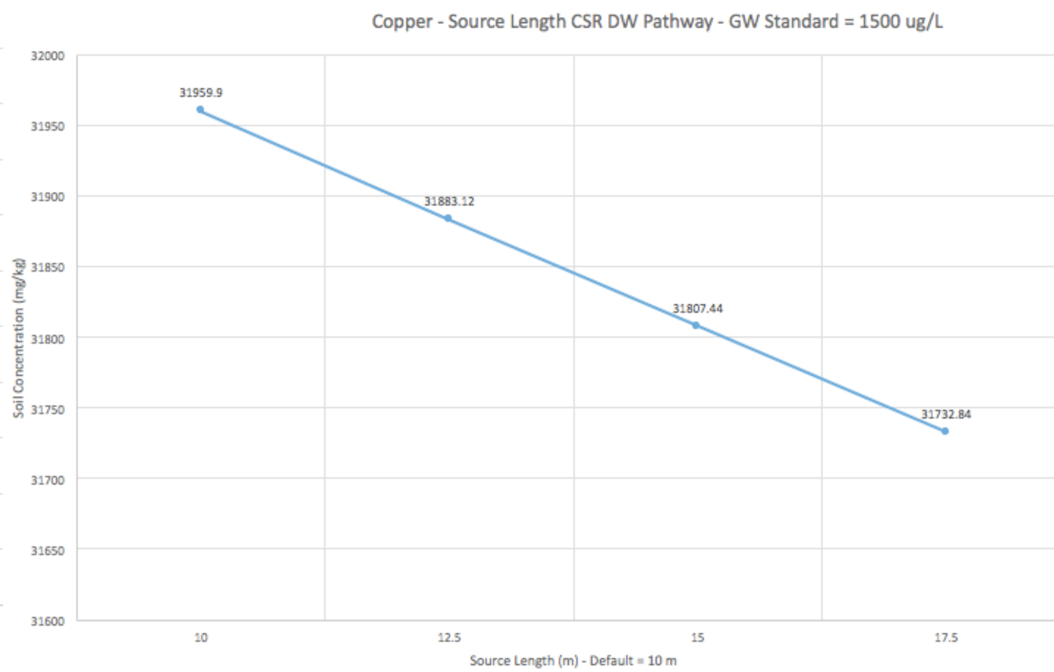
ORIGINAL SIGNED

Stephen Munzar *MSc, PGeo*
Senior Hydrogeologist / Partner

SENSITIVITY ANALYSIS GRAPHS

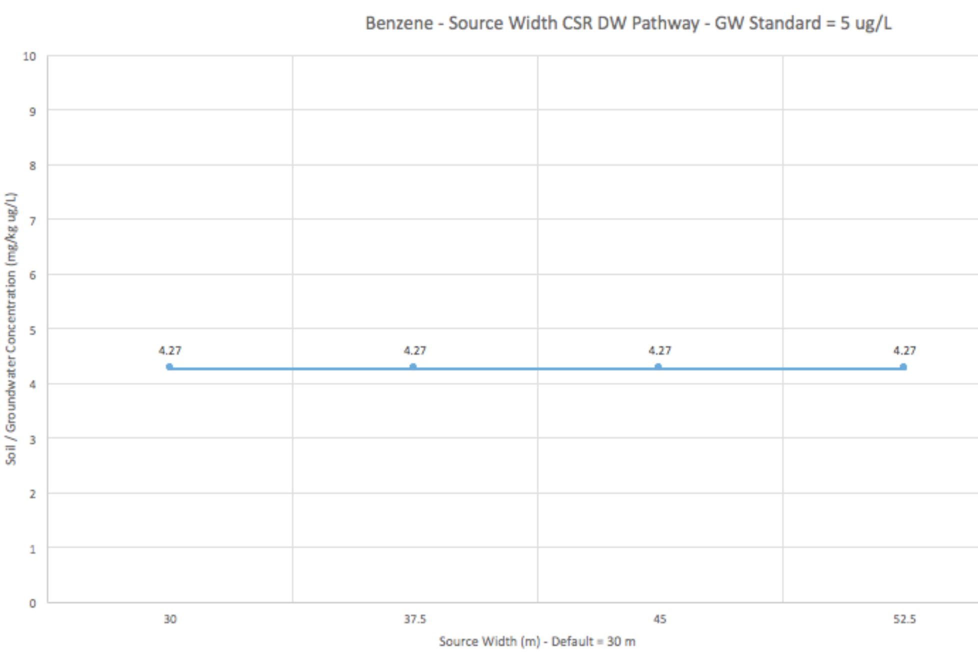
Source Length

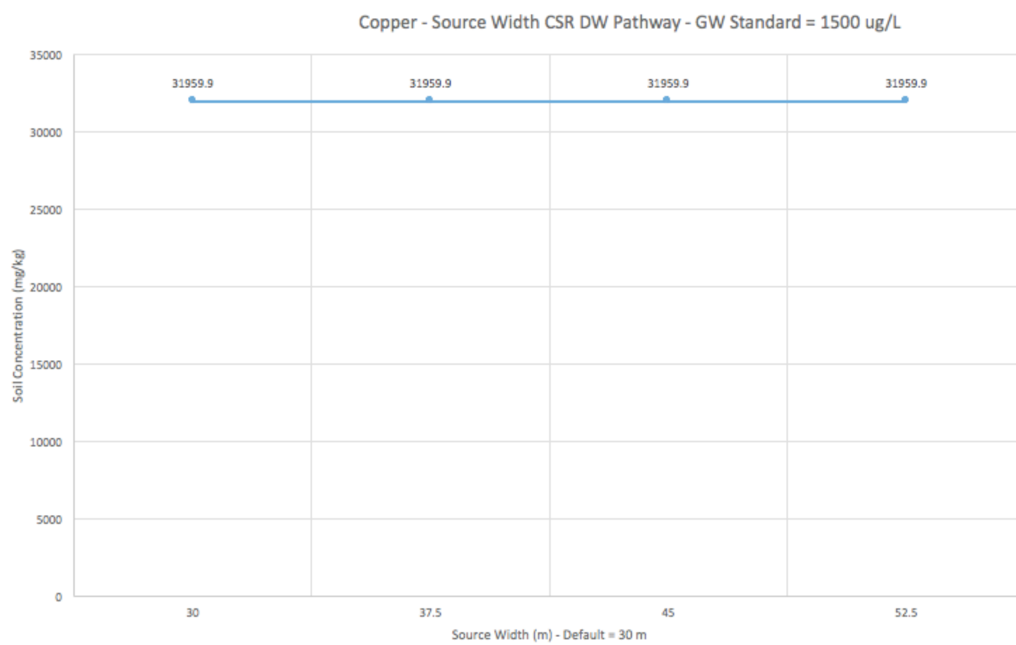




Cs - Calculated Soil Concentration

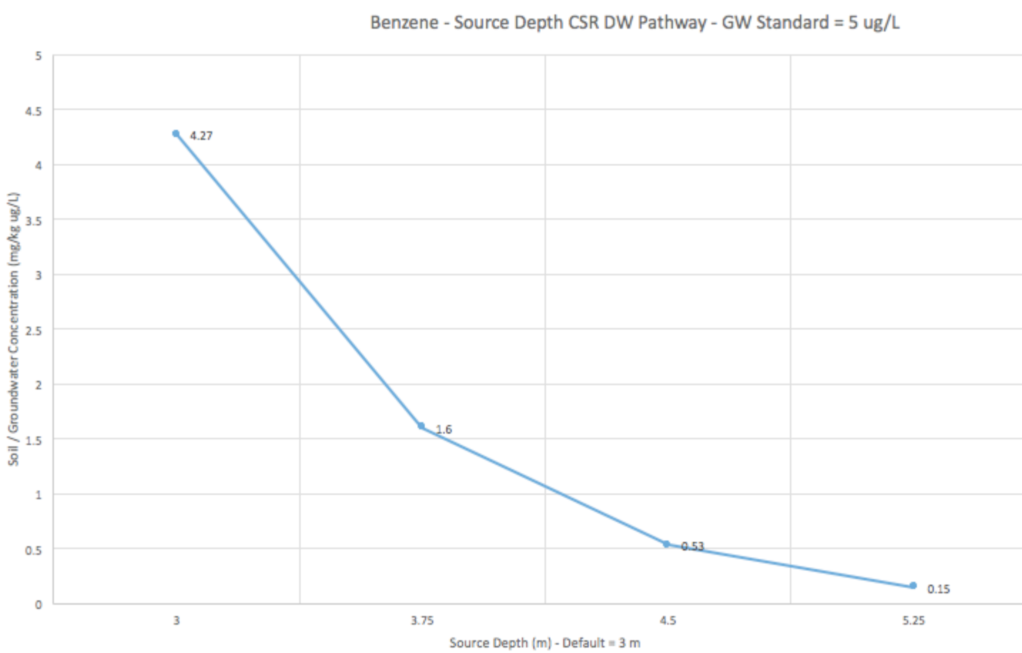
Source Width

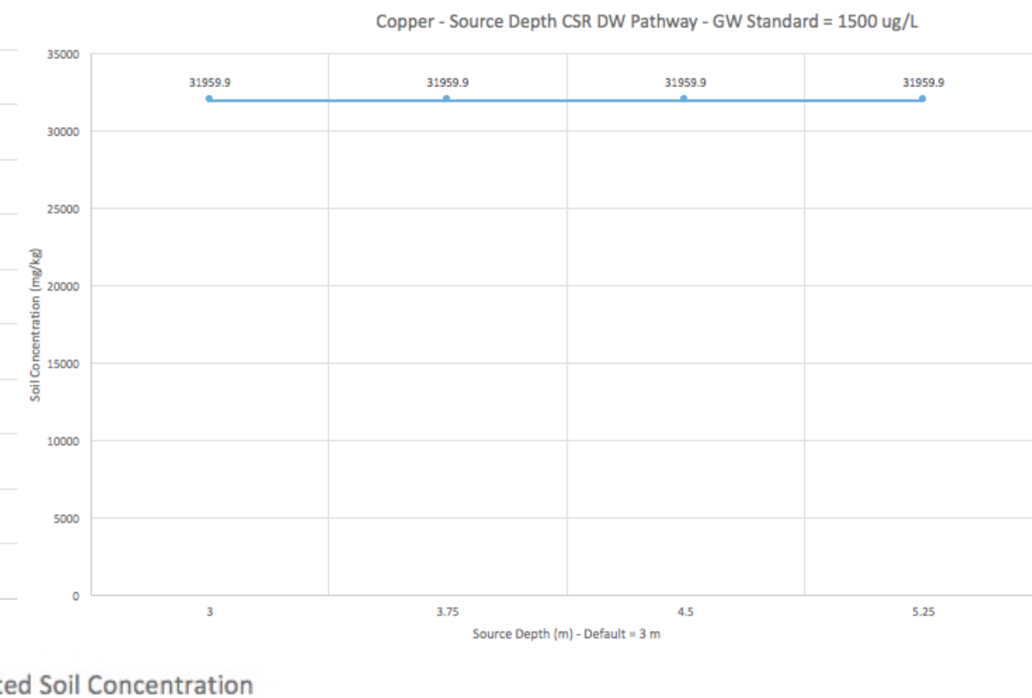




Cs - Calculated Soil Concentration

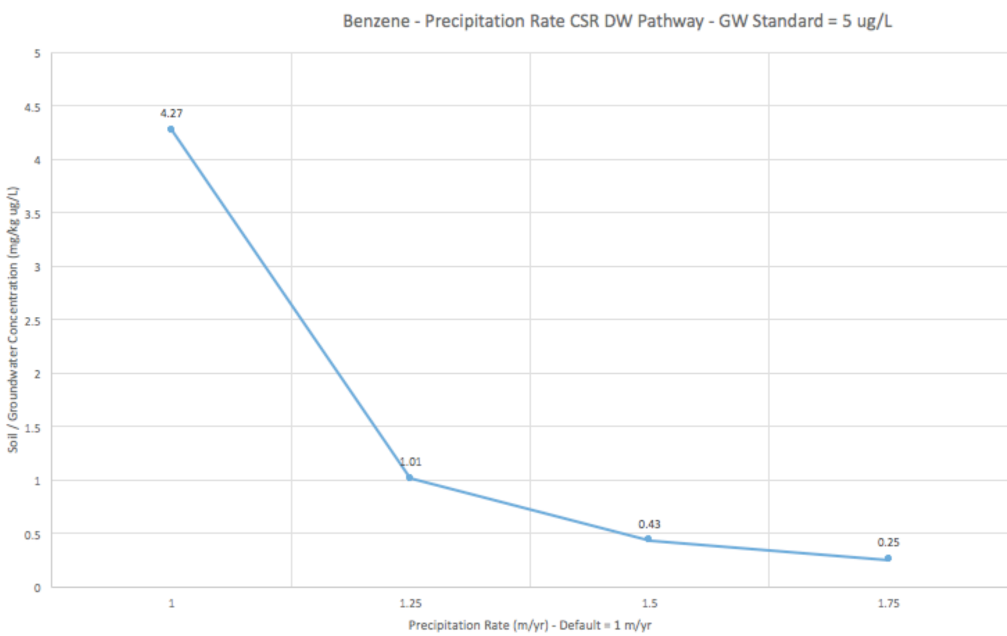
Source Depth

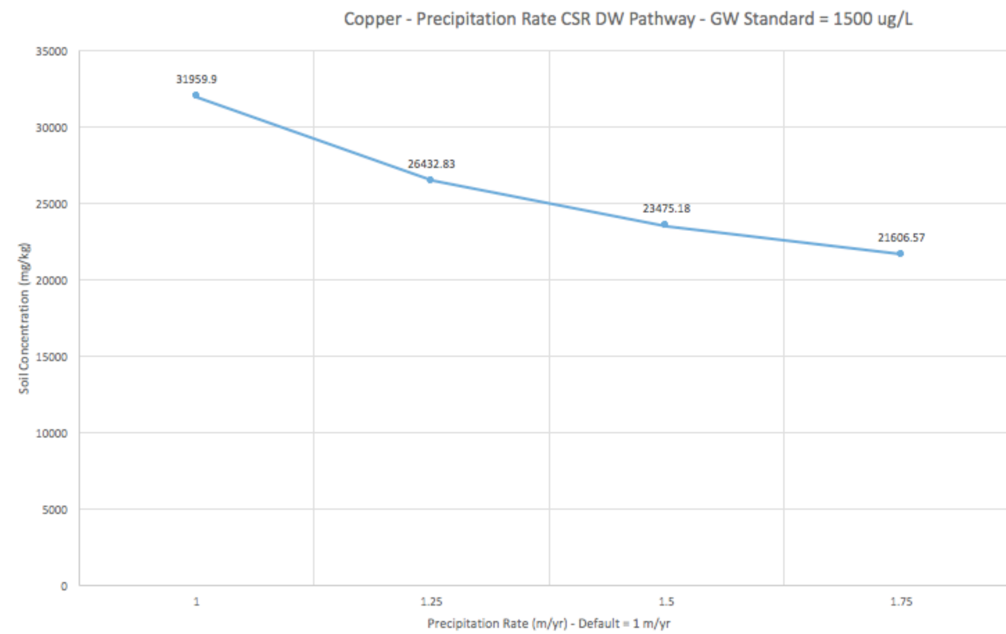




Notes: Water table depth set to 10 m

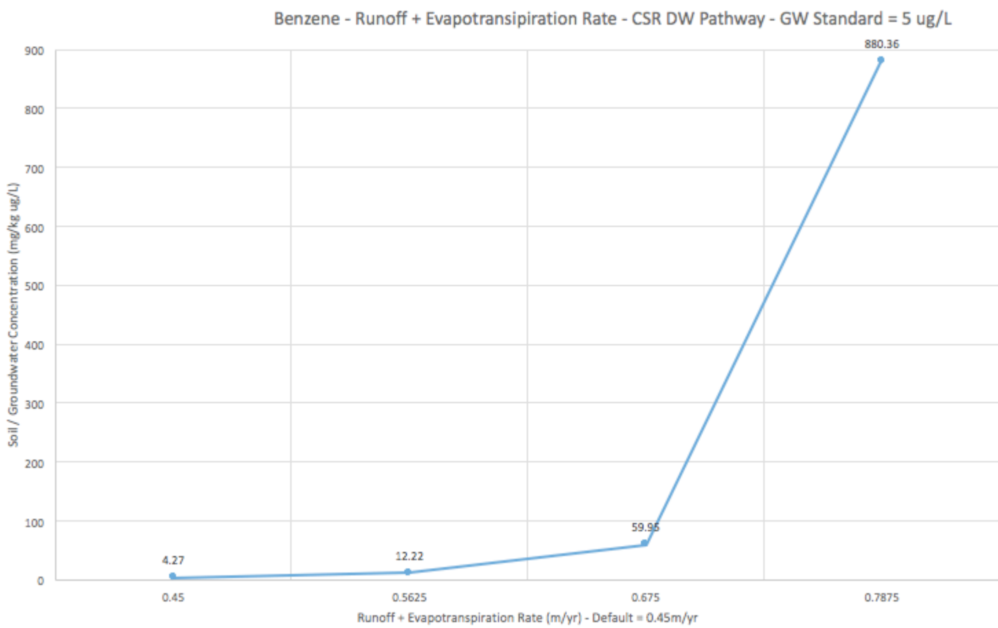
Precipitation

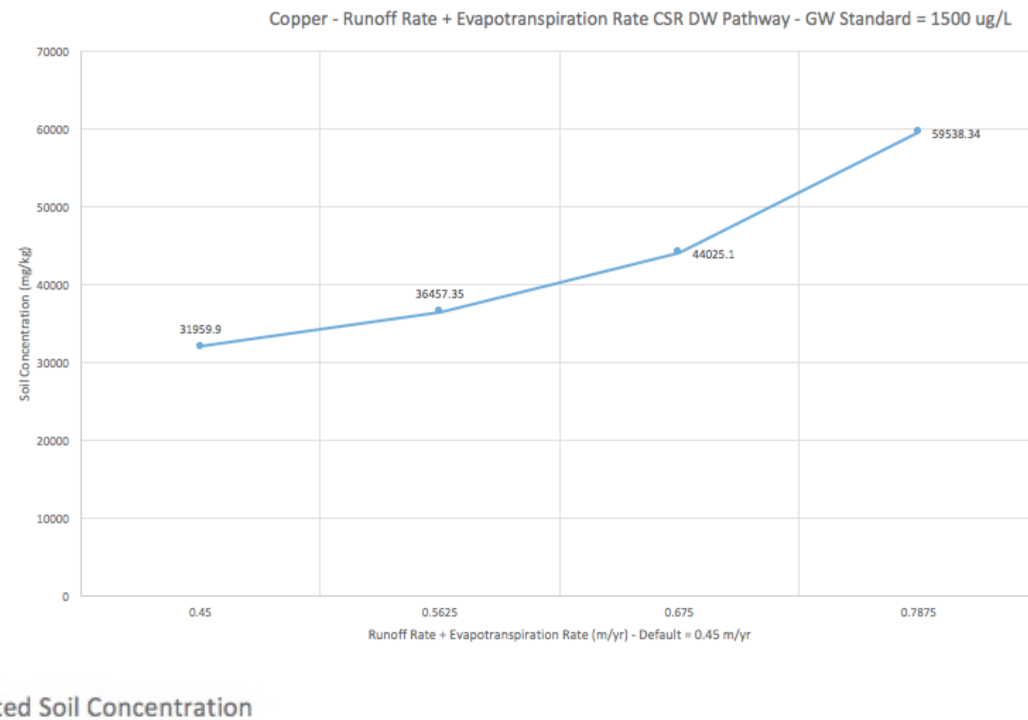




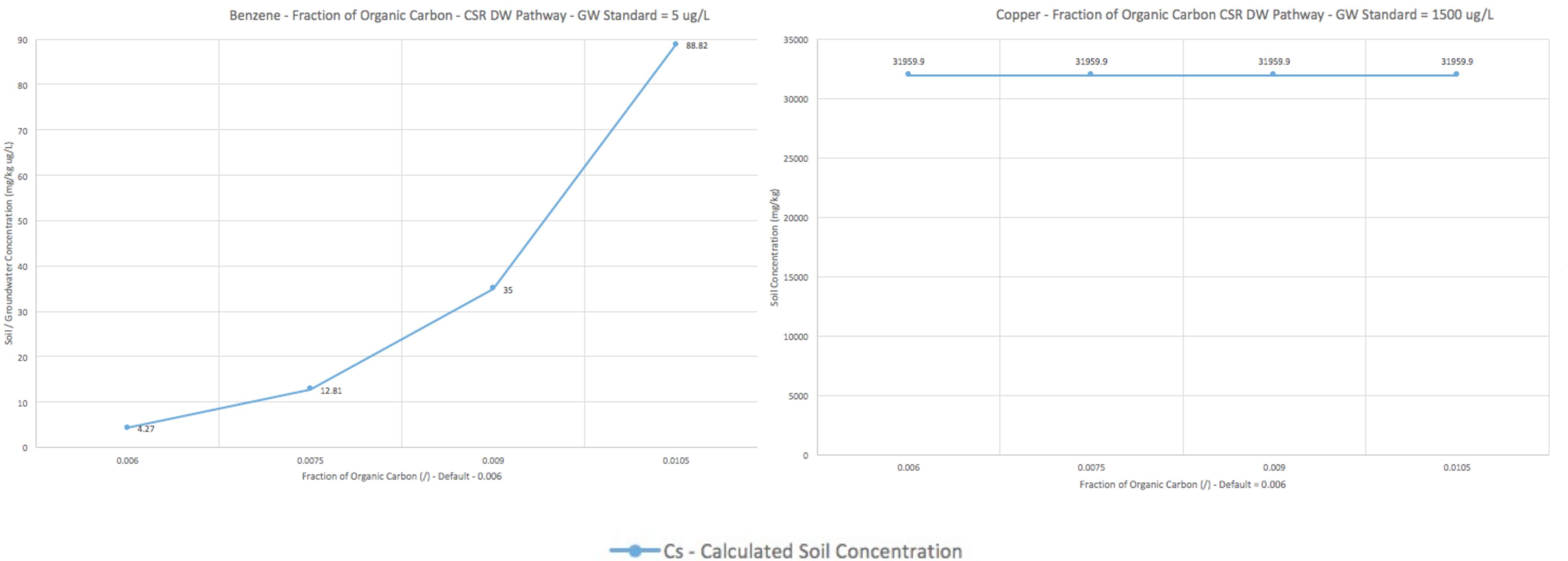
Cs - Calculated Soil Concentration

Runoff Rate + Evapotranspiration

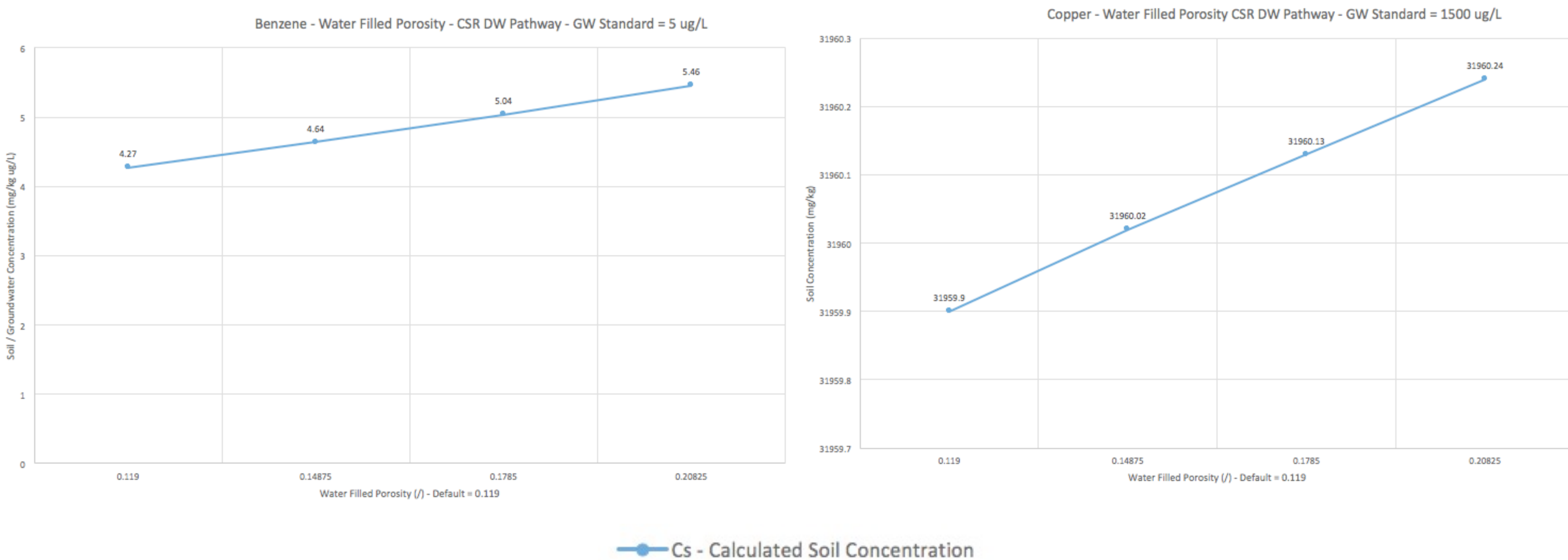




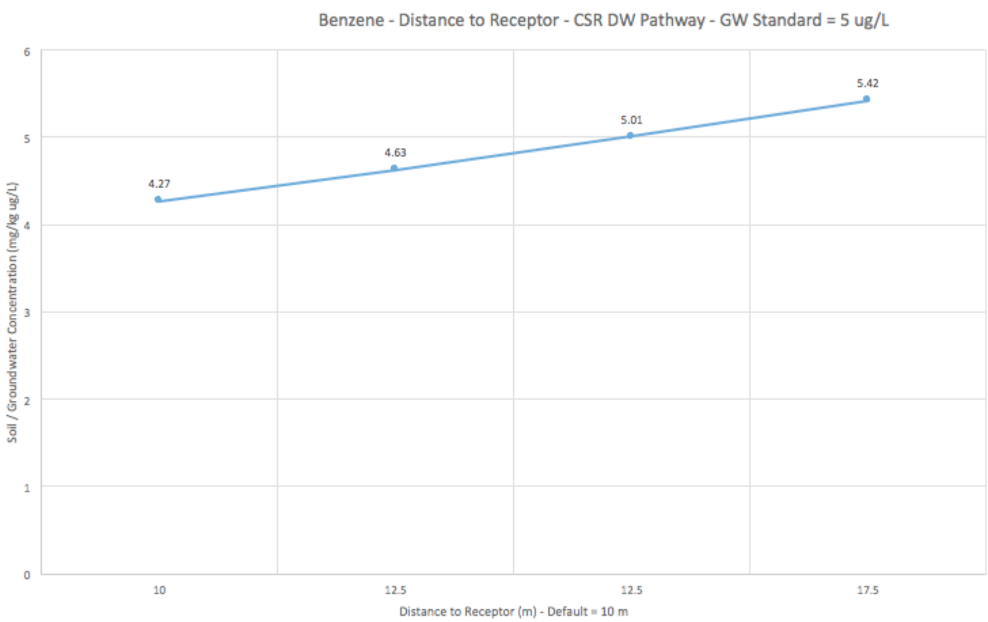
Fraction of Organic Carbon

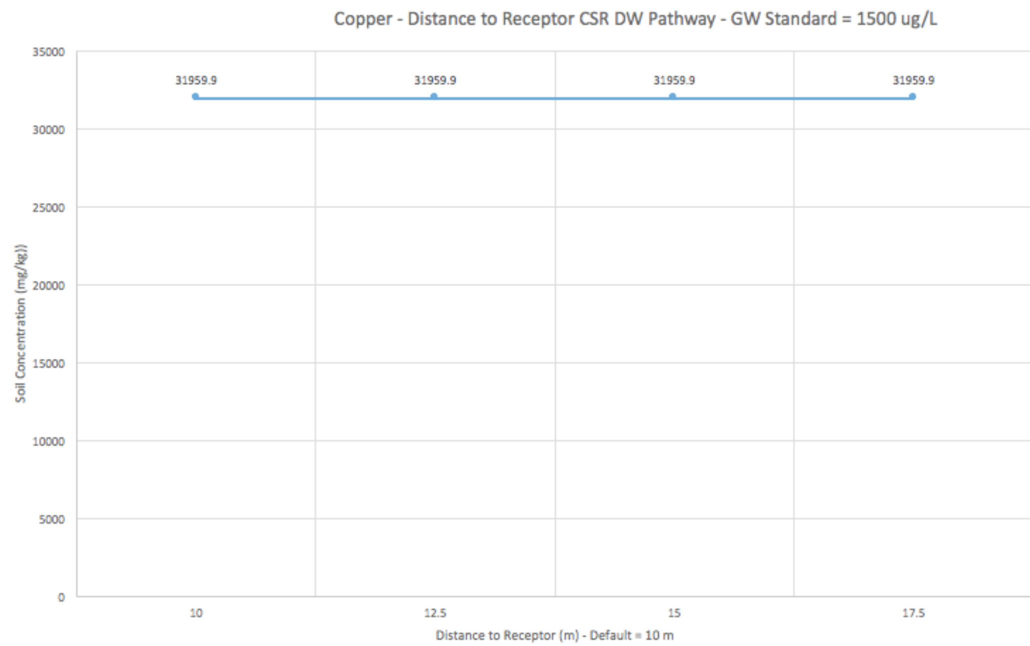


Water Filled Porosity



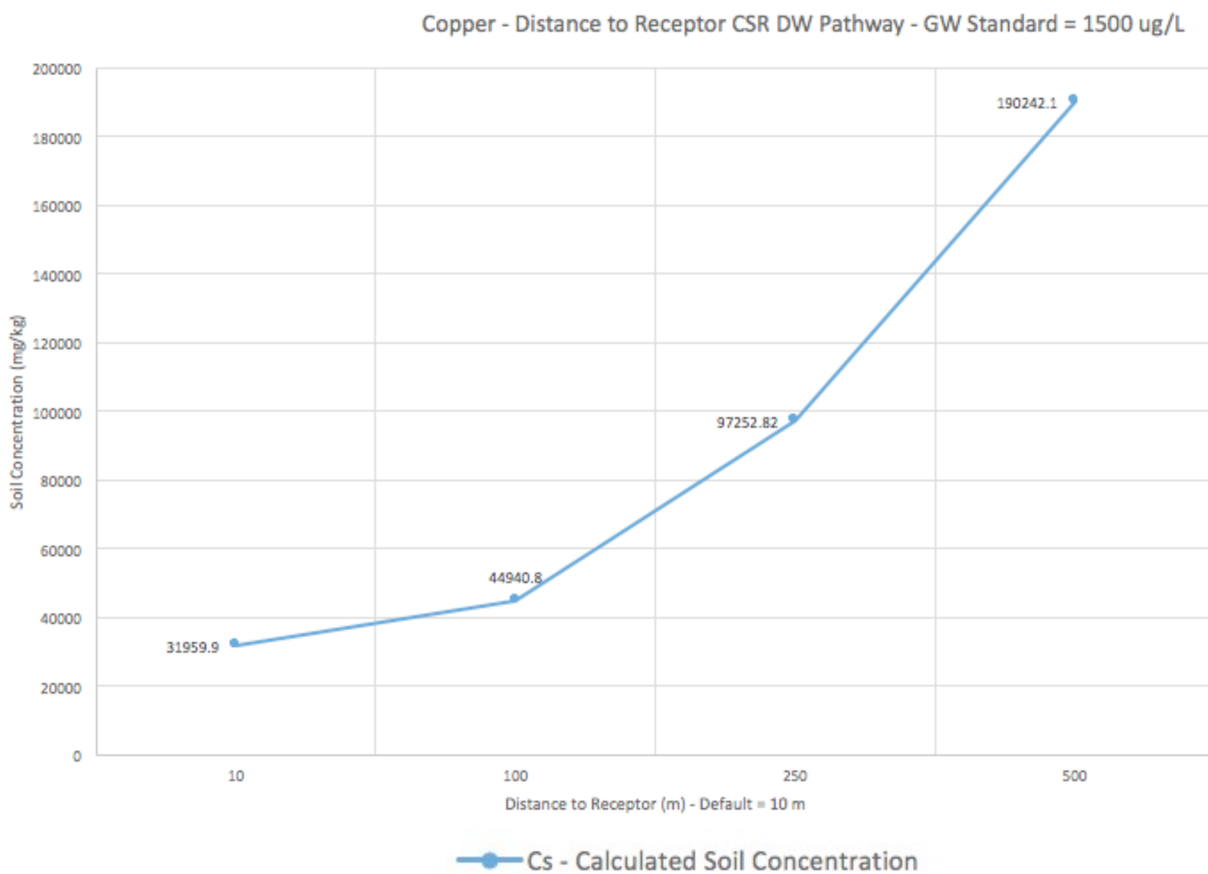
Distance to Point of Compliance



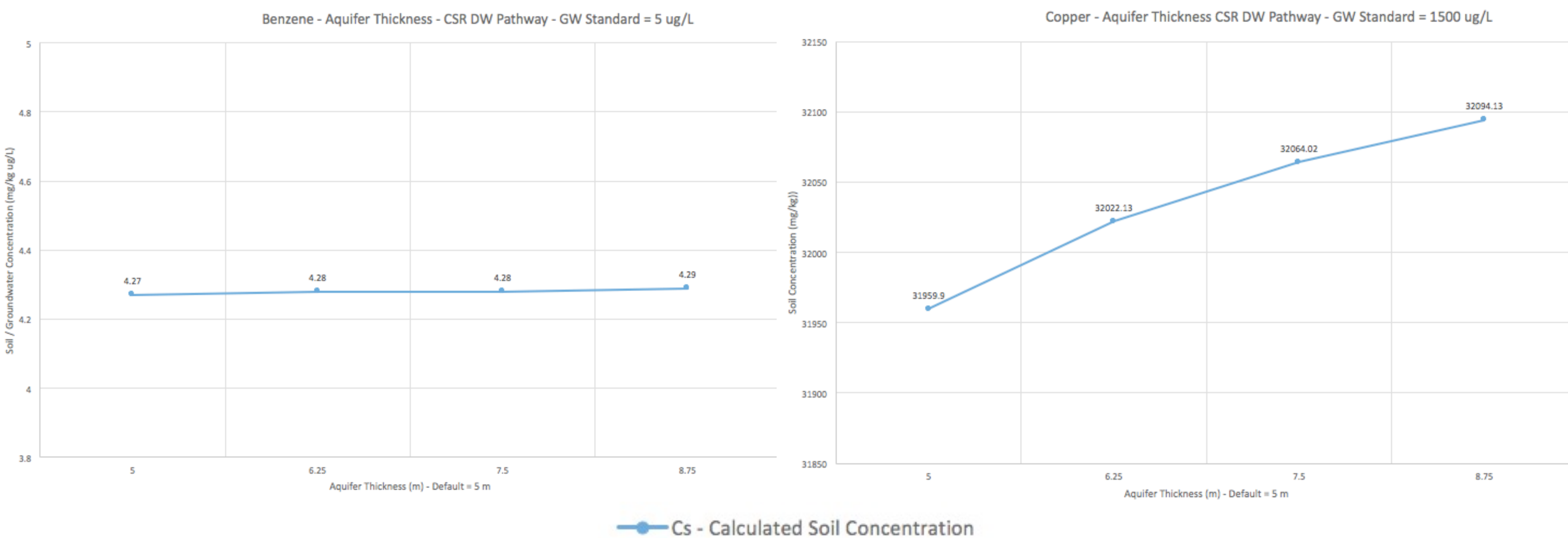


Cs - Calculated Soil Concentration

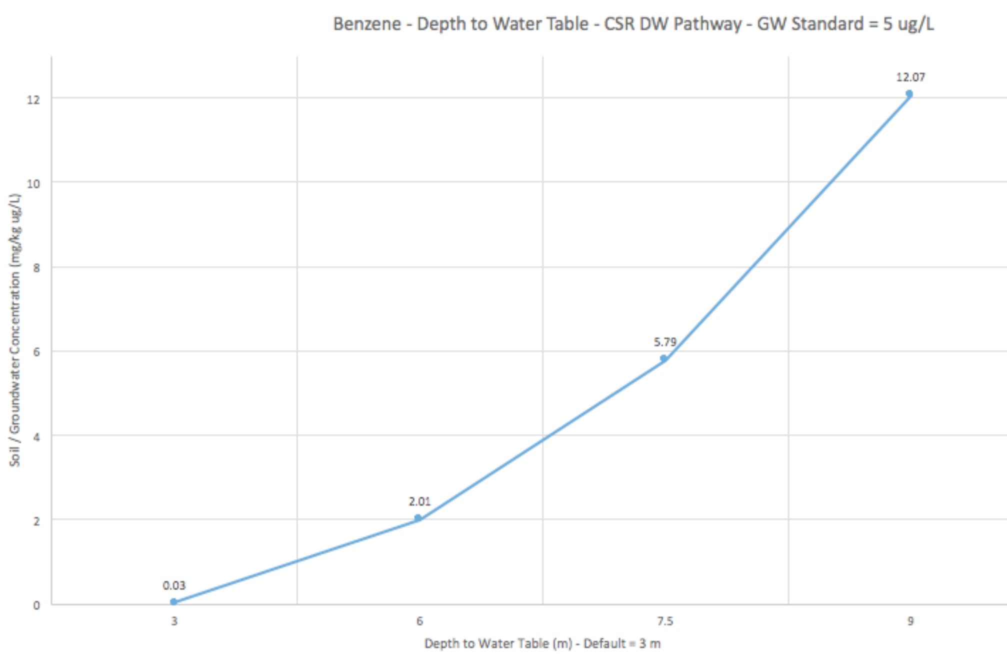
Distance to Point of Compliance – Copper (Greater Distance)

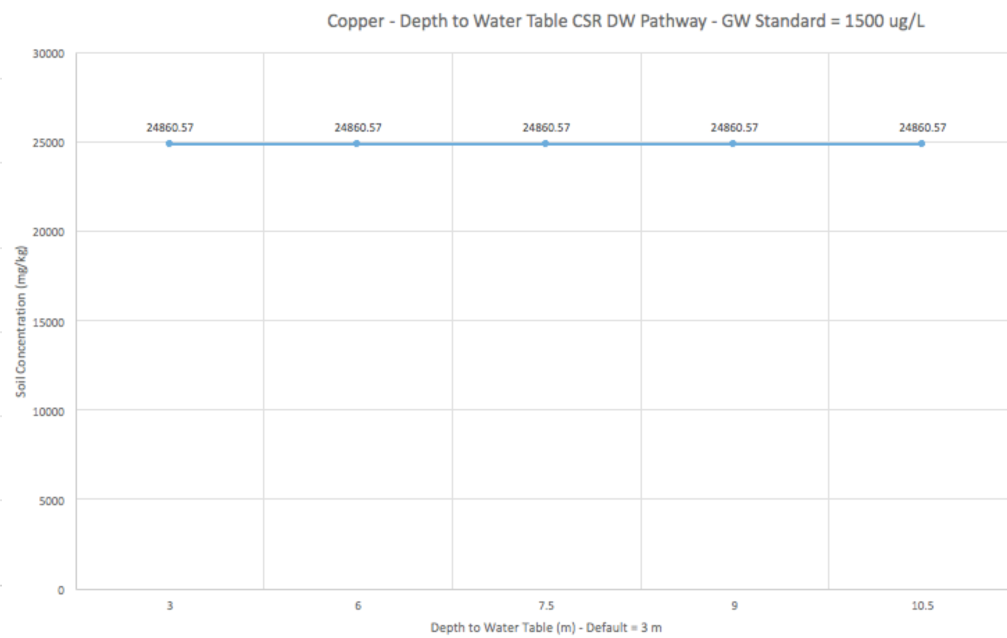


Aquifer Thickness



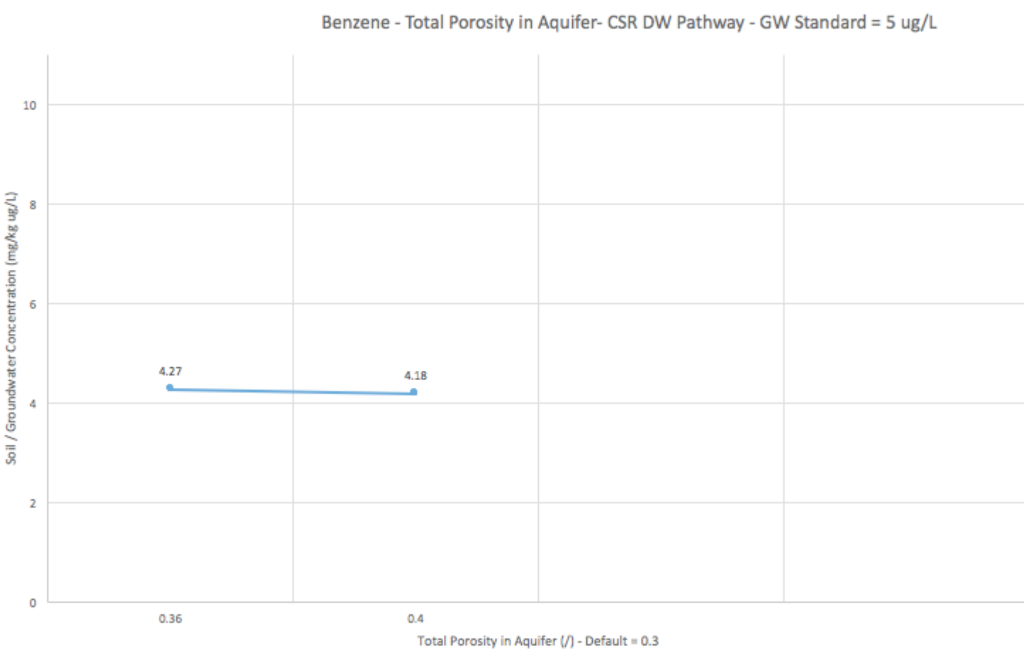
Depth to Water

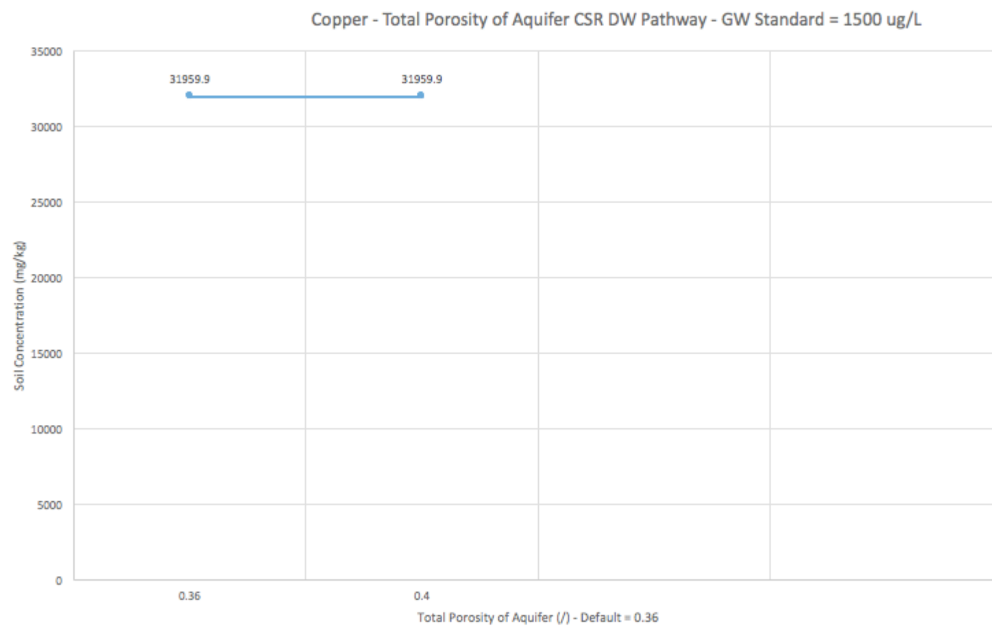




Cs - Calculated Soil Concentration

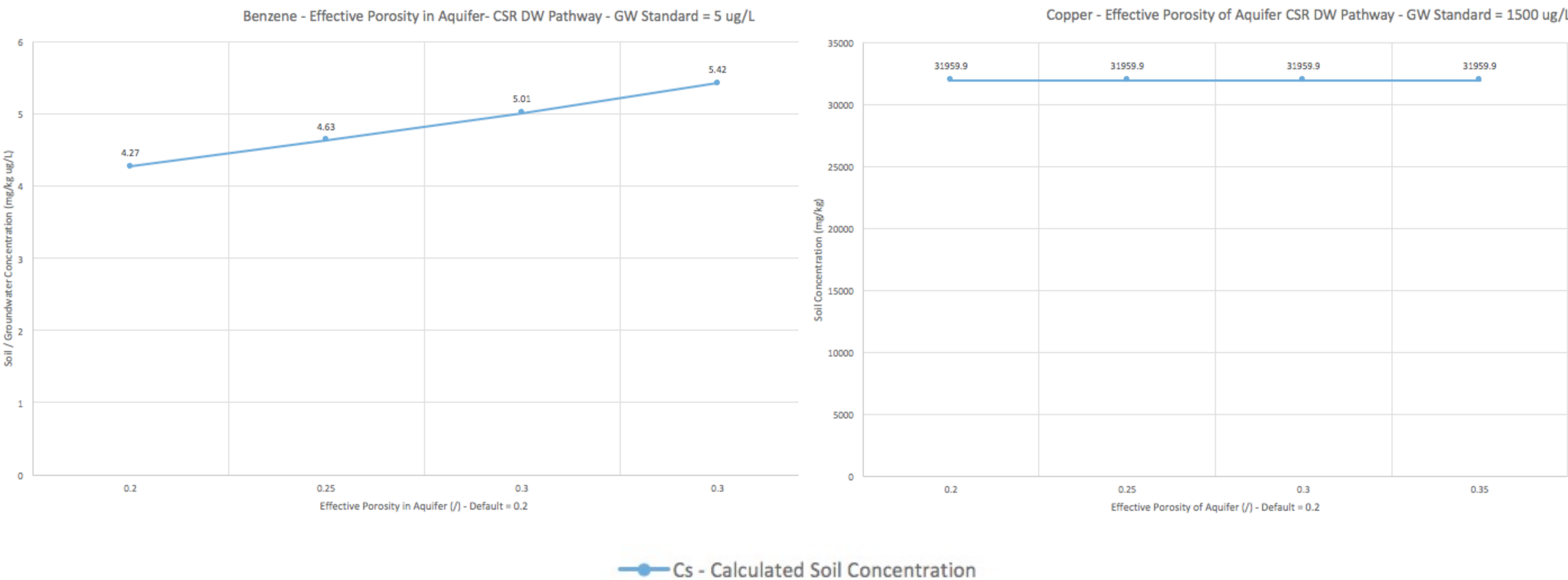
Total Porosity



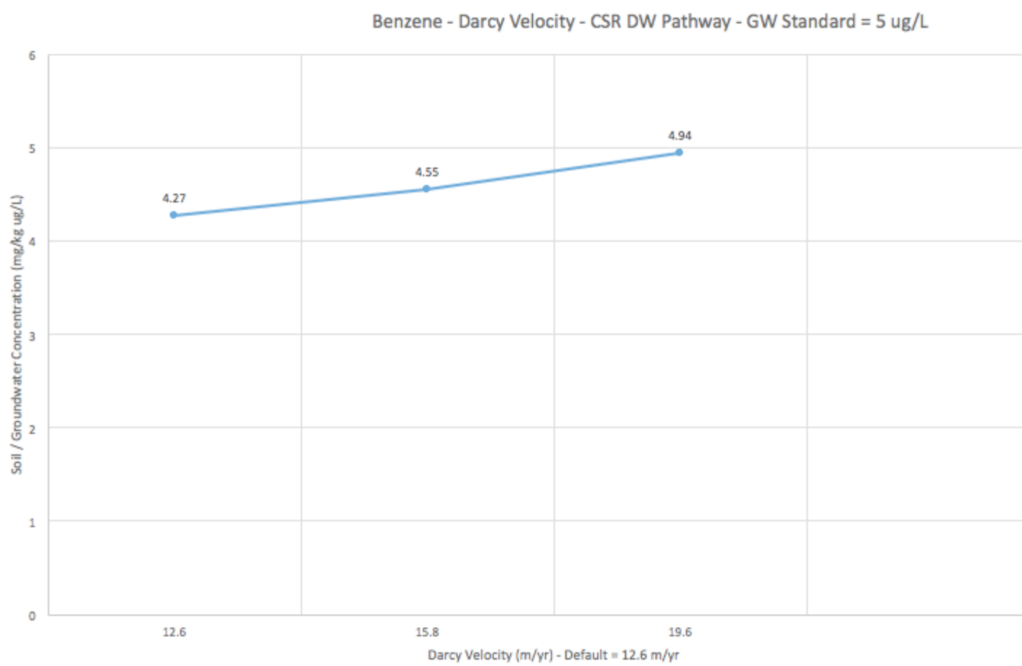


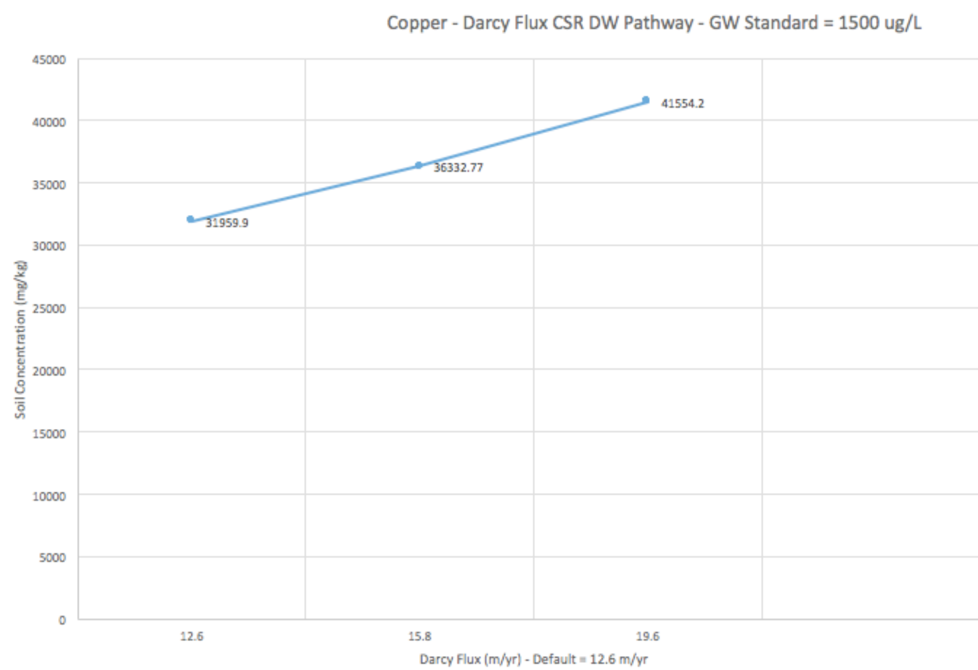
Cs - Calculated Soil Concentration

Effective Porosity



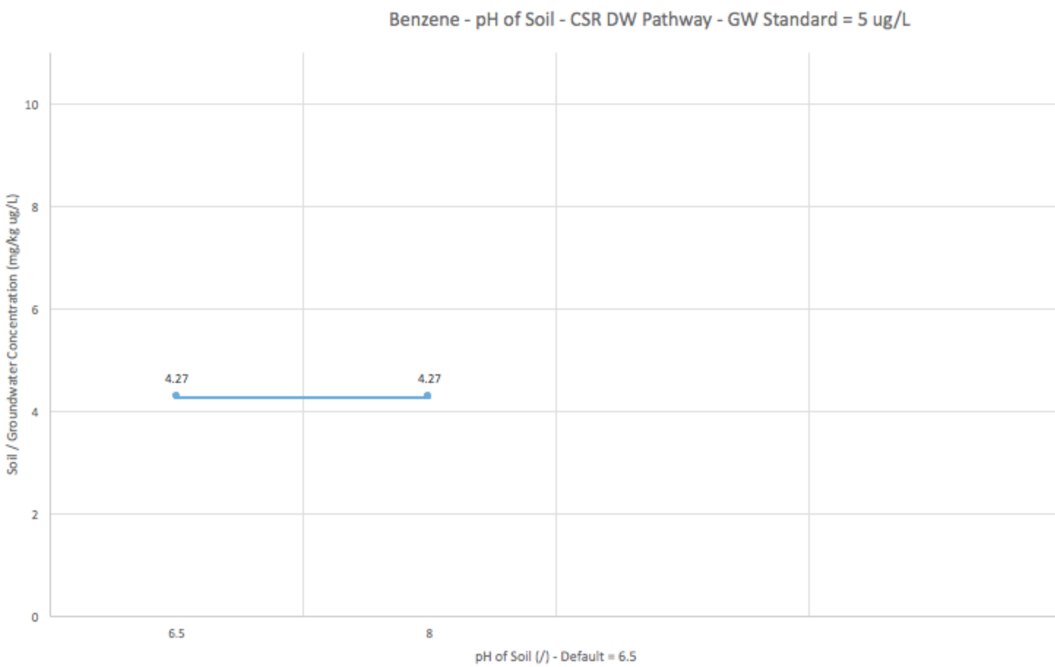
Darcy Flux

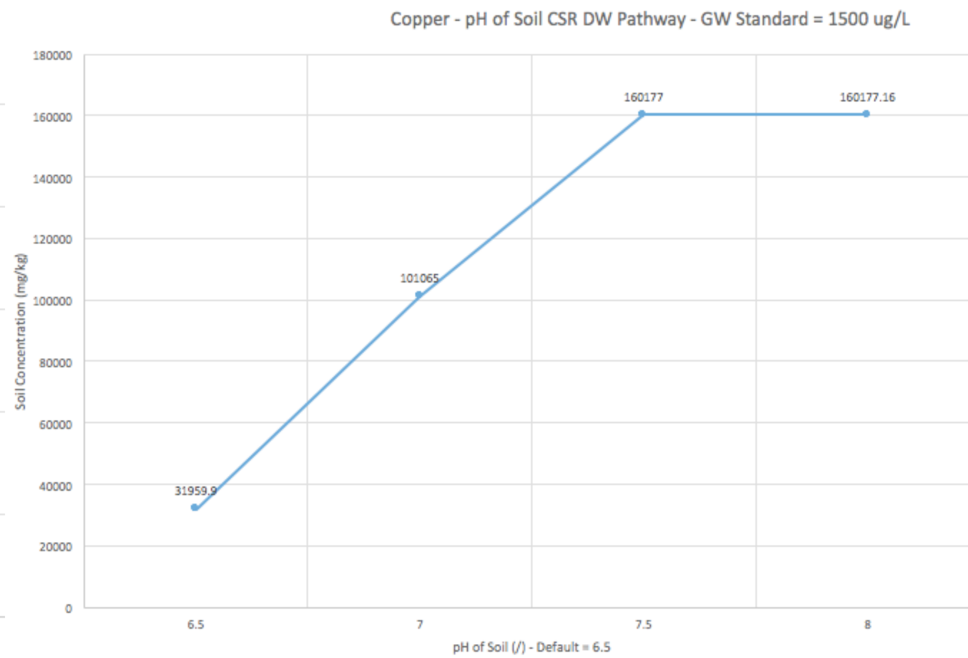




Cs - Calculated Soil Concentration

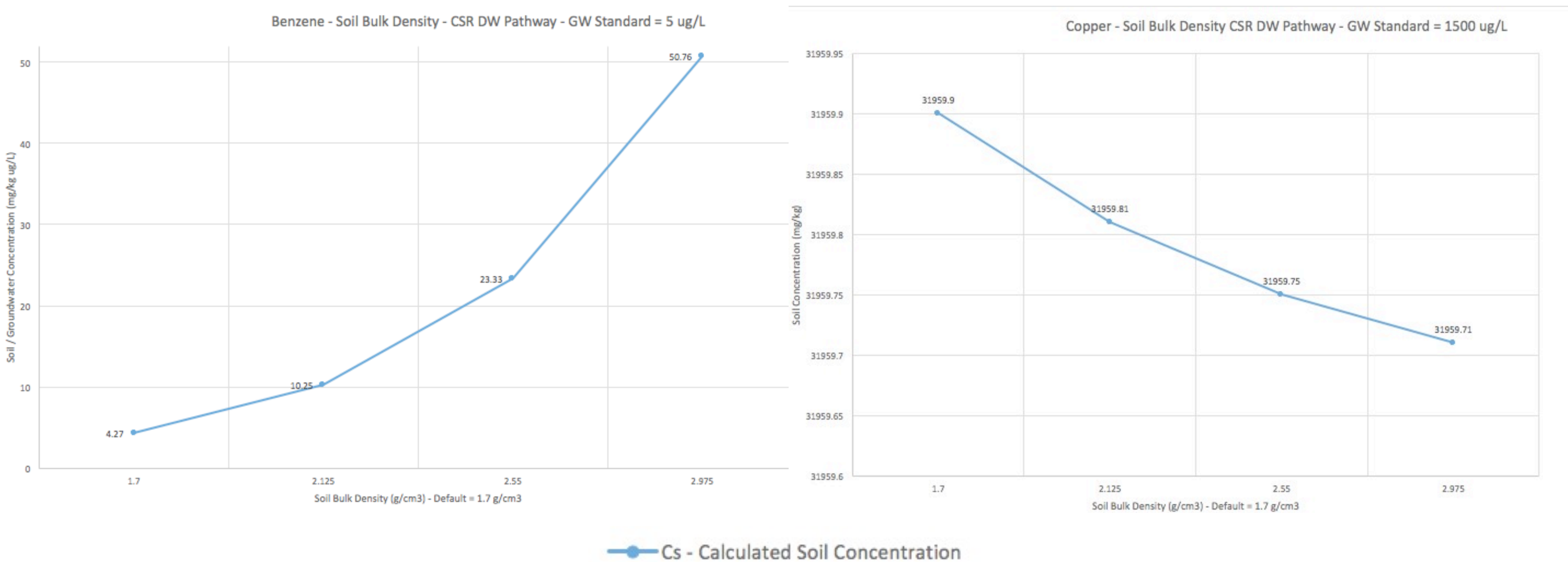
Soil pH



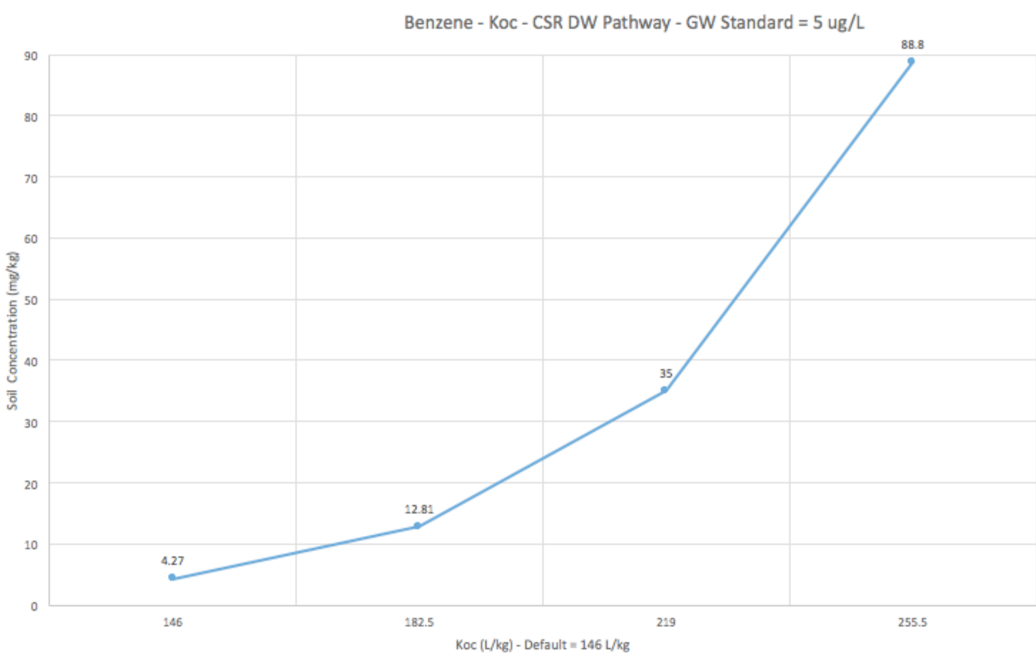


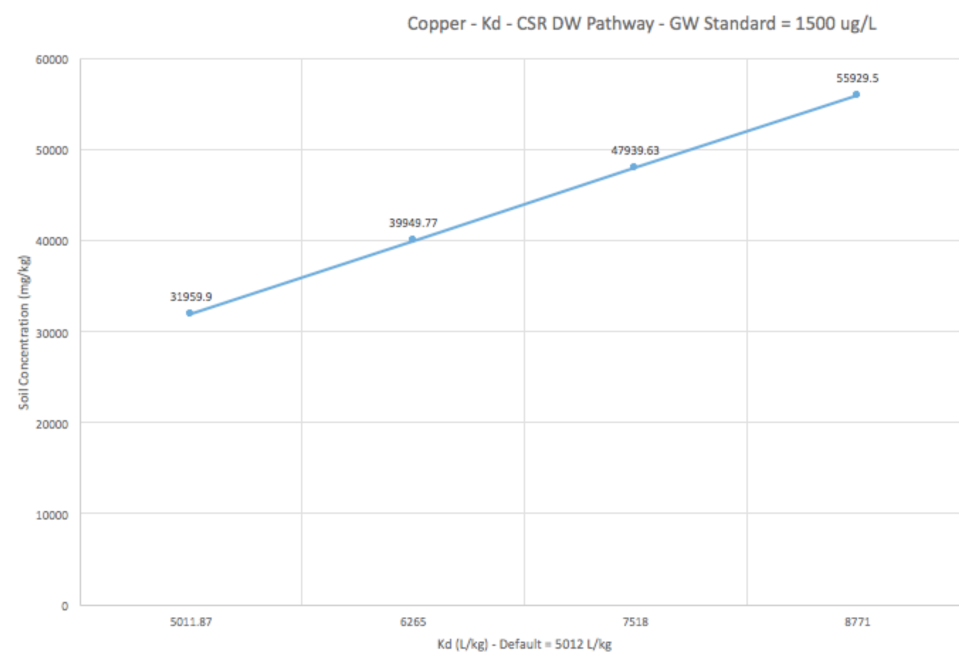
Cs - Calculated Soil Concentration

Soil Bulk Density



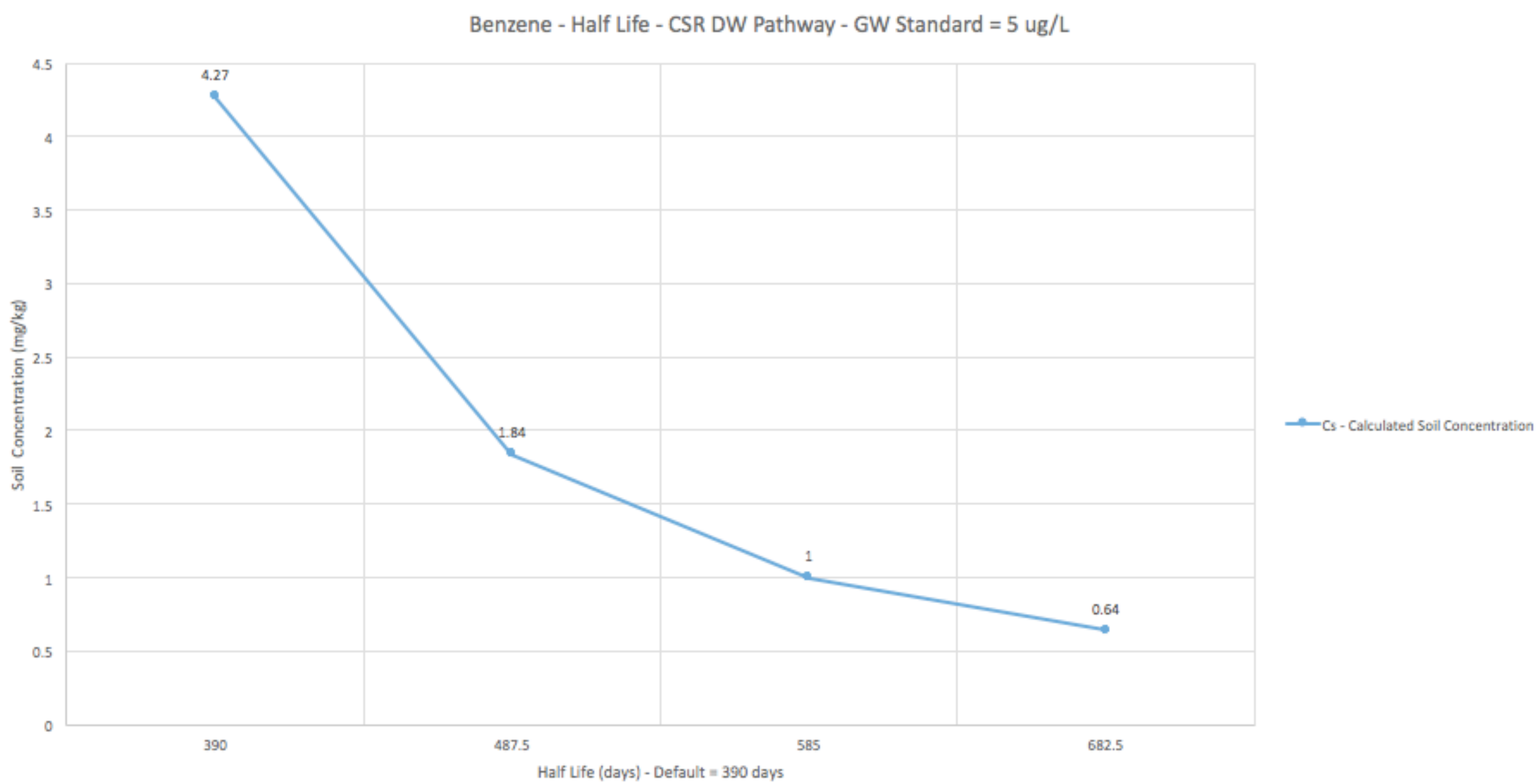
Distribution Coefficient (Koc / Kd)





Cs - Calculated Soil Concentration

Half-Life Benzene



Number of Frozen Days