GSI Water Solutions, Inc.

Technical Memorandum

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Re: **Determination of Waste Management Areas at Wet Feet UICs by Numerical Simulation of Pollutant Fate and Transport**

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1 Introduction

The City of Portland (City) has approximately 9,000 Underground Injection Controls (UICs) that collect stormwater from public rights-of-way and infiltrate the water into the subsurface. UICs are an essential element of a comprehensive watershed strategy to use stormwater as a resource by infiltrating it back into the ground, and in many areas east of the Willamette River, are the only form of stormwater management available.

The City's UICs are managed under UIC Water Pollution Control Facilities (WPCF) Permit No. 102830, which was issued to the City by the Department of Environmental Quality (DEQ) in 2005 (DEQ, 2005a). Under the City's UIC WPCF permit, UICs that have inadequate separation distance between the bottom of the UIC and groundwater (i.e., less than 10 feet) are considered to be noncompliant. The permit allows for continued use of a noncompliant UIC if a corrective action is implemented. Corrective action, as defined in the permit, can consist of groundwater monitoring, structural retrofitting of the UIC, or risk assessment using DEQ-approved protocols. Previously, the City has conducted risk assessments (i.e., unsaturated zone fate and transport modeling) to bring UICs with greater than 5 feet of separation distance into compliance (BES, 2008).

DEQ is currently developing a UIC WPCF template for municipalities and commercial industrial facilities in Oregon from which all new permits will be based. This template will allow for wet feet UICs. This will be accomplished by treating the UIC as a waste management area and allowing for the creation of a waste management boundary around the UIC. As defined under Oregon Administrative Rules (OAR) 340-040-0010(19), a waste management area is "any area where waste or material that could become waste if released to the environment, is located or has been located." The waste management area is used to specify the location at which groundwater quality parameters must be at or below permit-specific concentration limits [OAR 340-040-0030(2)(e)]. In the context of UICs with wet feet, a waste management area is comprised of the groundwater than contains stormwater pollutants above background levels (i.e., zero, or the method reporting limit). Wet feet UICs will be allowed under the revised UIC WPCF template if there are no receptors (e.g., domestic use water wells) within the UIC's waste management boundary. Based on conversations with DEQ, the waste management boundary for wet feet UICs can be determined using groundwater fate and transport models.

This technical memorandum describes numerical groundwater model and fate and transport simulations that evaluate pollutant transport from the City of Portland's wet feet UICs with the objective of determining the waste management boundary. Based on the City's sampling data and model simulations, pentachlorophenol (PCP) is the driver for determining the waste management boundary. The waste management boundary is estimated to extend from the UIC to 275 feet downgradient of the UIC.

1.1 Objectives

The objectives of modeling pollutant fate and transport from wet feet UICs are:

- Determine the extent of a waste management boundary for a City UIC.
- Develop a science-based, technical rationale that can be used to determine which wet feet UICs to decommission or retrofit, and which wet feet UICs to continue to operate based on the waste management boundary and the proximity to receptors (domestic use water wells).
- Determine the sensitivity of model results to the permeability of the aquifer.
- Evaluate "worst case" scenarios for pollutant transport, including the possibility for overlapping pollutant discharges from closely-spaced UICs.

1.2 Conceptual Model for Wet Feet UICs

A typical City-owned UIC system consists of a stormwater inlet (e.g., catch basin), sedimentation manhole, and the UIC. The sedimentation manhole is a solid concrete cylinder generally 3 to 4 feet in diameter and 10 feet deep, located upstream of the UIC. Sedimentation manholes provide pretreatment prior to stormwater discharging to the UIC, by allowing sediment in stormwater to settle before entering the UIC and by preventing floatables (e.g., debris, oil, and grease) from flowing into the UIC. Water leaves the sedimentation manhole though a "bent elbow" drainpipe that extends below the water surface to the UIC. City-owned UICs are generally 4 feet in diameter and range in depth from about 2 feet to 40 feet. Most of the City-owned UICs are approximately 30 feet deep.

Stormwater draining public right of ways contains low levels of pollutants from the urban environment. When stormwater enters a wet foot UIC, the pollutants are diluted into the standing water within the UIC. The standing water is a mixture of residual stormwater from the most recent storm, and groundwater that has entered the UIC from upgradient. The stormwater discharges from the wet foot UIC, and pollutants are further diluted into groundwater within the subsurface. Total organic carbon in the stormwater (from pollen, leaf debris, etc.) is filtered out of the water and accumulates, through filtration and sorption, a short distance from the UIC. After discharge into groundwater, pollutants are transported in the direction of groundwater flow. During transport, pollutant concentrations are attenuated by macrodispersion, diffusion and biodegradation. Pollutants are retarded primarily due to sorption on the organic carbon added to the soil from stormwater, and organic carbon incorporated in sediments during deposition. The amount of pollutant dilution and attenuation depends on soil properties of the aquifer, hydraulic properties of the aquifer, and pollutant properties.

2 Methods

Pollutant fate and transport from a wet foot UIC was simulated with a three dimensional finite difference numerical model for groundwater flow and pollutant fate and transport. The UIC was simulated as an injection well that discharges stormwater into the aquifer at a specified rate over 27 years, which was sufficiently long for PCP concentrations (the driver for determining waste management area) to stabilize. Pollutant concentrations downgradient of the wet feet UIC were measured downgradient of the UIC along the plume centerline, in the center of each grid cell. The transport scenarios were conducted for PCP, benzo(a)pyrene, lead, and di (2-ethylhexyl) phthalate (DEHP) because they:

- Most frequently exceed the Maximum Allowable Discharge Limit (MADL) based on the Kennedy Jenks (2009) statistical analysis stormwater quality in western Oregon. These pollutants include PCP (exceeded MADLs in 11.7% of samples), DEHP (exceeded MADLs in 4.7% of samples), and lead (exceeded MADLs in 12.7% of samples).

- Have resulted in noncompliant conditions in the City's permit by exceeding the MADL for two consecutive years of annual stormwater discharge monitoring (i.e., benzo(a)pyrene and PCP).

In addition to periodically exceeding MADLs, these pollutants are among the most mobile, persistent, or toxic stormwater pollutants in their respective class (i.e., metals, semivolatile organic compounds, and polynuclear aromatic hydrocarbons) (BES, 2008).

The pollutant fate and transport modeling is designed to conservatively estimate pollutant fate and transport so that it can be applied to all wet feet UICs within Portland. Specifically:

- Pollutant concentrations downgradient of the UIC were measured along the plume's centerline, which is where the highest concentrations occur,

- Groundwater flow direction was constant and did not exhibit seasonal changes, which underestimates dilution of the pollutant concentrations,

- The input concentration for PCP (the driver for determining waste management area) was 10 times the MADL, which is greater than any observed PCP concentration observed from over 1,200 stormwater samples that have been collected by the City during Years 1 through 6 of annual stormwater discharge monitoring.

- Pollutant transport and aquifer parameters were selected as averages based on field studies.

- Stormwater infiltration was assumed to occur when rainfall intensity was equal to or exceeded 0.04 inches per hour, which is half of the intensity threshold of 0.08 inches per hour cited in the Permit Evaluation report (DEQ, 2005b).

2.1 Model Software

Pollutant fate and transport from wet feet UICs was simulated using the 3D finite difference United States Geological Survey (USGS) block centered numerical groundwater flow model MODFLOW-2000. Three-dimensional finite difference numerical models divide an aquifer into discrete cubes (known as cells), and solve for groundwater elevation by minimizing mass balance errors in between the cells. The groundwater model outputs velocity vectors at each cell. The groundwater flow equation was solved using the Pre Conditioned Conjugant Gradient 2 package (PCG2).

The velocity vectors output by MODFLOW are used by the pollutant fate and transport code MT3D to simulate pollutant transport. Particle advection was simulated using the TVD solution scheme.

Groundwater Vistas version 6.15 (build 17) was used as a pre and post processor for model input and output, respectively.

2.2 Model Boundaries

Model boundaries are shown in Figure 1. The upgradient and downgradient model boundaries were assigned constant head boundaries. Constant head values were selected to simulate a horizontal hydraulic gradient of 0.002 feet/foot (see Section 2.4.1). Lateral boundaries were no flow boundaries oriented perpendicular to the direction of groundwater flow.

2.3 Spatial and Temporal Discretization

Spatial and temporal model discretization is summarized in Table 1. Cell sizes were chosen based on a Peclet number of 10 in order to prevent numerical dispersion. For simulation of pollutant transport, the MT3D time step was chosen to be ten percent of the MODFLOW time step in order to achieve a Courant number of 1.5, which is in the range of 0 to 2 necessary to prevent numerical dispersion (Van Ganutchen, 1994).

The aerial extent of the model domain (700 feet by 700 feet) was selected to maximize computational efficiency. Trial simulations with a larger model domain (approximately 10,000 feet by 10,000 feet) were conducted to confirm that the boundary conditions for the 700 feet by 700 feet model did not affect simulation results. The thickness of the model domain corresponds to the thickness of the Unconsolidated Sedimentary Aquifer, where several of the City's wet feet UICs are located (see Section 2.4.1).

2.4 Model Input Parameters

Model input parameters include aquifer properties (corresponding to the Unconsolidated Sedimentary Aquifer) and pollutant properties, and are summarized in Table 2 and Table 3, respectively.

2.4.1 Aquifer Properties

Aquifer properties are hydraulic characteristics of the aquifer that govern groundwater flow, and are summarized in Table 2.

Hydraulic Gradient

Hydraulic gradient (0.002 feet/foot) was calculated based on groundwater elevations presented in the USGS water table elevation map of the Portland Basin (Snyder, 2008). The gradient was based on groundwater elevations near Powell Butte, where several of the wet feet UICs are located.

Hydraulic Conductivity

The hydraulic conductivity used in the model (200 ft/day) is the median hydraulic conductivity for the Unconsolidated Sedimentary Aquifer based on analysis of single and multiple well aquifer tests presented in Morgan and McFarland (1996). This value was also used in the City's UIC WPCF Permit Evaluation Fact Sheet (DEQ, 2005b).

Aquifer Thickness

The aquifer thickness is based on USGS interpretation of well driller logs for water wells drilled through the Unconsolidated Sedimentary Aquifer in the vicinity of Powell Butte, where several of the City's wet feet UICs are located (Swanson et al., 1993).

Porosity, Effective Porosity, and Specific Yield

Porosity (0.325) was the midrange for a gravel from Freeze and Cherry (1979), to represent the gravels of the Unconsolidated Sedimentary Aquifer where several of the City's UICs are located. The effective porosity and specific yield (0.20) were taken from McFarland and Morgan (1996) for the Unconsolidated Sediments.

Dispersivity

Dispersivity (α) is a scale-dependent parameter that increases with increasing pollutant transport distance. The Environmental Protection Agency (EPA) recommends using the equation of Xu and Eckstein (1995) to calculate dispersivity (EPA, 1996). The Xu and Eckstein (1995) formula is preferred to other approaches for large transport distances (i.e., greater than about 30 meters) because Xu and Eckstein (1995) better-approximates dispersivities measured in field scale tracer tests (as opposed to the approach of Gelhar et al., 1992, which recommends using 10 percent of transport distance). Following recommendations in EPA (1996), transverse dispersivity was 33 percent of longitudinal dispersivity, and vertical dispersivity was 10 percent of longitudinal dispersivity.

Stormwater Infiltration Volume and Times

Calculations for stormwater infiltration volumes are shown in Table 4. The volume of stormwater discharges to a wet feet UIC was calculated for an average-sized UIC drainage basin (impervious area of 27, 437 ft^3). Runoff into a UIC occurs when storm intensity exceeds 0.08 inches per hour (DEQ, 2005b). For the purpose of infiltration calculations, it was conservatively assumed that all precipitation that falls during a storm intensity of greater than or equal to 0.04 inches per hour runs off into UICs. As shown on Table 4, approximately 2.02 feet of precipitation is produced annually by storm instensities greater than or equal to 0.04 inches per hour, which corresponds to an infiltration volume of about 42,000 cubic feet for an average-sized UIC drainage basin.

As shown on Table 4, on average, precipitation is equal to or exceeds 0.04 inches per hour for about 324 hours (13.51 days) per year. In the model, the UIC discharged stormwater to the aquifer over 14, one day-long storms that were allocated evenly from October through May of each year. Stormwater discharges did not occur from June through September.

Fraction Organic Carbon

Fraction organic carbon (f_{oc}) is a dimensionless measure of organic carbon content in a material (i.e., g_{carbon} / g_{soil}). Pollutants primarily sorb to organic carbon; therefore, pollutant retardation is directly proportional to fraction organic carbon.

Carbon in unsaturated soil beneath a UIC is derived from two sources:

- Organic carbon incorporated into the soil when the soil is deposited, and
- Particulate matter (e.g., degraded leaves, pine needles, pollen, etc.) that is filtered out of stormwater and accumulates in soil adjacent to UICs as stormwater discharges from the device.

The model included f_{oc} from both sources. The background f_{oc} level in sediments (i.e., due to incorporation of organic carbon in soil during deposition) was 0.00038, based on 14 f_{oc} measurements in the Unconsolidated Sedimentary Aquifer at the Baron Blakeslee Environmental Cleanup Site Information (ECSI) Site (ECSI No. 1274).

An estimate of f_{oc} based on accumulation of TOC in stormwater around a UIC by filtration and sorption was derived by calculating the grams of organic carbon added to the aquifer around the UIC during a 10-year period. The approach was also used to calculate grams of organic carbon added to the unsaturated zone for dry-feet UICs as a part of unsaturated zone fate and transport modeling (BES, 2008). The following equations were used in the analysis:

$$I = (A)(p)(1-e) \qquad (1)$$

$$CL = (t)\left[\sum (I_m)(C)\right]\frac{1\,\text{liter}}{1{,}000\,\text{cm3}}\,\frac{1\,\text{gram}}{1{,}000{,}000\,\text{milligrams}} \qquad (2)$$

$$\rho_{oc} = \frac{CL}{SV} \qquad (3)$$

$$f_{oc} = \frac{\rho_{oc}}{\rho_b + \rho_{oc}} \qquad (4)$$

Where:

I = Annual stormwater infiltration volume estimated using the average impervious area of a UIC catchment (A), monthly precipitation averages from 2000 – 2011 (p), and losses to evaporation (e) (cubic centimeters per year)

A = Average area of a UIC catchment (square feet) in a Portland

p = Precipitation (geometric mean feet per year, 2000 to 2011). Precipitation reflects the amount of annual precipitation that runs off into UICs (i.e., precipitation that falls during storm events that are $\geq$ 0.04 inches per hour).

e = Evaporative loss fraction (dimensionless)

CL = Organic carbon loaded into the unsaturated zone beneath a UIC during a 10-year period (grams)

C = TOC concentration in stormwater (milligrams per liter)

t = Time of carbon loading (years)

ρ_{oc} = Organic carbon weight per unit unsaturated zone material volume (grams per cubic centimeter)

SV = Material volume into which the organic carbon would accumulate because of filtration and adsorption (assumed to be the volume of a grid cell where the UIC is located)

F_{oc} = Fraction organic carbon (dimensionless)

ρ_b = Bulk density (grams per cubic centimeter)

Calculations of infiltration volumes at a City UIC are shown in Table 4, and calculation of $f_{oc,}$ based on the filtering of TOC as suspended solids are shown in Table 5. First, the volume of stormwater that infiltrates into a UIC each month was calculated by Equation (1). Next, Equation (2) was used to calculate the grams of carbon added to the unsaturated zone surrounding the UIC during a 10-year period. Equation (3) was used to calculate the mass of organic carbon per unit volume of material surrounding the UIC (ρ_{oc}), and Equation (4) was used to convert ρ_{oc} to f_{oc}. The calculated f_{oc} level in sediments immediately around the UIC was 0.00841.

2.4.2 Pollutant Properties

Pollutant properties are summarized in Table 3. With the exception of half-life, the pollutant properties used for modeling saturated transport from wet feet UICs are the same as used in previous unsaturated zone fate and transport models for City-owned UICs (BES, 2008). The wet feet transport simulations used half lives that were the midrange of field studies for degradation in aerobic groundwater from Howard et al. (1991). Other pollutant properties have been previously documented in the *Decision Making Framework for Groundwater Protectiveness Demonstrations* (BES, 2008) and peer-reviewed in SSPA (2008).

Pollutant input concentrations were 10 times the MADL, as shown on Table 3. Also shown on Table 3 are the maximum observed pollutant concentrations and 95% Upper Confidence Limit (UCL) on the mean for the over 1,200 stormwater samples collected by the City during annual stormwater discharge monitoring from Year 1 through Year 6. The 95% UCL on the mean concentrations for lead, benzo(a)pyrene, PCP and DEHP are significantly below the 10 times the MADL input concentration that was used in the model. In fact, using 10 times the MADL as an input concentration in the model exceeds the maximum observed value for lead and PCP in stormwater.

3 Simulation Results

Three groups of fate and transport simulations were conducted for determining the waste management area:

- **Average Conditions.** Simulation of pollutant transport for 27 years from a single UIC, using the aquifer parameters in Table 2 and the pollutant properties in Table 3. The objective of the average conditions scenario is to estimate the waste management area from a UIC to support decisions for UIC retrofits.

- **Sensitivity Analysis.** Determine the sensitivity of the simulated waste management area to hydraulic conductivity by lowering hydraulic conductivity by one order of magnitude (i.e., to 20 ft/day) and evaluating waste management area. Porosity was not varied during the sensitivity analysis because field-measured hydraulic conductivity exhibits significantly more variation than field-measured porosity (Gelhar, 1985; Freeze and Cherry, 1979).

- **Multiple UIC Scenario.** Simulates three UICs, located 100 feet apart, with the first UIC located directly upgradient of the second UIC, and the third UIC located directly upgradient of the second UIC. The objective of the multiple UIC scenario was to evaluate a “worst case” waste management boundary when the potential exists for pollutant discharges from closely-spaced UICs.

3.1 Average Conditions Results

Results of the average conditions scenario model are summarized in Table 6, and shown graphically in Figure 2 and Figure 3. As shown in Figure 2, the PCP and DEHP plumes stabilize within three years and nine years of transport, respectively. The benzo(a)pyrene and lead plumes continue to grow slightly over the 27 year lifetime of a UIC. PCP migrates significantly further than DEHP, lead, and B(a)P over the 27 year lifetime of a UIC, and is therefore the driver for determining the waste management area. This is because PCP has the lowest retardation of the four pollutants. Lead and B(a)P, which have the highest retardation factors, remain within several tens of feet of the UIC.

Plots of simulated PCP concentration verses time (i.e., “breakthrough curves”) at theoretical downgradient monitoring points are shown in Figure 3. On the figure, groundwater is shown as flowing from left to right. PCP concentrations decrease to below the EPA Maximum Contaminant Level (MCL) within 81 feet of the UIC, decrease to below the DEQ Risk Based Concentration (RBC) for residential tap water within 200 feet of the UIC, and decrease to below the MRL within 275 feet of the UIC. Therefore, the waste management area for a UIC extends from the UIC to approximately 275 feet downgradient of the UIC. The result is a conservative waste management area because the modeled initial PCP concentration (10 ug/L) is over 9 ug/L above the actual 95% UCL on the mean concentration (0.674 ug/L) based on over 1,200 stormwater samples collected during Years 1 to 6 of annual stormwater discharge monitoring.

3.2 Sensitivity Analysis Results

Results of the sensitivity analysis for pollutant transport distances (i.e., waste management area) and hydraulic conductivity are shown on Table 6. The sensitivity analysis indicates that the simulated waste management area is sensitive to hydraulic conductivity. Hydraulic conductivity was reduced by an order of magnitude to 20 ft/day. The order of magnitude decrease in hydraulic conductivity reflects transport conditions in the Troutdale Gravel Aquifer, where hydraulic conductivity of the gravel (median = 7 ft/day) is about an order of magnitude lower than in the Unconsolidated Sedimentary Aquifer (Morgan and McFarland, 1996).

This discussion of the sensitivity of transport results to hydraulic conductivity focuses on PCP, which is the most mobile of the four pollutants modeled and therefore the driver for determining the waste management area. An order of magnitude decrease in hydraulic conductivity (i.e., decreased to 20 ft/day) results in an approximately 200 feet decrease in the transport distance required for PCP to attenuate to below MRLs. However, the hydraulic gradient is inversely correlated to hydraulic conductivity and would reduce the magnitude of the effect of hydraulic conductivity.

3.3 Multiple UIC Scenario Results

Results of the multiple UIC scenario are summarized in Table 6. The waste management area for DEHP, benzo(a)pyrene, and lead for multiple UICs spaced 100 feet apart does not change from the average conditions scenario because the plumes from each UIC extend less than 100 feet from the UIC. The PCP plumes from each UIC do overlap, which extends the waste management area about 25 feet from the furthest downgradient relative to the single UIC scenario.

4.0 Conclusions and Recommendations

The pollutant fate and transport model was developed using conservative assumptions with the objective of estimating the waste management boundary from a City-owned UIC. The pollutant fate and transport simulations indicate that:

- PCP is the driver for determining the waste management boundary because it exhibits a low sorption to soil relative to lead, DEHP and benzo(a)pyrene, and would be expected to travel the farthest away from the UIC.
- Under average conditions, PCP concentrations reach steady-state conditions within about three years of transport. PCP concentrations of 10 times the MADL originating

from a single wet feet UIC attenuate to zero (i.e., the MRL) within 275 feet of the UIC. Under worst-case conditions (i.e., three closely-spaced UICs located 100 feet apart), PCP concentrations from the adjacent UICs comingle so that PCP in groundwater extends 300 feet.

- The waste management boundary is sensitive to the hydraulic conductivity of the aquifer. However, the hydraulic gradient is inversely correlated to hydraulic conductivity and would reduce the magnitude of the effect of hydraulic conductivity.

The waste management boundary (275 feet) simulated by the pollutant fate and transport model can be used as a decision making tool for determining if structural retrofits are necessary for wet feet UICs. If a receptor (e.g., domestice use water well) is located within a waste management boundary, then structural retrofits of the wet feet UIC would be necessary. If no receptors are located within the waste management boundary, then a structural retrofit would not be necessary based on contaminant transport modeling.

References

BES, 2006. Corrective Action Plan. Prepared by: City of Portland Bureau of Environmental Services, July.

BES, 2008. Decision Making Framework for Groundwater Protectiveness Demonstrations. Prepared by: City of Portland Bureau of Environmental Services, June.

DEQ, 2005a. Water Pollution Control Facilities Permit for Class V Stormwater Underground Injection Control Systems, Permit No. 102830, June 1.

DEQ, 2005b. Fact Sheet and Class V Underground Injection Control (UIC) WPCF Permit Evaluation. Permit Number 102830, June 1, 2005, 63 pp.

EPA, 1996. BIOSCREEN: Natural Attenuation Decision Support System. Office of Research and Development, August, 100 pp.

Freeze, A. and J. A. Cherry, 1979. Groundwater. Prentice Hall: Englewood Cliffs, NJ, 604 pp.

Gelhar, L. W., 1986. Stochastic subsurface hydrology from theory to application. *Water Resources Research*, Vol. 22, No. 9, 135S – 145S.

Gelhar, L. W., Welty, C., and K. R. Rehfeldt, 1992. A Critical Review of Data on Field Scale Dispersion in Aquifers. Water Resources Research, Vol. 28, No. 7, pg. 1955-1974.

Morgan, D. S., and W. D. McFarland, 1996. Simulation analysis of the groundwater flow system in the Portland Basin, Oregon and Washington. USGS Water Supply Paper 2470-B, Portland, Oregon 78 pp.

Snyder, D. T., 2008. Estimated depth to groundwater and configuration of the water table in the Portland, Oregon Area. USGS Scientific Investigations Report 2008-5059.

Swanson, R. D., McFarland, J. B., Gonthier, J. B., and J. M. Wilkinson, 1993. A description of the hydrogeologic units in the Portland basin, Oregon and Washington. USGS Scientific Investigations Reports 90-4196, 56 pp.

Xu, Moujin and Y. Eckstein, 1995. Use of a weighted least-squares method in evaluation of the relationship between dispersivity and scale. Journal of Groundwater, Vol. 33, No. 6, pp 905-908.

Tables

Table 1

Model Discretization

Saturated Fate and Transport at Wet Feet UICs

Variable	Reference
Spatial Discretization	
Horizontal *x* -extent	700 feet
Horizontal *y* -extent	700 feet
Vertical Exent	28 feet
Number of Rows	15
Number of Columns	15
Number of Layers	4
Total Number of Cells	900
Cell Size	56 feet to 14 feet
Temporal Discretization	
Simulation Length	27 years
Number of Time Steps	9,856
MODFLOW Time Step Length	1 day
MT3D Time Step Length	0.1 day

Table 2

Aquifer Properties

Saturated Fate and Transport at Wet Feet UICs

Variable	Symbol	Units	Value	Reference
Hydraulic Gradient	h	feet/feet	0.002	Snyder (2008) Portland Basin water table elevation map
Hydraulic Conductivity	K_h	feet/day	200	Fact Sheet and Class V UIC WPCF Permit Evaluation, UIC WPCF Permit 102830, page 32, (DEQ, 2005b), based on McFarland and Morgan (Figure 6, page 18, 1996) for the Unconsolidated Sediments
Anisotropy	K_h:K_v	dimensionless	100:1	McFarland and Morgan (pg. 1, 1996) for "aquifer units"
Aquifer Thickness	b	feet	35	UGA aquifer as identified at wells 01S/02E/14ABC and 01S/02E/14CBCB, located near City of Portland wet feet UICs, as reported in Swanson et al. (1993)
Porosity	η	dimensionless	0.325	Midrange of porosity for a gravel in Freeze and Cherry (Table 2.4, pg. 37, 1979)
Effective Porosity	η_e	dimensionless	0.20	McFarland and Morgan (pg. 20, 1996) for the Unconsolidated Sediments
Specific Yield	S_y	dimensionless	0.20	McFarland and Morgan (pg. 20, 1996) for the Unconsolidated Sediments
Longitudinal Dispersivity	α_L	feet	17.93	Calculated using Xu and Eckstein (1995). a_L = $(3.28)(0.83)[\log(L_p/3.28)]^{2.414.}$ A transport distance (L_p) of 500 feet was used in the calculation)
Transverse Dispersivity (y-direction)	α_T	feet	5.92	Calculated using EPA (1986). $a_T = 0.33(a_L)$
Vertical Dispersivity (z-direction)	α_V	feet	1.79	Calculated using EPA (1986). $a_v = 0.10(a_L)$
Fraction Organic Carbon	f_{oc}	dimensionless	0.00841	f_{oc} immediately around UIC due to carbon
			0.00038	Aquifer f_{oc}: average of 14 TOC measurements in the UGA at the Baron-Blakeslee RCRA Site (ECSI No. 1274)

Table 3

Pollutant Properties

Saturated Fate and Transport at Wet Feet UICs

Variable	Symbol	Units	Pollutant	Value	Reference
Organic Carbon Partitioning Coefficient	K_{oc}	L/kg	B(a)P	282,185	Calculated by Roy and Griffin (1985), which relates Koc to solubility in water
			PCP	877	From EPA (1996), based on a groundwater pH of 6.4 measured at 12 USGS wells screened at or near the water table on the east side of the Willamette River.
			DEHP	12,200	Calculated by Roy and Griffin (1985), which relates Koc to solubility in water
Distribution Coefficient	K_d	L/kg	Lead	1,001,923	Calculated by the equation of Bricker (1988), which calculates Kd based on concentrations of total metals, dissolved metals, and TSS. Calculations are documented in GSI (2008).
			B(a)P	107 to 2,373	Calculated from the relationship: $K_d = (f_{oc})(K_{oc})$ (Watts, 1998)
			PCP	0.33 to 7.0	Calculated from the relationship: $K_d = (f_{oc})(K_{oc})$ (Watts, 1998)
			DEHP	4.6 to 103	Calculated from the relationship: $K_d = (f_{oc})(K_{oc})$ (Watts, 1998)
Retardation Factor	R	dimensionless	Lead	5,518,285	Calculated from the relationship: $R = 1 + (\rho_b)(K_d)/(\eta)$. Based on a bulk density of 1.79 g/cm^3, calculated from porosity using equation 8.26 of Freeze and Cherry (1979).
			B(a)P	592 to 13,071	Calculated from the relationship: $R = 1 + (\rho_b)(K_d)/(\eta)$. Based on a bulk density of 1.79 g/cm^3, calculated from porosity using equation 8.26 of Freeze and Cherry (1979).
			PCP	2.84 to 39.6	Calculated from the relationship: $R = 1 + (\rho_b)(K_d)/(\eta)$. Based on a bulk density of 1.79 g/cm^3, calculated from porosity using equation 8.26 of Freeze and Cherry (1979).
			DEHP	26.5 to 568	Calculated from the relationship: $R = 1 + (\rho_b)(K_d)/(\eta)$. Based on a bulk density of 1.79 g/cm^3, calculated from porosity using equation 8.26 of Freeze and Cherry (1979).
Half Life	h	days	B(a)P	587	Based on midrange observed biodegradation rate for B(a)p in aerobic groundwater (Howard et al., 1991)
			PCP	46	Based on observed biodegradation rate for PCP in aerobic groundwater (Howard et al., 1991)
			DEHP	10	Based on observed biodegradation rate for DEHP in aerobic groundwater (Howard et al., 1991)
95% UCL Observed Pollutant Concentration	C_{Obs}	ug/L	Lead	0.431	95% KM (BCA) UCL based on N=1,223 data points, Year 1-6 SWDM
			B(a)P	0.0301	95% KM (% Bootstrap) UCL based on N=1,223 data points, Year 1-6 SWDM
			PCP	0.674	95% KM (Chebyshev) UCL based on N=1,271 data points, Year 1-6 SWDM
			DEHP	3.069	95% KM (BCA) UCL based on N=1,223 data points, Year 1-6 SWDM
Maximum Observed Pollutant Concentration	C_{max}	ug/L	Lead	20.5	Based on N=1,223 data points, Year 1-6 SWDM
			B(a)P	2.6	Based on N=1,223 data points, Year 1-6 SWDM
			PCP	6.3	Based on N=1,271 data points, Year 1-6 SWDM
			DEHP	264	Based on N=1,223 data points, Year 1-6 SWDM
10X the Maximum Allowable Discharge Limit	C_{EDL}	ug/L	Lead	500	DEQ (2005)
			B(a)P	2	DEQ (2005)
			PCP	10	DEQ (2005)
			DEHP	60	DEQ (2005)

Table 4

Infiltration Volume and Rate

Saturated Fate and Transport at Wet Feet UICs

Impervious Area in UIC Drainage Basin [1] (ft^2)	**Annual Number of Days with Precipitation ≥ 0.04 inches/hour** [2] (days)	**Annual Precipitation ≥ 0.04 inches/hour** [2] (ft)	**Annual Infiltration Volume** [3] (ft^3)
27,437	13.51	2.02	42,147

Notes

(1) Geometric mean impervious area from 30 drainage basins in the City of Portland, as reported on Table 7-5 and Table 7-6 of the Year 4 Annual Stormwater Discharge Monitoring Report

(2) Based on precipitation records from the Airport Way No. 2 raingage located at 14614 NE Airport Way in Portland, Oregon. Value is based on the geometric mean of precipitation data from 2000 to 2011.

(3) Assumes an evaporative loss factor of 26%.

Table 5

Carbon Loading Calculations

Saturated Fate and Transport at Wet Feet UICs

Annual Infiltration Volume [1] (cm^3/yr)	**TOC Concentration** (mg/L)	**Time** (years)	**Conversion Factor**	**Grams Carbon Added Over 10 Years** (g)	**Cell Width** (cm)	**Cell Length** (cm)	**Cell Depth** (cm)	**Aquifer Volume** (cm^3)	**g TOC per cm^3/soil** (g/cm^3)	**Bulk Density** (g/cm^3)	f_{oc} (-)
1,161,354,087	9.07	10	1,000,000	105,306	213.3	213.3	152.4	6,936,612	0.0152	1.79	0.00841

Notes

(1) Calculations from Table 3 (equivalent to 42,147 ft^3/yr)

mg/L = milligrams per liter

cm^3/yr = cubic centimeters per year

g = grams

cm = centimeters

g/cm^3 = grams per cubic centimeter

Table 6

Model Simulation Results

Saturated Fate and Transport at Wet Feet UICs

	Waste Management Area Size (Distance to Attenuate to Below the MRL)			
	PCP	DEHP	B(a)P	Lead
Average Conditions (K=200 ft/day)	275 feet	75 feet	70 feet	7 feet
Sensitivity Analysis (K= 20 ft/day)	80 feet	53 feet	42 feet	4 feet
Multiple UICs (K=200 ft/day, distance from furthest-downgradient UIC)	300 feet	75 feet	70 feet	7 feet

Figures

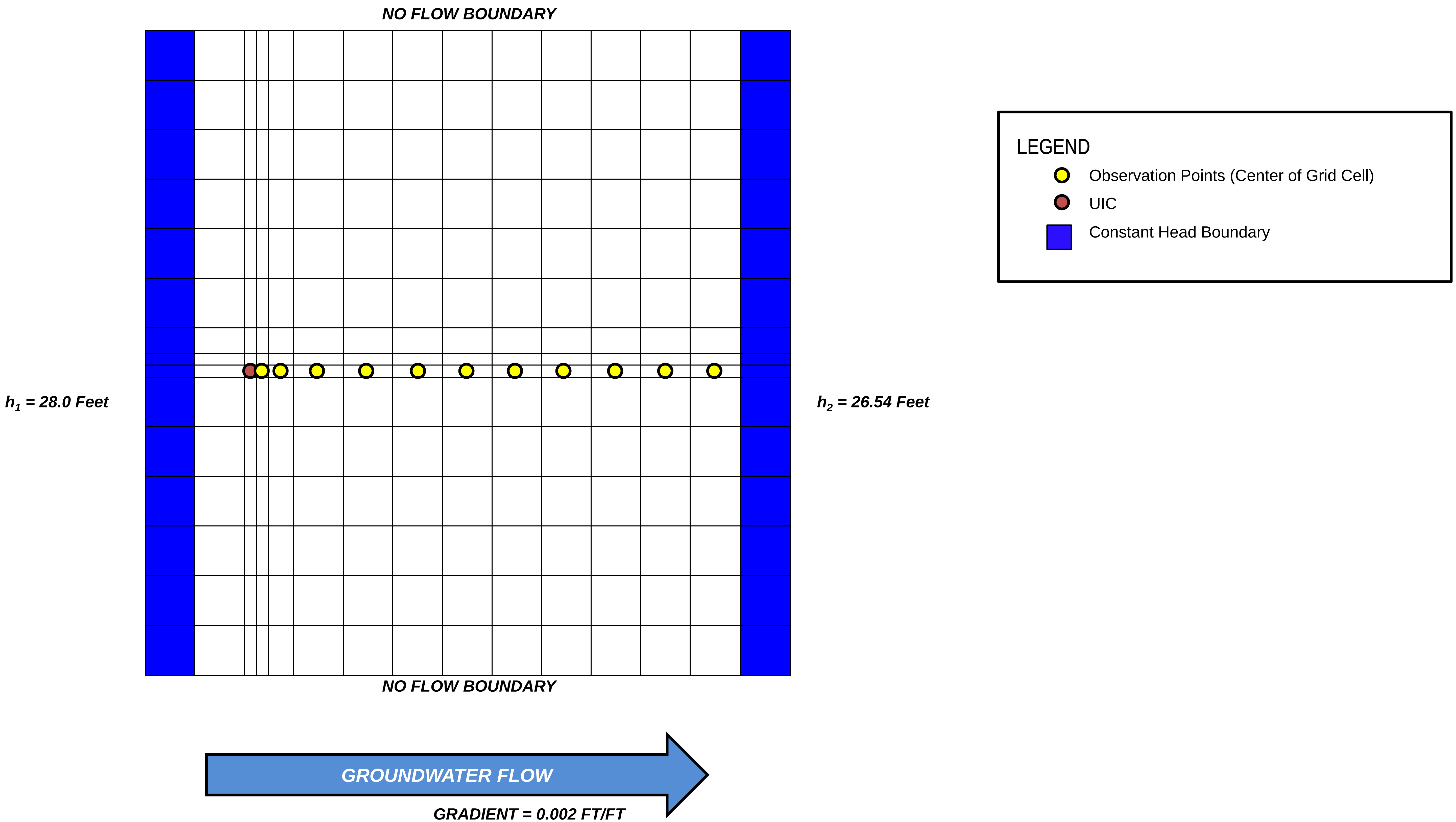

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FIGURE 1
Model Discretization
City of Portland, Oregon

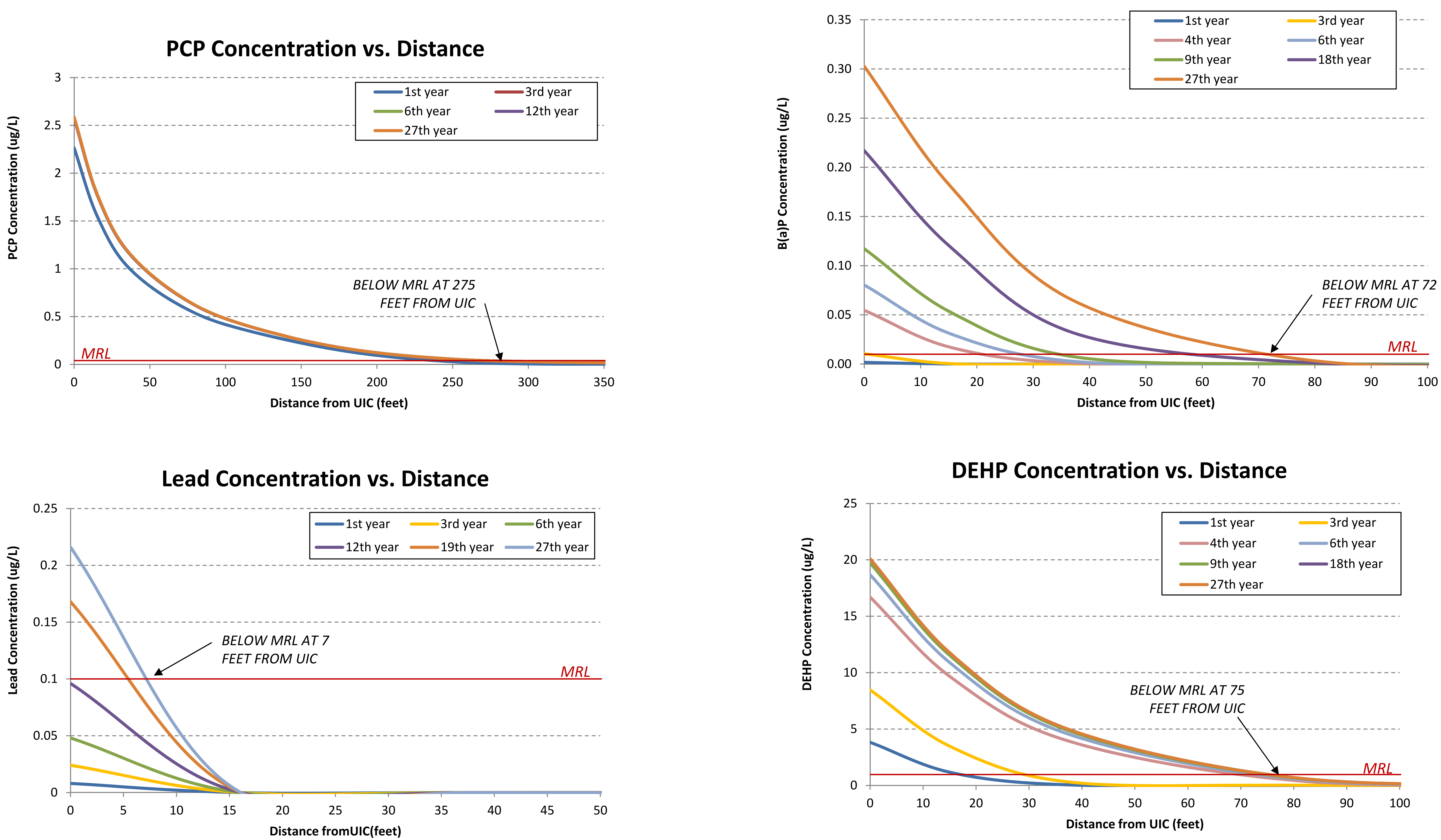

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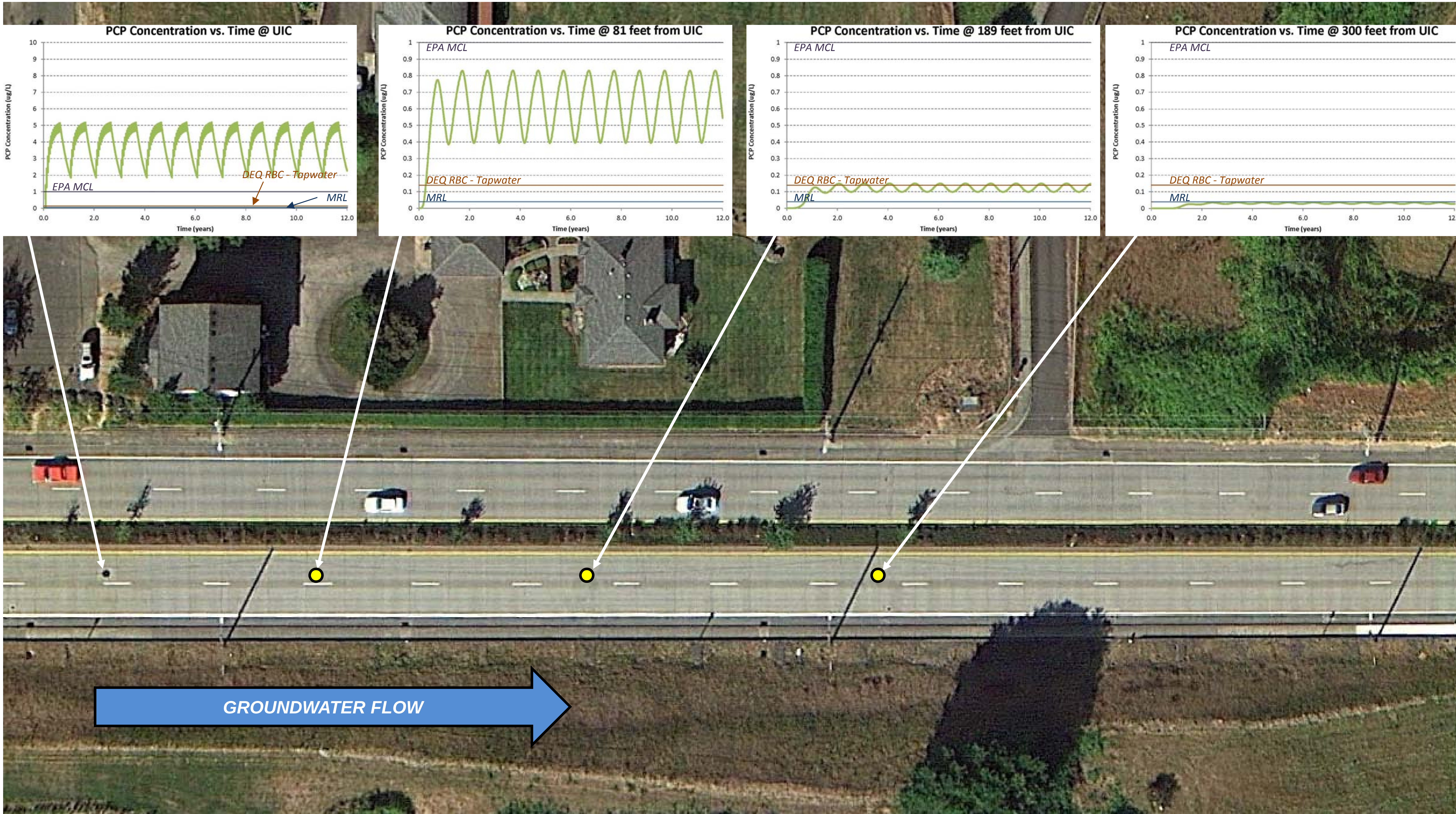
FIGURE 2
Pollutant Concentrations vs. Distance
City of Portland Wet Feet Transport



LEGEND

- Observation Point
- UIC

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FIGURE 3

PCP Breakthrough Curves

City of Portland, Oregon