Water Solutions, Inc.

Technical Memorandum

To: Shannon Ostendorff/City of Redmond

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Date: September 21, 2011

Re: **Pollutant Fate and Transport Model Results in Support of the City of Redmond UIC WPCF Permit – Groundwater Protectiveness Demonstration and Proposed EDLs**

Executive Summary

The City of Redmond (City) uses over 1,600 drywells and drillholes, or Underground Injection Controls (UICs), to manage urban stormwater within its City boundaries. The City has applied for a UIC Water Pollution Control Facilities (WPCF) permit with the Department of Environmental Quality (DEQ) and wants to use fate and transport modeling to proactively demonstrate groundwater protectiveness of the City's UICs through the DEQ's risk evaluation process described in Schedule D.6 of the UIC WPCF Permit Template. GSI Water Solutions, Inc. (GSI) developed a fate and transport model to support the City's application for an UIC WPCF Permit and risk evaluation goals. The objectives of the model simulations were to 1) demonstrate groundwater protectiveness for stormwater discharged from UICs that potentially are in the 500-foot well setback or the two-year Time-of-Travel from water wells and 2) propose Effluent Discharge Limits (EDLs) for the City's UIC WPCF Permit that meet Oregon's groundwater protectiveness standards.

Water discharged from UICs travels downward through the unsaturated zone, which is over 150 feet thick across the City, and in many areas of the City is greater than 400 feet thick. Downward transport of stormwater occurs along both fractures in the compound basalt flows underlying the City and through sedimentary and flow top interbeds also present within the complex geologic deposits of the region. Percolation of stormwater runoff through UICs is considered a source of recharge to the groundwater system, however runoff modeling indicates that this recharge from public and private UICs is a very small percentage of total recharge to the groundwater aquifer in Redmond (i.e., anticipated to reach less than one percent of total recharge under full build-out of the urban growth boundary).

An unsaturated zone fate and transport model (i.e., Fate and Transport Tool) using site-specific geologic and hydrogeologic conditions was developed to evaluate and demonstrate groundwater protectiveness of UICs discharging in the vicinity of water wells and propose EDLs. The Fate and Transport Tool modeled attenuation of representative pollutants (copper, lead, benzo(a)pyrene, naphthalene, pentachlorophenol (PCP), di(2-ethylhexyl)phthalate (DEHP), 2,4-D, and toluene) from stormwater during transport through the basalt's fracture systems after discharge from the UIC. These pollutants were selected for the model because they tend to have a higher frequency of detection in Oregon stormwater based on the Oregon Association of Clean Water Agencies (ACWA) statewide study of municipal stormwater water quality results and stormwater data from the Cities of Bend and Redmond (Kennedy/Jenks, 2009 and Kennedy/Jenks, 2011), and have relatively high mobility, persistence, and toxicity when compared to other common stormwater pollutants.

The Fate and Transport Tool uses a one-dimensional pollutant fate and transport equation [Advection Dispersion Equation (ADE)] to estimate the magnitude of pollutant attenuation during transport through the unsaturated zone. This constant source ADE incorporates sorption, degradation (biotic and abiotic), and dispersion to estimate pollutant attenuation during transport. Two scenarios were evaluated using the Fate and Transport Tool: 1) the average scenario, which models the central tendency or expected mean value for attenuation and 2) the reasonable maximum scenario, which models the minimum amount of attenuation that could potentially occur (i.e., worst-case scenario).

Using the average and reasonable maximum scenario of the Fate and Transport Tool, pollutant attenuation was simulated for UICs with a separation distance (i.e., vertical unsaturated zone transport distance between seasonal high groundwater and the bottom of UICs) of five (5) feet. The pollutant concentrations discharging to UICs used as input to the Fate and Transport Tool were equal to:

- The existing EDLs (as listed in the UIC WPCF Municipal Stormwater Template) for copper, 2,4-D, and toluene, or
- A maximum of ten (10) times the existing EDLs for ubiquitous pollutants that exceed regulatory standards at a relatively higher frequency based on ACWA studies by Kennedy/Jenks (2009) and Kennedy/Jenks (2011) (lead, PCP, and DEHP), and pollutants that have caused noncompliant conditions under other jurisdictions' permits (benzo(a)pyrene)

Under the average scenario, the eight pollutants evaluated attenuate to below method reporting limits (MRLs) within five (5) feet of transport. Under the worst-case transport scenario (reasonable maximum scenario), copper, lead, benzo(a)pyrene, PCP, and DEHP attenuate to below MRLs within five (5) feet of transport. 2,4-D and toluene require greater than five (5) feet to attenuate to below the MRL under the reasonable maximum scenario, but do not reach groundwater due to the large depths to groundwater in the City. **Therefore, the Fate and Transport Tool demonstrates groundwater protectiveness for UICs that are in water well setbacks or the two-year Time-of-Travel delineation.**

The Fate and Transport Tool was also used to develop proposed EDLs for the City of Redmond's UIC WPCF Permit for lead, benzo(a)pyrene, PCP, and DEHP. In the Spring 2011 DEQ recommended developing proposed EDLs for these four pollutants because they are considered more likely to exceed regulatory standards in municipal stormwater in Oregon based on the ACWA studies (Kennedy/Jenks, 2009 and Kennedy/Jenks, 2011), and/or have resulted in noncompliant conditions under other jurisdictions' permits. The proposed EDLs were developed based on the assumption that groundwater is protected when pollutant concentrations just above the water table are below the MRL. Proposed EDLs were based on the average scenario of the Fate and Transport Tool, which DEQ considers the most reasonably likely scenario based on previous groundwater protectiveness demonstrations approved by DEQ, and the basis for regulatory decision-making, and a five-foot separation distance between the bottom of the UIC and seasonal high groundwater. The pollutant concentrations discharging to UICs used as input to the Fate and Transport Tool were capped at 10 times the existing EDLs for lead, benzo(a)pyrene, PCP, and DEHP. The Fate and Transport Tool simulation results indicated that concentrations of lead, benzo(a)pyrene, PCP, and DEHP could be 1000 times higher than the EDL while still being protective of groundwater. Although the modeling results indicate that acceptable proposed EDLs for lead, benzo(a)pyrene, PCP, and DEHP could be greater than 10 times the EDL, to be conservative, 10 times the EDL is suggested as the proposed EDL. The City of Redmond's proposed EDLs and separation distance recommendation for protectiveness are summarized in Tables ES-1 and ES-2.

1.0 Introduction

The City uses 1525 drywells and 169 drillholes, or UICs, to manage urban stormwater within its City boundaries. The City has applied for a UIC WPCF permit with DEQ and wants to use fate and transport modeling to proactively demonstrate groundwater protectiveness of the City's UICs through the DEQ's risk evaluation process described in Schedule D.6 of the UIC WPCF Permit Template.

This technical memorandum (TM) presents the technical methodology used to evaluate the fate and transport of representative stormwater pollutants in the unsaturated zone. GSI used the Fate and Transport Tool, modified specifically for the geologic and stormwater pollutant conditions in the City of Redmond, to determine separation distances between the bottom of the UICs and the seasonal high groundwater needed for pollutants to reach background concentrations (i.e., the MRL) and to determine proposed EDLs that are protective of groundwater.

The Fate and Transport Tool simulation results will be submitted to the Department of Environmental Quality (DEQ) by the City in support of their UIC WPCF permit application. DEQ has indicated that the Fate and Transport Tool is appropriate for demonstrating groundwater protectiveness for UICs that are in well setbacks or the two-year Time-of-Travel. In addition, DEQ has indicated that the Fate and Transport Tool is appropriate for recommending proposed EDLs as a part of the City's UIC WPCF permit application.

1.1 Objectives

The objectives of this TM are:

- Demonstrate groundwater protectiveness of UICs that potentially are in well setbacks or the two-year Time-of-Travel.
- Develop proposed EDLs for vertical separation distances of 5 feet that are protective of groundwater quality in accordance with Oregon Administrative Rules (OAR) 340-040.

1.2 UIC Conceptual Model

UICs are used to manage stormwater by infiltrating precipitation (e.g., stormwater runoff) into the ground. For many areas in Redmond, UICs are the only form of stormwater disposal available. Infiltration of stormwater into the ground contributes to aquifer recharge in urbanized areas, however in Redmond stormwater infiltration is estimated to be a minor (less than 1 percent) contributor to ground water recharge.

Two conceptual site models for stormwater infiltration are shown schematically in Figure 1. The schematic on the left depicts the actual conditions present at and beneath UICs in Redmond and the schematic on the right depicts the modeled conditions used for the fate and transport calculations. The differences between the actual conditions and the modeled conditions are described in more detail in Sections 3.1 and 3.4 of this TM. UICs in Redmond consist of two construction types: drywells and drillholes. Note that Figure 1 depicts stormwater infiltration from a drywell rather than a drillhole; however, the modeled conditions used for the fate and transport calculations are the same for drywells and drillholes. Both UIC construction types typically contain a stormwater inlet (e.g., catch basin) and the UIC. Most City-owned drywells are generally 4 feet in diameter and range in depth from about 4 feet to 22 feet. Most City-owned drillholes are generally 0.5 feet in diameter and range in current depth from about 2 feet to 134 feet. In accordance with the UIC WPCF Municipal Stormwater Template, the compliance point for EDLs is the end-of-pipe (EOP), where stormwater is discharged into the UIC.

As shown in Figure 1, stormwater discharges into the UIC, infiltrates through the unsaturated zone, and recharges groundwater. Before entering the unsaturated zone, large-size particulate matter (which pollutants may be sorbed to) falls out of suspension into the bottom of the UIC. During transport through the unsaturated zone, pollutant concentrations attenuate because of degradation, dispersion, volatilization, and retardation. Therefore, pollutant concentrations in the vadose zone beneath the UIC are lower than pollutant concentrations measured at the stormwater inlet.

1.3 Technical Memorandum Organization

This TM is organized as follows:

- **Section 1: Introduction.** Outlines the TM's objectives, and discusses the conceptual model for stormwater infiltration fate and transport calculations.
- **Section 2: Geologic and Hydrogeologic Conditions.** Describes the geology and hydrogeology near Redmond, including the unsaturated zone and the regional aquifer.
- **Section 3: Unsaturated Zone Fate and Transport Tool.** Describes the Fate and Transport Tool, including fate and transport processes, rationale for choosing pollutants, governing equations, and justification for the input parameters.
- **Section 4: Groundwater Protectiveness Demonstration for UICs within Water Well Setbacks.** Summarizes the results of the fate and transport modeling in the unsaturated zone with respect to demonstrating groundwater protectiveness for UICs within well setbacks or the two-year Time-of-Travel.
- **Section 5: Development of Proposed EDLs.** Summarizes the results of the fate and transport modeling in the unsaturated zone and proposes EDLs for lead, benzo(a)pyrene, PCP, and DEHP.

- **Section 6: Groundwater Quality Data near Redmond.** Presents available groundwater quality data from Safe Drinking Water Act (SDWA) sampling events at municipal water supply wells to further demonstrate groundwater protectiveness of UICs.
- **Section 7: Conclusions**
- References

2.0 Geologic and Hydrogeologic Conditions

This section describes the geologic and hydrogeologic conditions near Redmond. Where applicable, selection of the Fate and Transport Tool input parameters was based on site-specific geologic and hydrogeologic conditions near Redmond.

2.1 Geology

A geologic map of the Redmond vicinity is shown in Figure 2. The geology of Redmond is primarily related to volcanic activity from a north-south trending volcanic arc currently represented by the Cascade Range, fluvial sedimentation from the ancestral Deschutes River and associated drainages, and volcanic activity within the City (i.e., Forked Horn Butte), east of the city (i.e., Powell Buttes) and south of the city (i.e., Newberry volcano) (Sherrod et al., 2004; Smith, 1986).

Subsurface geology in Redmond is comprised primarily of volcanic rock with interbeds of alluvial material reaching thicknesses of several hundred feet. The thick alluvial interbeds are present because of Redmond's relatively large distance from eruptive sources (Lite and Gannett, 2002) and deposits from the ancestral Deschutes River and associated tributaries which may have flowed near or through Redmond (see Figure 8.10 of Smith, 1986, which shows the location of the ancestral Deschutes River channel as just north of Redmond, but not in Redmond). The cumulative thickness of sedimentary interbeds in the unsaturated zone beneath Redmond is shown in Figure 3.

This description of Redmond vicinity geology is divided into two sections: geology of the Deschutes Formation and geology of volcanic rocks that were erupted after the Deschutes Formation.

Miocene to Pliocene Deschutes Formation

The Deschutes Formation is a thick (i.e., over 1,400 feet where exposed at Green Ridge) sequence of over 225 lava flows and interbedded fluvial gravels and pyroclastic deposits (Conrey, 1985) that were deposited from 7.4 to 4.0 Ma (Armstrong et al., 1975; Smith, 1986; Smith et al., 1987) and erupted primarily from the ancestral Cascade range (Smith, 1986). The City of Redmond is located in the arc-adjacent alluvial plain and/or ancestral Deschutes River facies of the Deschutes Formation (Smith, 1986). The arc-adjacent alluvial plain facies contains lava flows, pyroclastic deposits, volcanoclastic sediment, debris flows, and conglomerate to sand flood deposits. The ancestral Deschutes River facies contains conglomerate to sand flood deposits, alluvial-channel deposits, pyroclastic deposits, and inter-canyon lava flows.

Basalts (Tdb) and fluvial and tuffaceous sedimentary deposits (Tds) of the Deschutes Formation outcrop at ground surface just west of the Redmond city limits, and extend beneath Redmond to the east (Sherrod et al., 2004). Based on driller's logs, individual sedimentary interbeds range from less than 20 feet thick (DESC 51647) to over 400 feet thick (DESC 5583). Cuttings logs indicate that the sedimentary interbeds are comprised of weakly indurated tuffaceous sands with fine gravel (Eco:Logic Engineering, 2006), and subrounded to rounded basalt gravels with some (<10%) felsic clasts (Lite, unpublished data). As is shown in Figure 3, thick fluvial gravel and sand lenses occur in the unsaturated zone above the water-bearing zones of the Deschutes Formation in most of the water wells.

Debris flow deposits of the Deschutes Formation (Tddf) are found at ground surface in the southwest portion of the City and comprise Forked Horn Butte. Debris flow deposits are poorly sorted and contain clasts as large as 2 meters across (Sherrod et al., 2004).

Pliocene to Pleistocene Volcanic Rocks Erupted After the Deschutes Formation

Basalt of Dry River (Tbdr)

The basalt of Dry River was formed during the Pliocene epoch, and erupted from volcanic vents near Powell Buttes to the east of Redmond. The basalt of Dry River overlies the Deschutes Formation, is about 100 feet thick in the vicinity of Redmond, and is likely about the same age as the basalt of Redmond (Sherrod et al., 2004).

According to driller logs, the basalt of Dry River is unsaturated within Redmond's city limits. Most driller logs for wells drilled through the basalt of Dry River report interbeds of cinders (i.e., flow tops/flow bottoms), sands, and gravels ranging from a few feet to several tens of feet in thickness.

Basalt of Redmond (Tbr)

The basalt of Redmond was erupted during the Pliocene epoch, approximately 3.56 million years ago (Smith, 1986). The basalt of Redmond overlies the Deschutes formation, and is likely the same age as the basalt of Dry River (Sherrod et al., 2004).

According to driller logs, the basalt of Redmond is unsaturated within Redmond's city limits. Most driller logs for wells drilled through the Basalt of Redmond report interbeds of cinders (i.e., flow tops/flow bottoms), sands, and gravels ranging from a few feet to several tens of feet in thickness.

Newberry Basalt (Qbn)

The Newberry basalt is comprised of basalt flows that erupted from the vicinity of Newberry Volcano south of Bend within the past 780,000 years (Sherrod et al., 2004), and flowed north across the Deschutes Plain through Bend and Redmond. Individual basalt flow thickness ranges from a few feet to more than 100 feet (MacLeod et al., 1981), and the total area covered by eruptions from Newbery Crater is about 3,000 square kilometers (Jensen et al., 2009). The Newberry basalt is present in the southeast portion of Redmond where it flowed over the Deschutes plateau, and locally as canyon flows where it flowed through the ancestral Deschutes River canyon. Locally, the Newberry basalt overlies the Deschutes Formation, basalt of Dry River or basalt of Redmond (Sherrod et al., 2004), and based on a natural gamma log for DESC 4656, is approximately 75 feet thick (Lite and Gannett, 2002).

According to driller logs, the Newberry basalt is unsaturated within Redmond's city limits. Most driller logs for wells drilled through the Newberry basalt report interbeds of cinders (i.e., flow tops/flow bottoms) ranging from a few feet to about 10 feet in thickness. Occurrence of sandstone and conglomerate interbeds is rarely reported in driller's logs for wells drilled through the Newberry basalt.

2.2 Hydrogeology

Unsaturated Zone

The unsaturated zone in Redmond is greater than 150 feet thick, and in many areas of the City is greater than 400 feet thick. The unsaturated zone in Redmond is comprised of the Pliocene to Pleistocene volcanic rocks erupted after the Deschutes Formation. In much of the City, the unsaturated zone also is comprised of the upper portion of the Deschutes Formation and is represented diagrammatically on Figure 1. The thickest unsaturated zones in the Deschutes Formation occur where wells were drilled on buttes, and the thinnest unsaturated zones in the Deschutes Formation occur where wells were drilled near the Deschutes River. Based on water wells where cuttings were logged by USGS or GSI, the unsaturated zone in the Deschutes Formation is about 150 to 200 feet thick in Redmond (excluding the buttes or very near the Deschutes River).

As described above, numerous interbeds and sedimentary deposits, including tephra, sands, and fluvial gravels, occur between volcanic flows. Figure 3 shows estimates of the combined thickness of interbed and sedimentary deposits above the water table based on logging of cuttings collected from water well borings and driller logs. In the City, the average combined thickness of interbeds and sedimentary deposits above the water table is 130 feet.

The average linear groundwater velocity (pore water velocity) in the unsaturated zone is directly proportional to the moisture content in the unsaturated zone. Published estimates of average linear groundwater velocity in the unsaturated zone (i.e., over a month) are based on the timing of groundwater level response to canal leakage (Gannett et al., 2001). These estimates do not adequately characterize infiltration from UICs [stormwater flow to UICs is in short duration and the volume infiltrating into UICs is significantly less than the volume of water infiltrating from canal leakage (refer to "Aquifer Description and Sources of Groundwater Recharge" section)]. Therefore, linear groundwater velocity was estimated using the hydraulic conductivity from infiltration tests conducted at Redmond's UICs.

The City of Redmond infiltration tests within different geologic units indicated that the younger volcanic deposits (basalt of Redmond and Dry River flows) have the overall highest infiltration rate. Based on results from the infiltration tests, the median linear vertical velocity in the unsaturated zone across all geologic deposits in Redmond is 0.86 feet/day. Because the highest velocities were found in the youngest volcanic deposits, the Fate and Transport Tool is conservatively using the median linear groundwater velocity from these deposits of 2.1 feet/day for the average transport scenario. For the reasonable maximum transport scenario, the Fate and Transport Tool is conservatively using the maximum of the youngest deposits (3.0 ft/day). The infiltration test methods, results, and parameters used are discussed in more detail in Section 3.5.8 of this TM.

Aquifer Description and Sources of Groundwater Recharge

Saturated basalts and sediments of the Deschutes Formation are highly permeable, and serve as the principle aquifer in Redmond (Gannett et al., 2001). The water table in the Redmond area is generally at least 150 feet below land surface. The water table in the Redmond region is generally flat (i.e., very low gradient) between an elevation of about 2,690 feet and 2,720 feet and slopes towards the northwest.

As shown in Figure 4, sources of recharge to groundwater in Redmond include UICs, infiltration of precipitation, canal leakage, stream leakage, infiltration from irrigation (on-farm losses), and groundwater inflow. The total volume of groundwater recharge per year was estimated for the various sources of recharge and is shown below in Table 1. Estimates of recharge from UICs are based on analysis of runoff to UICs in the City conducted by Brown and Caldwell (2011) (see Appendix A). The analysis conservatively assumed full build out of the City (i.e., to the urban growth boundary) and includes runoff from City as well as private UICs. The primary source of groundwater recharge in Redmond city limits is from groundwater inflow (87.4 percent). The second largest source of groundwater recharge is from leakage from canals (11.2 percent). Groundwater recharge from all other sources combined (UICs, infiltration of precipitation, leakage from streams and on-farm losses) comprises 1.4 percent of total groundwater recharge in Redmond.

Table 1. Groundwater Recharge Sources in the City of Redmond.
City of Redmond, Oregon

	Recharge (ac-ft/yr)		Percent of Recharge in Redmond City Limits
UICs (private and public)	4,045	1	0.9%
Infiltration of Precipitation	435	2	0.1%
Canal Leakage	48,892	3	11.2%
Stream Leakage	0		0.0%
On Farm Losses	1,949	4	0.4%
Groundwater Inflow	382,081	5	87.4%
Total	*437,402*		*100.0%*

Notes:
[1] From Brown and Caldwell, 2011. Annual Stormwater Runoff Recharge to UICs. Value represents UIC contributions in the City Urban Growth Boundary at full build out. April 20, 2011. See Appendix A.
[2] From USGS WRIR 00-4162, Figure 6. According to the Deep Percolation Model (DPM) developed by Bauer and Vaccaro (1987), the city of Redmond received about 3.5 inches of recharge per year from precipitation, and the city of Redmond received about 0.5 inches of recharge per year from precipitation during the 1993 - 1995 water years.
[3] From USGS WRIR 00-4162, Figure 9. Canal lengths through each City were determined by digitizing major canals.
[4] This number includes on farm losses digitized from Figure 9 of WRIR 00-1462.
[5] Groundwater influx into the Redmond city limits, estimated using the steady state USGS Deschutes Basin Model.

3.0 Unsaturated Zone Fate and Transport Tool

This section describes the fate and transport processes, rationale for pollutant selection, equations, and input parameters used in the Fate and Transport Tool.

3.1 Conceptual Site Model of UIC Stormwater Infiltration and Pollutant Fate and Transport in Unsaturated Soils

The stormwater EDLs in the UIC WPCF Municipal Stormwater Template (June 2011) are based on Oregon groundwater protection standards (measured in groundwater), federal drinking water standards (measured in drinking water), and other health-based limits. Compliance with

EDLs is based on pollutant concentrations detected at the point stormwater enters the top of the UIC (i.e., end-of-pipe [EOP]) and for most pollutants, with the exception of lead, does not account for the treatment/removal (i.e., attenuation) of pollutants by subsurface soils between the point of discharge and seasonal high groundwater. The Fate and Transport Tool approach was developed to estimate pollutant attenuation during transport through the unsaturated zone (i.e., soils and rock above the water table and below the UIC) before reaching groundwater.

Stormwater discharge to a UIC infiltrates into the unsaturated zone and is transported downward by matric forces that hold the water close to mineral grain surfaces. Pollutants are attenuated during transport through the unsaturated zone by:

- **Volatilization.** Volatilization is pollutant attenuation by transfer from the dissolved phase to the vapor phase. Because soil pores are only partially filled with water, chemicals with a high vapor pressure volatilize into the vapor phase. The propensity of a pollutant to volatilize is described by the Henry's constant. Volatilization within the UICs likely occurs as stormwater falls into the structure and within the UIC. Although likely, this process was conservatively not included in the model. In addition, because volatilization is not significant at depths below most UIC bottoms (i.e., 25 feet), volatilization is not included for any of the pollutants included in the Fate and Transport Tool (EPA, 2001).

- **Adsorption.** Adsorption is pollutant attenuation by partitioning of substances in the liquid phase onto the surface of a solid substrate. Physical adsorption is caused mainly by van der Waals forces and electrostatic forces between the pollutant molecule and the ions of the soil molecule's surface. Adsorption is a function of f_{oc} (fraction organic carbon) in soil, K_{oc} (organic carbon partitioning coefficient), and mineralogy of the fracture faces. The model ignores adsorption to fracture faces and only considers sorption to organic carbon in soil that fills fractures.

- **Degradation.** Degradation is pollutant attenuation by biotic and abiotic processes. Abiotic degradation includes hydrolysis, oxidation-reduction, and photolysis. Biotic degradation involves microorganisms metabolizing pollutants through biochemical reactions. Degradation is described by a first-order decay constant.

- **Dispersion.** Dispersion describes pollutant attenuation that results from pore water mixing. Dispersion is described by the dispersion coefficient, which is a function of pore water velocity and distance traveled by the pollutant.

Figure 1 shows schematics of the actual stormwater infiltration conditions present at and beneath UICs in Redmond (actual conditions) and the modeled stormwater infiltration conditions used for the fate and transport calculations (modeled conditions). Table 2 highlights the differences between the actual conditions and the modeled conditions and the implications of these differences with respect to pollutant attenuation. Differences between modeled and actual conditions exist because simplifying assumptions were necessary in order to model pollutant attenuation in the subsurface. The simplifying assumptions are conservative (i.e., simulated attenuation is less than actual attenuation) as shown in Table 2. The key assumptions used for the fate and transport calculations (i.e., modeled conditions) are discussed further in Section 3.4 of this TM.

Table 2. Actual and Modeled Conditions of Stormwater Infiltration into UICs.
City of Redmond, Oregon

Actual Conditions	Modeled Conditions	Implications
Volatilization occurs within the UIC	Volatilization is not accounted for in the model	Model conservatively simulates less attenuation
Stormwater discharge occurs across the perforated zone of a drywell and across the open interval of a drillhole	Stormwater only discharges from the bottom of the UIC	Model conservatively simulates less transport and attenuation
The groundwater table fluctuates seasonally	The groundwater table is constantly at its seasonal high	Model conservatively simulates less transport and attenuation
Stormwater flow is highly variable and short in duration	Stormwater flow is uniform and constant	Model simulates maximum infiltration
Stormwater flows horizontally away from the UIC and then vertically downward – attenuation is three-dimensional	Stormwater flows vertically down from the UIC and horizontal flow does not occur – attenuation is one-dimensional	Model conservatively simulates less transport and attenuation
Numerous interbeds and sedimentary deposits occur between volcanic flows	UICs are completed in the most permeable geologic unit and there are no interbeds	Model conservatively simulates less attenuation

3.2 Pollutant Selection

Stormwater pollutants for evaluation were chosen based on chemical toxicity, frequency of detection, and mobility and persistence in the environment. The following process was used to rank chemicals according to toxicity, mobility, persistence, and frequency of detection:

1. All chemicals were assigned a toxicity category based on maximum contaminant levels (MCL), where available. Where MCLs were not available, the EPA Preliminary Remediation Goal (PRG) was used. Lower values correspond to higher toxicity. Chemical toxicity was ranked as:

   - High (MCL<10 μg/L)
   - Medium (MCL 10 to 100 μg/L)
   - Low (MCL >100 μg/L)

2. All chemicals were assigned a mobility category based on their EPA groundwater mobility ranking value (for liquid, non-karst). Values were obtained from EPA's Superfund Chemical Data Matrix Methodology, Appendix A (EPA, 2004). In the absence of an EPA mobility ranking value, mobility categories were assumed on the basis of the chemicals' solubility and partition coefficient using professional judgment. Chemical mobility was ranked as:

   - High (EPA mobility ranking of 1.0)
   - Medium (EPA mobility ranking of 0.01)
   - Low (EPA mobility ranking of <0.01)

Solubility also was considered when assigning chemicals to mobility categories. Use of EPA mobility ranking and solubility resulted in chemicals being assigned to the same mobility category.

3. All chemicals were evaluated on the basis of their persistence in the environment. Persistence represents the residence time a chemical remains in the system. This is best evaluated through degradation rates because speciation and availability can be reversible. Persistence was ranked on the basis of the chemical half-lives. Chemical half-lives were taken from Canadian Environmental Modeling Center Report No. 200104, as follows:

    - Low (0 to 49 days)
    - Medium (50 to 499 days)
    - High (500 days and greater)
    - Infinite (does not degrade)

4. All chemicals were evaluated with respect to frequency of detection, as determined by the frequency of detection during the Redmond 2007 - 2010 stormwater sampling events and the Oregon ACWA stormwater data report (Kennedy/Jenks, 2009 and Kennedy/Jenks, 2011). Frequency of detection was ranked as:

    - High (75 to 100 percent)
    - Medium (21 to 74 percent)
    - Low (<20 percent)

Table 3 (attached at the end of this TM) summarizes the information used to assign these categories for each chemical and their resulting ranking by characteristic.

As noted previously, chemicals were selected by the ranking criteria described above. However, chemicals also were selected based on five broad chemical categories: VOCs, SVOCs, metals, PAHs, and pesticides/herbicides. For each of the five chemical categories, the following characteristics were considered in the following order:

1. Frequency of detection (chemicals in the "low" category from both the Redmond 2007 - 2010 stormwater sampling events and the ACWA stormwater data report were not considered further, except in the case of pesticides/herbicides, which all were in the "low" category).
2. Mobility (chemicals in the "low" category were not considered further, with the exception of PAHs and DEHP, which have low mobility).
3. Persistence
4. Toxicity

In the event that multiple chemicals had similar scores, chemicals from the common pollutant list were selected instead of chemicals from the screening pollutant list.

Based on the process described above, the following representative chemicals were selected for analysis in the Fate and Transport Tool:

1. VOCs: Toluene
2. SVOCs: Pentachlorophenol and di(2-ethylhexyl)phthalate
3. PAHs: Benzo(a)pyrene and naphthalene
4. Metals: Copper and lead
5. Pesticides/herbicides: 2,4-D

Selection of representative chemicals for the five chemical categories was straightforward, with the exception of the PAHs. Many PAHs have a high frequency of detection and toxicity, but low mobility. Benzo(a)pyrene was selected because it is the only PAH on the common pollutant list. Naphthalene also was selected because it represents a low molecular weight PAH which is more mobile and, therefore, would be transported faster through the unsaturated zone.

3.3 Data Collection

City of Redmond staff collected stormwater samples at 11 sites during 2007 through 2010. An analysis of the Central Oregon stormwater data (Kennedy/Jenks 2011) indicated that Central Oregon stormwater is similar to stormwater in the rest of Oregon based on a comparison of screening level exceedances in Bend and Redmond. Additionally, fewer analytes exceeded screening levels in Central Oregon compared to elsewhere in Oregon. Table 3 shows the frequency of detection and exceedance for pollutants in Redmond stormwater samples. Of the 21 analytes tested for, Redmond's stormwater had no detections for 11 of the analytes. In addition, 3 of the 9 common pollutants in the UIC WPCF Permit Template (benzo(a)pyrene, di(2-ethylhexyl)phthalate, pentachlorophenol) have never been detected in Redmond stormwater. Plots of pollutant concentrations in Redmond stormwater for evaluated pollutants [benzo(a)pyrene, di(2-ethylhexyl)phthalate, pentachlorophenol, toluene, naphthalene, copper, and lead (data are not available for 2,4-D)] are presented in Appendix B.

3.4 Governing Equation

A one-dimensional pollutant fate and transport equation was used to estimate the magnitude of pollutant attenuation during transport through the unsaturated zone. This constant source ADE incorporates sorption, degradation (biotic and abiotic), and dispersion to estimate pollutant concentration at the water table (e.g., Watts, 1998). This equation is provided below:

$$\frac{C(y,t)}{C_0}=\frac{1}{2}\left[\left(e^{A_1}\right)erfc(A_2)+\left(e^{B_1}\right)erfc(B_2)\right] \qquad (1)$$

For B[a]P:

where:

$$A_1=\left(\frac{y}{2D'}\right)\left(v'-\sqrt{(v')^2+4D'k'}\right)$$

= (152 m / 2(5.5E-6 m²/d)) (7.22E-5 − √((7.22E-5)² + 4(5.5E-6)(1.43E-4)))

$$A_2=\frac{y-t\sqrt{(v')^2+4D'k'}}{2\sqrt{D't}}$$

$$B_1 = \left(\frac{y}{2D'}\right)\left(v' + \sqrt{(v')^2 + 4D'k'}\right)$$

$$B_2 = \frac{y + t\sqrt{(v')^2 + 4D'k'}}{2\sqrt{D't}}$$

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

$$D' = \frac{D}{R}$$

$$k' = \frac{k}{R}$$

and:

y is distance in the vertical direction (L),
v is average linear velocity (L/T),
D is the dispersion coefficient (L^2/T),
R is the retardation factor (dimensionless),
k is the first-order degradation constant (T^{-1}),
t is average infiltration time (T),
C_0 is initial pollutant concentration (M/L^3),
$C(y, t)$ is pollutant concentration at depth y and time t (M/L^3), and
erfc is complementary error function used in partial differential equations

Equation (1) is an exact solution to the one-dimensional ADE. The exact solution can be used for both short (i.e., less than 3.5 meters) and long transport distances (greater than 3.5 meters; Neville and Vlassopoulos, 2008). An approximate solution to the 1-dimensional ADE has also been developed, and can only be used for long transport distances. Because the separation distances that are being evaluated are potentially both short and long, this TM uses the exact solution to the ADE for the Fate and Transport Tool.

The key assumptions in applying this equation include:

- Basalt fractures are filled with sedimentary material. The sedimentary material was introduced into the fractures by filtering of suspended solids in stormwater and retards pollutants in the subsurface.

  Although there may be anomalous localized occurrences of rapid infiltration associated with features within the compound volcanic deposit in Central Oregon, these instances are very localized, laterally discontinuous, and horizontal in nature. Water infiltrating into these local structures will ultimately experience similar vertical infiltration through the basalt fractures to move downwards toward the water table. Because this analysis is representing the average conditions of the subsurface system beneath the City, coupled with eventual downward movement of the water through basalt fractures under these anomalous conditions, we believe this approach accounts for these local small scale anomalies.

- Transport is one-dimensional vertically downward from the bottom of the UIC to the water table. In reality, water typically exfiltrates from holes in the side of the UIC, as well as from the bottom.

- The stormwater discharge rate into the UIC is constant and maintains a constant head within the UIC to drive the water into the unsaturated soil. In reality, stormwater flows are highly variable, short duration, and result in varying water levels within the UIC dependent on the infiltration capacity of the formation.
- Pollutant concentrations in water discharging into the UIC are uniform and constant throughout the period of infiltration. In reality, concentrations vary seasonally and throughout storm events.
- The pollutant undergoes equilibrium sorption (instantaneous and reversible) following a linear sorption isotherm.
- The pollutant is assumed to undergo a first-order transformation reaction involving biotic degradation.
- The pollutant does not undergo transformation reactions in the sorbed phase (i.e., no abiotic or biotic degradation).
- There is no portioning of the pollutant to the gas phase in the unsaturated zone.
- The soil is initially devoid of the pollutant.

The above assumptions provide a conservative evaluation of pollutant fate and transport for the following reasons:

- Modern drywells are constructed with a solid concrete bottom so stormwater is discharged horizontally through the sides of the UIC (depending on the depth of the UIC, up to 100 or more feet above the bottom of the UIC) and then migrates vertically downward. Thus, the assumption that stormwater flows vertically downward from the base of the UIC underestimates the travel distance of stormwater in the unsaturated zone.
- Stormwater flow from the UIC is assumed to be constant with a uniform flow through the unsaturated zone, while in reality stormwater flows are highly variable and short in duration resulting in varying water levels within the UIC depending on the infiltration capacity of the formation. Thus, the UIC periodically will fill with water and then drain. This will cause variable flow from the UIC. It is not feasible to simulate complex cycles of filling and drainage for each UIC. Thus, the simplified approach is implemented in which the analytical solution is used to predict concentrations at a time corresponding to the period over which the UIC likely contains water. This approach is conservative because it predicts the maximum infiltration that would be expected at the water table sustained for the period during which the UIC contains water.
- Pollutant concentrations are assumed to be constant, while in reality they are variable throughout storm events. This likely over-predicts the concentration throughout the duration of a storm event. In addition, the Fate and Transport Tool does not take into account pollutant attenuation that occurs while in the UIC (i.e. through volatilization, or adsorption to sediment or organic matter in the UIC) before entering the surrounding unsaturated zone.

The following sections discuss calculation of the retardation factor, dispersion coefficient, and average linear groundwater velocity.

Retardation Factor

The retardation factor, *R*, is estimated by the following equation (Freeze and Cherry, 1979):

$$R = 1 + \frac{(\rho_b)(K_{oc})(f_{oc})}{\eta} \tag{2}$$

where:

ρ_b is soil bulk density (M/L^3),
K_{oc} is the organic carbon partitioning coefficient (L^3/M),
f_{oc} is fraction organic carbon (dimensionless), and
η is total porosity (dimensionless).

Dispersion Coefficient

Dispersion is the spreading of a pollutant plume caused by pore water mixing and differential advection. The dispersion coefficient, *D*, is defined as:

$$D = \alpha_L v \tag{3}$$

where:

v is average linear groundwater velocity (L/T), and
α_L is longitudinal dispersivity (L).

The dispersivity (and therefore the dispersion coefficient) is a scale-dependent parameter. According to a review of tracer tests conducted under saturated conditions, dispersivity is estimated as (Gelhar et al., 1992):

$$\alpha_L \leq \frac{L}{10} \tag{4}$$

where:

L is the length scale of transport (i.e., separation distance) (L).

However, according to a review of tracer tests conducted in the unsaturated zone, dispersivity can be significantly less than would be estimated by Equation (4) (Gehlar et al., 1985):

$$\frac{L}{10} \leq \alpha_L \leq \frac{L}{100} \tag{5}$$

Because the unsaturated zone under the UICs is assumed to be at near-saturated conditions, this TM assumes that $\alpha_L = \frac{L}{20}$, which is less than saturated dispersivity, but is on the high end of the reported range in unsaturated dispersivity.

Vertical Groundwater Velocity

Vertical groundwater velocity in the unsaturated zone is calculated by Darcy's Law (Stephens, 1996):

$$q_y = -K_u\left(\frac{\partial \psi}{\partial y} + \frac{\partial y}{\partial y}\right) \tag{6}$$

where:

q_y is specific discharge (L/T),
K_u is unsaturated hydraulic conductivity (L/T),
$\left(\frac{\partial \psi}{\partial y}\right)$ is the pressure gradient (L/L), and
$\left(\frac{\partial y}{\partial y}\right)$ is the head gradient (L/L).

In the unsaturated zone, $\left(\frac{\partial y}{\partial y}\right) = 1$. When the unsaturated zone is stratified and pressure head is averaged over many layers, $\left(\frac{\partial \psi}{\partial y}\right) = 0$. Under these conditions, equation (6) reduces to (Stephens, 1996):

$$q_y = -K_u \tag{7}$$

According to Stephens (1996), the velocity in Equation (7) (called the Darcy flux) should be used to calculate recharge in the unsaturated zone.

3.5 Input Parameters

The Fate and Transport Tool is based on available local geology and hydrogeology information. Physical and chemical properties of the unsaturated zone and pollutants are obtained from selected references and available regulatory guidance, as noted below. Parameter values were chosen to characterize the average and reasonable maximum scenarios. The average scenario parameter values represent the central tendency or expected mean of pollutant transport and the reasonable maximum scenario parameter values represent the plausible upper bound or worst-case scenario for pollutant transport.

The magnitude of pollutant attenuation during transport through the unsaturated zone is controlled by physical and chemical properties of the unsaturated zone soil and the pollutant, including:

1. **Pore Water Velocity, v.** Pore water velocity is the rate that water moves downward through the unsaturated zone, and is directly proportional to moisture content.
2. **Porosity, η.** Porosity is the percent of pore space in soil filling fractures in the basalt bedrock.
3. **Soil Moisture Content, Θ.** Soil moisture content is the percent of water in soil filling fractures, and is equal to or less than porosity.
4. **Soil Bulk Density, ρ_b.** Soil bulk density is the density of soil filling fractures, including soil particles and pore space.

5. **Fraction Organic Carbon, f_{oc}.** Fraction organic carbon is a dimensionless measure of the quantity of organic carbon in soil (i.e., g_{carbon} / g_{soil}) filling fractures, and is used to estimate the capacity of a soil to adsorb pollutants.
6. **Organic Carbon Partitioning Coefficient, K_{oc}.** The organic carbon partitioning coefficient is defined for the pollutant, and specifies the degree to which it will partition between the organic carbon and water phases. In the case of PCP, this parameter is also pH-specific.
7. **Distribution Coefficient, K_d.** The distribution of metals between solid (sorbed to solids or organic materials) and dissolved phases.
8. **Hydraulic Conductivity, K.** Hydraulic conductivity is a proportionality constant that, under unsaturated conditions, is equivalent to groundwater velocity
9. **Degradation Rate Constant, k (Biodegradation Rate).** Microbial process by which organic compounds are broken down into other substances. Degradation rate is a chemical-specific, first-order rate constant, and depends on whether the unsaturated zone is aerobic or anaerobic. Metals (copper and lead) are elements and therefore do not undergo degradation.
10. **Infiltration Time.** Length of time during the year that rainfall occurs and causes runoff into a UIC.

3.5.1 Pore Water Velocity

Of the ten parameters listed above, the most important in fate and transport analysis is average linear groundwater velocity (pore water velocity) in the unsaturated zone. Because estimates of unsaturated zone groundwater velocity are not available for the unsaturated zone throughout Redmond under conditions similar to stormwater infiltration from UICs, unsaturated zone groundwater velocity was estimated using the hydraulic conductivity from pump-in tests conducted on a subset of Redmond's UICs. Pump-in tests are described in detail in Section 3.5.8.

3.5.2 Total Porosity

Total porosity (η) is the percent of pore space in the material filling fractures in basalt. Porosities are correlated with material type. Typical fracture widths in basalt (based on estimates of fracture widths in Columbia River Basalt) are 0.143 mm (Lindberg, 1989). The infilling material is assumed to be fine sand-sized material (Fetter, pg. 84, 1994). Therefore, the analysis conservatively used a value of 0.375, a typical porosity of sand (Freeze and Cherry, pg. 37, 1979).

3.5.3 Soil Moisture Content

Soil moisture content is the percent of water in soil filling fractures, and is equal to or less than porosity.

3.5.4 Soil Bulk Density

Bulk density (ρ_b) is the density of the soil filling fractures, including material particles and pore space. According to Freeze and Cherry (1979), bulk density is calculated from porosity by the following formula:

$$\rho_b = 2.65(1-\eta) \tag{8}$$

Bulk density was calculated using the porosity of sand from Freeze and Cherry (1979) discussed above. According to Equation (8), the bulk density is 1.66 g/cm^3.

3.5.5 Fraction Organic Carbon

In the subsurface, pollutants are retarded by sorption onto basalt fracture faces and organic carbon in the soil that fills fractures (Freeze and Cherry, 1979). The City of Redmond model makes the simplifying assumption that sorption occurs only on organic carbon. This assumption is conservative because it results in less pollutant sorption, which allows pollutants to be transported further and faster in the model than they would under actual conditions. Incorporating the other sorption mechanisms would require bench-scale studies of pollutant sorption on basalt fractures.

Pollutant sorption on organic carbon is related to the fraction organic carbon (f_{oc}), a dimensionless measure of organic carbon content in a material (i.e., g_{carbon} / g_{soil}). Pollutants sorb to organic carbon; therefore, pollutant retardation is directly proportional to fraction organic carbon. Organic carbon in the subsurface beneath UICs is derived from two sources: organic material that is incorporated into the sedimentary matrix at the time of deposition and particulate matter (e.g., degraded leaves, pine needles, pollen, etc.) that is filtered out of stormwater and accumulates in fractures adjacent to the UIC as stormwater discharges from the UIC:

- Organic carbon incorporated into sediments at the time of deposition is encountered in alluvial materials deposited by the ancestral Deschutes River and associated tributaries, and in the interbeds that represent ancestral soil horizons. The average combined thickness of interbeds and sedimentary deposits in the unsaturated zone is 130 feet. For example, carbonized wood, twigs, and branches have been encountered in pumice layers (lower zone of the Bend Pumice) in central Oregon (Hill, 1984), and carbonized rootlets are encountered in paleo soils (Chitwood et al., 1977).

- Samples collected by the City of Redmond indicate that stormwater in central Oregon contains total organic carbon (TOC) at levels ranging from 1.54 mg/L to 11.5 mg/L (number of samples (N)=11 samples) collected in the City's most recent sampling event (September 2010) at 11 UIC sites. This dataset has a mean TOC concentration of 5.42 mg/L; a median of 4.21 mg/L; and a geometric mean of 4.39 mg/L. The organic carbon will be filtered by the fracture network beneath the UIC, and will accumulate around the UIC.

As discussed previously, the City of Redmond model conservatively does not include sedimentary interbeds in the pollutant attenuation calculations, so the organic carbon content of subsurface material is based on filtering of organic carbon in stormwater by fractured rock.

TOC loading in rock beneath city UICs was estimated from literature references, field studies of filtering in fractured bedrock, and data collected in the field. According to a field study conducted to evaluate filtering of coliform bacteria from septic systems in fractured bedrock, on average 79.5 percent of the coliform bacteria are retained within 15 feet of the source (Allen and Morrison, 1973). Most coliform bacteria are larger than 0.5 microns (Donahue, 2010), which makes them a good proxy for total organic carbon in stormwater (which is mostly larger than 0.45 microns). As such, the Redmond carbon loading calculations assumed that 79.5 percent of the influent TOC would accumulate within 15 feet of the UIC, based on observed coliform filtering. The remaining 21.5 percent of influent TOC was conservatively not included in the model. The influent stormwater

TOC concentration used in the tool is79.5 percent of the geometric mean (4.39 mg/L) calculated from 11 stormwater samples collected at 11 sites in Redmond.

An estimate of f_{oc} based on the loading of TOC was derived by calculating the grams of organic carbon added to unsaturated materials surrounding the UIC during a 10-year period. A 10-year accumulation period was selected to 1) be consistent withother jurisdiction's accepted protectiveness demonstration study, which selected 10 years based on the age of their newer UICs, and 2) because literature evaluating the longevity of organic material in bioretention cells indicates that it lasts about 20 years before it begins to degrade (Weiss et al., 2008). The following equations were used in the analysis:

$$I = (A)(p)(1-e) \tag{9}$$

$$CL = (I)(0.795)(C)(t)\left(\frac{1\text{ liter}}{1{,}000\text{ cm}^3}\right)\left(\frac{1\text{ gram}}{1{,}000\text{ milligrams}}\right) \tag{10}$$

$$\rho_{oc} = \frac{CL}{SV} \tag{11}$$

$$f_{oc} = \frac{\rho_{oc}}{\rho_b + \rho_{oc}} \tag{12}$$

where:

I = Average annual stormwater infiltration volume estimated using the average impervious area of a UIC catchment (A), precipitation (p), and losses to evaporation (e) [$I=(A)(p)(1-e)$] (cubic centimeters per year)

A = Area of a typical UIC catchment (square feet)

p = Precipitation (feet per year)

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). The geometric mean TOC concentration in stormwater was used for the average scenario, and half of the geometric mean TOC concentration was used for the reasonable maximum scenario. These concentrations were each reduced by 79.5 percent based on filtering studies in fractured bedrock (Allen and Morrison, 1973).

t = Time of carbon loading (years)

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

SV = Material volume (i.e., the volume of fracture openings in the subsurface) into which the organic carbon would accumulate because of filtration and adsorption. The volume of fractures was calculated based on a fracture aperture width of 0.143 mm [based on fracture aperture measurements in the Columbia River Basalt Group by

Lindberg (1989)] and a fracture spacing of 19 fractures per meter [based on fracture spacing in the Columbia River Basalt Group by PNNL (2002)]. It was assumed that organic carbon accumulates in a box beneath the UIC that is 15 feet on a side and 15 feet deep.

f_{oc} = Fraction organic carbon (dimensionless)

ρ_b = Bulk density (grams per cubic centimeter). The bulk density of silt was used based on the 0.143 mm aperture width in Lindberg (1989).

Calculations of f_{oc}, based on the filtering of TOC as suspended solids for the average and reasonable maximum scenarios, are shown in Table 4. First, the volume of stormwater that infiltrates into a UIC during a typical year was calculated by Equation (9). Next, Equation (10) was used to calculate the grams of carbon added to the unsaturated zone surrounding the UIC during a 10-year period. Equation (11) was used to calculate the mass of organic carbon per unit volume of material surrounding the UIC (ρ_{oc}), and Equation (12) was used to convert ρ_{oc} to f_{oc}.

Table 4. Estimated f_{oc} in Soils beneath City of Redmond's UICs.
City of Redmond, Oregon

	I Calculation (Eq. 9)				*CL* Calculation (Eq. 10)			ρ_{oc} Calculation (Eq. 11)						f_{oc} calculation (Eq. 12)	
	A (ft^2)	*p* (ft/yr)	*e* (-)	*I* (cm^3/yr)	*C* TOC (mg/L)	*t* (years)	*CL* (g)	Length and Width of Fracture (cm)	Depth of Filtering Aquifer (cm)	Fracture Spacing (fractures/meter)	Fractures in filtering Box	Total *SV* (aperture = 0.143 mm) (cm^3)	ρ_{oc} (g TOC per cm3/soil)	Bulk Density (g/cm3)	f_{oc}
Average Scenario	12,500	0.68	0.26	1.8×10^8	4.39	10	6,173	457	457	19	173	519,248	0.0119	1.66	0.0071
Reasonable Maximum Scenario	12,500	0.68	0.26	1.8×10^8	2.20	10	3,087	457	457	19	173	519,248	0.0060	1.66	0.0036

Notes:
A =Area of a typical UIC catchment (square feet)
p= Precipitation (feet per year)
e = Evaporative loss fraction (dimensionless)
I = Average annual stormwater infiltration volume
C = TOC geometric mean concentration in stormwater (milligrams per liter). This value is then multiplied by 79.5%.
t = Time of carbon loading (years)
CL = Organic carbon loaded into the unsaturated zone beneath a UIC during a 10-year period (grams)
UIC = underground injection control device
SV = Material volume into which the organic carbon would accumulate because of filtration and adsorption. It was assumed that organic carbon accumulates in a box beneath the UIC that is 15 feet on a side and 15 feet deep. (cubic centimeters)
ρ_b = Bulk density (grams per cubic centimeter)
f_{oc} = Fraction organic carbon (dimensionless)
ρ_{oc} = Organic carbon weight per unit unsaturated zone material volume (grams per cubic centimeter)
ft = feet
yr = year
(-) = dimensionless
mg = milligrams
L = liter
g = gram
cm = centimeter
TOC = total organic carbon

3.5.6 Organic Carbon Partitioning Coefficient

The organic carbon partitioning coefficient (K_{oc}) is pollutant specific, and governs the degree to which the pollutant will partition between the organic carbon and water phases. Higher K_{oc} values indicate that the pollutant has a higher tendency to partition in the organic carbon phase, and lower K_{oc} values indicate that the pollutant will have a higher tendency to partition in the water phase.

K_{oc} was assigned differently for PCP than for other pollutants, according to the following criteria:

- **PCP.** The K_{oc} for PCP is pH dependent. Soil and groundwater pH are in equilibrium; therefore, soil pH can be estimated from groundwater pH. The City of Redmond measured pH at 3 municipal wells (wells 4, 5, and 6), which ranged from 7.93 to 8.17. The average groundwater pH was 8.01, which corresponds with a K_{oc} value of 410 L/Kg. This was used for the average and reasonable maximum scenarios. Low ~1000 L/Kg

- **All Organic Pollutants except PCP.** For the average scenario, K_{oc} was estimated from empirical regression equations relating K_{oc} to the octanol water partitioning coefficient (K_{ow}) and/or pollutant solubility. For the reasonable maximum scenario, K_{oc} was assumed to be either the lowest-reported literature value or the K_{oc} calculated by empirical equations, which ever was lower (i.e., more conservative).

K_{oc} for each pollutant is listed in Table 5.

Table 5. K_{oc} for Stormwater Pollutants.
City of Redmond, Oregon

Pollutant	Average Scenario (L/Kg)	Reasonable Maximum Scenario (L/Kg)
Naphthalene	1,300 [1]	830 [3]
PCP	410 [4]	410 [4]
Bis-(2-ethylhexyl) phthalate	12,200 [1]	12,200 [2]
2,4-D	201 [5]	20 [6]
Toluene	162 [7]	37 [8]
Benzo(a)pyrene	282,185 [1]	282,185 [2]

Notes:
[1] From Fetter (1994), Table 11.3, pages 467 – 469. For the average scenario, K_{oc} was calculated from two equations in Roy and Griffin (1985). The first equation is an empirical-based equation relating K_{oc} to K_{ow}, and the second equation is an empirical-based equation relating K_{oc} to solubility. K_{oc} results from both equations were averaged together to determine K_{oc} for each constituent. The Roy and Griffin (1985) equation was used because it resulted in a lower (i.e., more conservative) K_{oc} than the regression equations in EPA (1996) (Equations 70 and 71, pages 140-141).
[2] For reasonable maximum scenarios, K_{oc} was chosen based on the lowest (i.e., most conservative) literature values. However, K_{oc} for this compound was calculated using the empirical equations in Roy and Griffin (1985) because they resulted in lower K_{oc}s (i.e., more conservative) than the lowest-reported literature value.
[3] The lowest K_{oc} reported for naphthalene in the EPA (1996) review of 20 naphthalene K_{oc}s from field testing. The range of K_{oc} was 830 L/Kg to 1,950 L/Kg
[4] The K_{oc} for pentachlorophenol is pH-dependent. Soil and groundwater pH are in equilibrium; therefore, soil pH can be estimated from groundwater pH. The City of Redmond measured pH at 3 municipal wells (wells 4, 5, and 6), which ranged from 7.93 to 8.17. The average groundwater pH was 8.01, which corresponds with a K_{oc} value of 410. This value was used for both the average and reasonable maximum Scenarios.
[5] Calculated from equation (71) in EPA (1996), which relates Koc to Kow for certain chlorinated pesticides. The Kow was taken from EPA (2010a).
[6] The lowest K_{oc} for 2,4-D acid in EPA (2010a), based on a range of 20.0 to 109.1 L/Kg
[7] Calculated from Equation (71) on page 141 of EPA (1996), which is a regression equation relating K_{oc} to K_{ow} for VOCs, chlorobenzenes, and certain chlorinated pesticides. The log K_{ow} for toluene was taken from EPA (2010b). Equation (70) of EPA (1996) was used because it resulted in a lower K_{oc} than the Roy and Griffin (1985) equations.
[8] The lowest K_{oc} reported for toluene in EPA (2010b). The range of K_{oc} was 37 – 178 L/Kg.

3.5.7 Distribution Coefficient

The distribution coefficient, K_d, was estimated from the following equation (e.g., Watts, 1998):

$$K_d = f_{oc} K_{oc} \quad (13)$$

For metals, K_d was estimated from equations in Bricker (1998). The most important solid phases for sorption in environmental porous media are clays, organic matter, and iron/manganese oxyhydroxides (Langmuir et al., 2004). The distribution of a trace metal between dissolved and sorbed phases is described by the following equation:

$$K_d = \frac{C_s}{C_w} \quad (14)$$

where:

C_s is the concentration of the metal adsorbed on the solid phase (M/L^3), and
C_w is the dissolved concentration (M/L^3).

The value of K_d for metals can depend on a number of environmental factors, including the nature and abundance of the sorbing solid phases, dissolved metal concentration, pH, redox conditions, and water chemistry. Measured K_d values for a given metal range over several orders of magnitude depending on the environmental conditions (Allison and Allison, 2005). Therefore, site-specific K_d values are preferred over literature-reported K_ds. K_d values can be determined empirically for a particular situation from Equation (14) (Bricker, 1998).

Site-specific K_ds for lead and copper in the City of Redmond were estimated based stormwater samples collected by the City of Bend because dissolve and total metals data from the same sampling event were not available from the Redmond stormwater dataset. To estimate site-specific K_ds, the City of Bend collected 10 stormwater samples at eight UICs during spring 2011 stormwater sampling events. If the concentrations of total and dissolved metals were below detection limits or the sample size was insufficient for measurement, the samples could not be used for the K_d analysis. As such, only 4 of the 10 stormwater samples were used for estimating site-specific K_ds for metals. An empirical approach was used to derive site-specific K_ds for lead and copper. The partitioning coefficients were estimated from total and dissolved metals concentrations and TSS data for four stormwater samples collected from four different locations. The stormwater chemistry data are summarized in Table 6.

Sorbed concentrations were calculated by normalizing the particulate metals concentrations to the concentration of TSS. For each sample, an apparent K_d value was calculated for each metal from the following equation:

$$K_d = \frac{([Me]_t - [Me]_d)}{[Me]_d \times TSS} \times 10^6 \quad (15)$$

where:

$[Me]_t$ is total metals concentration (M/L^3), and
$[Me]_d$ is dissolved metal concentration (M/L^3)

Table 6. Copper and Lead Stormwater Quality Data.
City of Redmond, Oregon

Parameter	Mean	Minimum	Maximum	Median
Total Copper (μg/L)	17	13	21	16
Dissolved Copper (μg/L)	2.75	2	4	2.5
Total Lead (μg/L)	2.75	1	4	3
Dissolved Lead (μg/L)	ND [1]	ND [1]	ND [1]	ND [1]
TSS (mg/L)	76	36	115	76.5

Notes:
ND = non detect
[1] Where dissolved metal concentrations were non-detect but total metal concentrations were detected, half the detection limit was used for the K_d calculation.

Note that in Equation (15), metals concentrations are in micrograms per liter, and TSS are in units of milligrams per liter. The calculated K_d values for lead and copper are summarized in Table 7. The median K_d value for copper (71,300 liters per kilogram [L/Kg]) is substantially lower than for lead (230,000 L/Kg). The higher K_d values for lead are expected (Laxen and Harrison, 1977).

Table 7. Calculated K_d Values for Copper and Lead based on Stormwater Data.
City of Redmond, Oregon

Metal	Mean (L/kg)	Minimum (L/kg)	Maximum (L/kg)	Median (L/kg)
Lead	220,000	157,000	260,000	230,000
Copper	73,400	58,000	92,600	71,300

The average scenario uses median K_d values for lead and copper, and the reasonable maximum scenario uses the minimum K_d values.

The distributions of calculated partition coefficients derived for copper and lead can be compared to other sources of information to assess the reasonableness of the derived values. A recent EPA compilation provides critically selected K_d value ranges for metals in soil and sediments (Allison and Allison, 2005). This compilation includes K_d values determined from batch and column leaching experiments with natural media, in a pH range of 4 to 10 and low total metal concentrations (Table 8). The ranges of K_d values for lead and copper in the EPA compilation overlap with the values derived for copper and lead in Central Oregon stormwater although the median values are lower in the compiled values. The lower median values in the EPA compilation may reflect leaching under more acidic conditions than are observed in our dataset.

Table 8. Compiled K_d Values for Lead and Copper (Allison and Allison, 2005).
City of Redmond, Oregon

Metal	Median (L/Kg)	Minimum (L/Kg)	Maximum (L/Kg)
Lead	130,000	100	10,000,000
Copper	13,000	5	1,600,000

Notes:
L/Kg = liter per kilogram

The calculated K_d distributions also can be compared to similarly calculated K_ds from stormwater quality data from other sources. These include data from the National Stormwater

Quality Database (NSQD; Pitt et al., 2004), and stormwater runoff data from the City of Seattle, Washington, (Engstrom, 2004) and California (Kayhanian et al., 2007). The data and calculated K_d values are summarized in Table 9.

The median K_d values for lead and copper derived from the NSQD and California data are lower than the corresponding median values derived for copper and lead in Central Oregon stormwater. However, the median lead values for the Central Oregon stormwater are within the range of median lead values for the City of Seattle and California. The median copper value for the City of Seattle is closer to the median copper value for the Central Oregon stormwater. Therefore, the calculated K_d distributions for lead and copper appear to provide a reasonable representation of sorption of these metals from stormwater onto soil particles filling fractures.

Table 9. Stormwater Quality from Various Sources and Calculated K_d Values.
City of Redmond, Oregon

Parameter	*NSQD*	*California*			*Seattle*		
	Median	Min	Max	Median	Min	Max	Median
Total Lead (µg/L)	17	1	2,600.00	12.7	3.9	38.7	11.6
Dissolved Lead (µg/L)	3	1	480	1.2	0.28	14.2	0.96
Total Copper (µg/L)	16	1.2	270	21.1	8.23	44.8	13.85
Dissolved Copper (µg/L)	8	1.1	130	10.2	1.8	28.1	7.1
Total Suspended Solids (mg/L)	58	1	2,988.00	59.1	4	204	40
pH	7.5	4.5	10.1	7	6.3	7.8	6.8
Lead K_d (L/Kg)	80,000			160,000			550,000
Copper K_d (L/Kg)	17,000			18,000			33,000

Notes:
(µg/L) = microgram per liter
mg/L = milligram per liter
L/Kg = liter per kilogram
NSQD = National Stormwater Quality Database

Although the K_ds are determined from systems containing lower concentrations of sorbing particle surfaces than is typical of stormwater infiltrating through a soil column, this is considered to be conservative because (1) the low levels of suspended solids in the stormwater may result in nonlinear sorption regime, in which case calculated K_d values may be significantly lower than would be expected in a higher surface area environment (i.e., the unsaturated zone), and (2) site-specific K_ds calculated in the stormwater already account for the effect of dissolved organic carbon, which could lower apparent K_d values by complexing with trace metals, and thereby shifting the partitioning to the solution.

3.5.8 Hydraulic Conductivity

Hydraulic conductivity is a proportionality constant that, under unsaturated conditions, is equivalent to groundwater velocity (see Equation 7). In the unsaturated zone beneath UICs, groundwater velocity is equivalent to unsaturated hydraulic conductivity (K_u). However, the fate and transport analysis uses saturated hydraulic conductivity (K_s) in Equation (7) to calculate groundwater velocity. Because of the tortuosity of unsaturated flow paths, K_u is always smaller than K_s (usually by several orders of magnitude); therefore, using K_s in Equation (7) is conservative.

Saturated hydraulic conductivity, K_s, in the fractured volcanic bedrock in Redmond was estimated from pump-in tests (i.e., infiltration tests) conducted by the City of Redmond. Note that the pump-in tests are conducted in the unsaturated zone; however, because of the large volumes of water injected during the tests the hydraulic conductivity calculated from the test data is considered "saturated". Selection of test locations were chosen to represent typical, to worst-case, pollutant load locations spanning a variety trips per day, adjacent usage and pretreatment types. Selection criteria also included having a large enough storm-shed to provide sufficient runoff for sampling in an arid climate. Figure 5 shows a conceptual diagram of a UIC during a pump-in test. Pump-in tests were performed by introducing potable water into the UIC from a nearby fire hydrant until the water level reached the top of the active portion of the UIC. After the water level reached the invert of the inlet pipe in the UIC, the flow rate was adjusted so that the water level would stabilize. The flow rate required to maintain the constant water level in the UIC was monitored and recorded. In most cases, the flow rate and water level were held relatively constant for 60 minutes. The tests were completed in general accordance with the Central Oregon Stormwater Manual, 2010 (Appendix 4B).

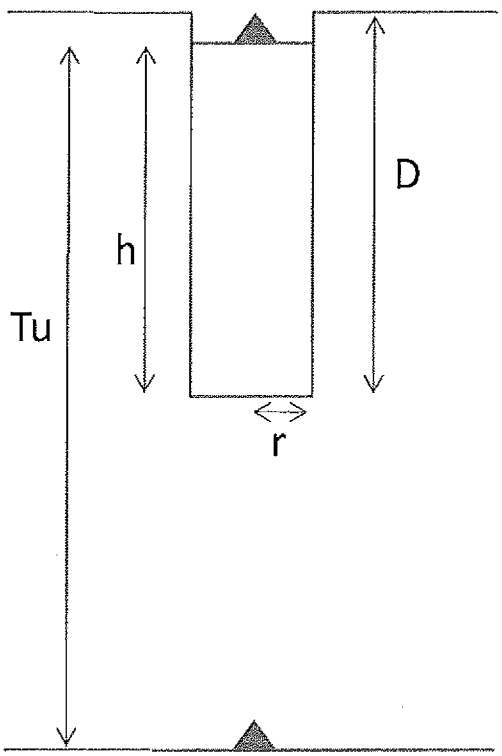

Figure 5. Pump-In Test Conceptual Model.
City of Redmond, Oregon

According to USDI (1993), horizontal hydraulic conductivity in the unsaturated zone is calculated from a pump-in test by the following formulae:

$$K_s = \frac{\left[\ln\left(\frac{h}{r}+\sqrt{\left(\frac{h}{r}\right)^2+1}\right)-1\right]Q}{2\pi h^2} \quad \text{if } T_u \geq 3h \qquad (16)$$

$$\left[\frac{3\ln\left(\frac{h}{r}\right)}{\pi h\left(h+2T_U\right)}\right]Q \quad \text{if } 3h \geq T_u \geq h \qquad (17)$$

where:

K_s is saturated hydraulic conductivity (L/T),

h is the height of the stable water level above the UIC bottom (L),

D is the depth of the UIC from ground surface to bottom (L)

T_u is the separation distance between the water table and stable water level in the UIC (L),

Q is the rate water enters the UIC when the water level is stable (L^3/T), and

r is the radius of the UIC (L).

Because water is transported vertically through the unsaturated zone, the horizontal hydraulic conductivity calculated by the pump-in test must be converted to a vertical hydraulic conductivity. Anderson and Woessner (1992) state that ratios of horizontal to vertical hydraulic conductivity commonly range from 1:1 to 1,000:1. According to Gannett and Lite (2004), the ratio of horizontal to vertical hydraulic conductivity in Upper Deschutes Basin is 1,000: 1 and, in the vicinity of Redmond, may be as great as 42,200:1. A ratio of 100:1 for horizontal to vertical hydraulic conductivity was conservatively used for fate and transport modeling. Therefore, the vertical hydraulic conductivity was calculated by dividing the horizontal hydraulic conductivity by 100. Dividing the horizontal hydraulic conductivity by 100, rather than 1,000 or 42,200, provides a larger estimate of vertical hydraulic conductivity; thus, the model conservatively simulates more rapid transport.

Hydraulic conductivities were calculated from 90 pump-in tests conducted in Redmond (test locations shown in Figure 6, which is presented at the end of this TM). Summary statistics from the pump-in test analyses are provided in Table 10.

Table 10. Hydraulic Conductivity in the Quaternary Basalt and Andesite (Qbn), Tertiary Basalt and Andesite (Tbr, TBdr), and Debris Flow Deposits (Tddf) Geologic Units.

City of Redmond, Oregon

Geologic Unit	Unit Symbol of Sherrod et al. (2004)	Number of Tests	Minimum K_v (ft/d)	Maximum K_v (ft/d)	Mean K_v (ft/d)	Median K_v (ft/d)	95% UCL K_v (ft/d) [1]
Quaternary Basalt and Andesite	Qbn	5	1.6	3.0	2.3	2.1	
Tertiary Basalt and Andesite	Tbr, Tbdr	53	0.01	3.9	1.1	0.73	1.5
Debris Flow Deposits	Tddf	32	0.002	6.2	1.6	1.1	2.2
All Tests		90	0.002	6.2	1.3	0.86	1.6

Notes:
K_v = vertical hydraulic conductivity
Qbn = Quaternary Basalt of Newberry Volcano
Tbr = Basalt or Redmond
Tbdr = Basalt of Dry River
Tddf = Debris Flow Deposits
[1] 95% UCL = Upper Confidence Limit (only calculated when more than 8 tests were conducted). 95% Approximate Gamma UCL was used.

The maximum calculated vertical hydraulic conductivity was used in the reasonable maximum transport scenario (as opposed to the 95% UCL on the mean) because there were not enough hydraulic conductivity values in the highly permeable Quaternary Basalt and Andesite to calculate a 95% UCL on the mean. This approach is consistent with Singh et al. (2007), which recommends using the maximum value when less than 8 data points are available (at least 8 data points are recommended for calculating a meaningful 95% UCL). Because the median is a better measure of central tendencies of a dataset and is more resistant to outliers (especially with smaller datasets), the median parameter is used in the average scenario of the Fate and Transport Tool to best represent the average conditions of the system and is used in other protectiveness demonstrations accepted by DEQ. This is consistent with recommendations by the USGS for statistical methods in water resources (Helsel and Hirsch 2002).

The median vertical groundwater velocity of the Quaternary Basalt and Andesite geologic unit (2.1 feet/day), which is the most permeable geologic unit that Redmond UICs are completed in, was conservatively used for the average scenario. The maximum vertical groundwater velocity of the Quaternary Basalt and Andesite geologic unit (3.0 feet/day) was conservatively used for the reasonable maximum scenario. The 95 percent UCL on the mean is typically used for the reasonable maximum transport scenario, but the maximum was used because only 5 pump-in tests were conducted in the Quaternary Basalt and Andesite, which is not a large enough sample size to calculate a 95 percent UCL on the mean.

Vertical hydraulic conductivities calculated from pump-in tests were compared to the range of hydraulic conductivities in published literature. Because published literature commonly provide only horizontal hydraulic conductivities, a $K_H : K_V$ anisotropy ratio of 100 : 1 was used to calculate vertical hydraulic conductivities. According to Freeze and Cherry (pg. 29, 1979), the horizontal hydraulic conductivity of "permeable basalt" is 0.04 to 6,000 feet/day (equivalent to a vertical hydraulic conductivity of 0.0004 to 60 feet/day). Based on Gannett and Lite (2004), aquifer tests in volcanic deposits dominated by basaltic lava and scoria of the Deschutes Formation and age-equivalent units yielded hydraulic conductivity estimates of 14 to 2,300 feet/day (equivalent to a vertical hydraulic conductivity of 0.14 to 23 feet/day). The final calibrated horizontal hydraulic conductivity in the vicinity of Redmond used in the USGS regional groundwater flow model of the upper Deschutes Basin (USGS, pg. 24 and 31, 2004) was equal to 60.5 feet/day (equivalent to a vertical hydraulic conductivity of 0.605 feet/day). Therefore, the vertical hydraulic conductivity calculated from pump-in tests is within the range of values estimated from aquifer tests in volcanic deposits of the Deschutes Formation (Gannett and Lite, 2004) and reported in Freeze and Cherry (1979). The vertical hydraulic conductivities calculated from pump-in tests and used in the Fate and Transport Tool (2.1 feet/day for the average scenario and 3.0 feet/day for the reasonable maximum scenario) are one order of magnitude larger than the final calibrated value reported in the regional groundwater flow model of the upper Deschutes Basin (Gannett and Lite, 2004) (assuming an anisotropy of 100:1). However, the larger vertical hydraulic conductivity value used in the Fate and Transport Tool conservatively simulates more rapid transport.

3.5.9 Degradation Rate Constant (Biodegradation Rate)

The organic pollutants evaluated in this TM are biodegradable under aerobic conditions (Aronson et al., 1999; MacKay, 2006); therefore, it is expected that these compounds will biodegrade to some extent within the unsaturated zone after discharging from the UIC. Degradation rate is a chemical-specific, first-order rate constant, and depends on whether the unsaturated zone is aerobic or anaerobic. Metals do not undergo biodegradation so are not included in this section.

Aerobic biodegradation rate constants were compiled from a review of the scientific literature, including general reference guides as well as compound-specific studies. The review included degradation in soils, surface water, groundwater, and sediment. However, soil aerobic degradation rates were considered to be most representative of UIC field conditions and these are summarized for each of the compounds of interest. First-order rate constants are generally appropriate for describing biodegradation under conditions where the substrate is limited and there is no growth of the microbial population (reaction rate is dependent on substrate concentration rather than microbial growth). Because of the low concentrations of the organic pollutants detected in stormwater, it is appropriate to consider biodegradation as a pseudo-first-order rate process for the UIC unsaturated zone scenario.

The ranges of biodegradation rates representative of conditions expected to be encountered in the unsaturated zone beneath UICs are summarized in Table 11. Summary statistics provided in Table 11 include minimum, maximum, number of measurements, average, 10th, 25th, and 50th percentile (median) values. For the average scenario, the median biodegradation rate was used. For the reasonable maximum scenario, the 25th percentile biodegradation rate was used.

Table 11. Summary of First-Order Aerobic Biodegradation Rates.
City of Redmond, Oregon

Compound	First-Order Biodegradation Rate (day^{-1})					
	N	*Median*	*Mean*	*Maximum*	*25th percentile*	*Minimum*
Benzo(a)pyrene [1]	38	0.0013	0.0021	0.015	0.00026	ND
Bis-(2-ethylhexyl)phthalate [2]	34	0.015	0.021	0.082	0.010	0.0040
Naphthalene [3]	22	0.075	0.14	0.39	0.025	ND
Toluene [4]	44	0.33	0.65	4.71	0.082	0.0097
2,4-D [5]	14	0.0053	0.091	0.48	0.0022	0.00012

Notes:
N = number of samples
[1] Rate constants under aerobic conditions in soil were compiled from Aronson et al. (1999) Ashok et al. (1995); Bossart and Bartha (1986); Carmichael and Pfaender (1997); Coover and Sims (1987); Deschenes et al. (1996); Grosser et al. (1991); Grosser et al. (1995); Howard et al. (1991); Keck et al. (1989); Mackay et al. (2006); Mueller et al. (1991); Park et al. (1990); and Wild and Jones (1993).
[2] From Dorfler et al. (1996); Efroymson and Alexander (1994); Fairbanks et al. (1985); Fogel et al. (1995); Maag and Loekke (1990); Mayer and Sanders (1973); Ruedel et al. (1993); Schmitzer et al. (1988); Scheunert et al. (1987) and Shanker et al. (1985).
[3] From Mackay (2006), Howard et al. (1991), Fogel, et al. (1982), Kaufman (1976), Jury et al., 1987), and Hornsby et al. (1996).
[3] From Aronson et al. (1999); Ashok et al. (1995); Ellis et al. (1991); Flemming et al. (1993); Fogel et al. (1995); Mihelcic and Luthy (1988); Mueller et al. (1991); Park et al. (1990); Pott and Henrysson (1995); Smith (1997); Swindoll et al. (1988); and Wischmann and Steinhardt (1997).
[4] From Aronson et al. (1999); Howard et al. (1991); Davis and Madsen (1996); Fan and Scow (1993); Fuller et al. (1995); Jin et al. (1994); Kjeldsen et al. (1997); McNabb et al. (1981); Mu and Scow (1994); Venkatraman et al. (1998); and Wilson et al. (1981).
[5] From Howard et al. (1991); Mackay et al. (2006); Chinalia and Killham (2006); McCall et al. (1981); Nash (1983); and Torang et al. (2003).

3.5.10 Infiltration Time

Infiltration time is the length of time during the year that stormwater discharges into a UIC and, therefore, migrates downward through the unsaturated zone. Because stormwater discharges into UICs only when the precipitation rate exceeds a threshold value, the infiltration time is dependent on the occurrence of rain events equal to or greater than this amount. The DEQ (2005) City of Portland permit fact sheet assigns a threshold precipitation rate of 0.08 inch/hour for stormwater to discharge into UICs, which is consistent with City of Redmond field staff observations. This fate and transport evaluation conservatively assumes that stormwater discharges into UICs at one-half of the threshold precipitation rate (i.e., 0.04 inch/hour).

Precipitation and infiltration times from 2002 to 2008 in Redmond are shown in Table 12. The geometric mean number of hours that precipitation rate was equal to or exceeded 0.04 inch/hour from 2002 through 2008 (53 hours or 2.22 days) was used for infiltration time in the fate and transport analysis. Because the fate and transport equation simulates pollutant breakthrough only until the time at which maximum pollutant concentration is reached, infiltration times were reduced for some pollutants (i.e., 2,4-D under the reasonable maximum scenario) that reached a maximum concentration within a shorter infiltration time. Because metals do not degrade over time, the metals' infiltration time allows for 100 years of transport (222 days of infiltration).

Table 12. Precipitation and Infiltration Time, 2002–2008.
City of Redmond, Oregon

Year	Annual Precipitation (inches)	Hours With ≥ 0.04" Precipitation	Days With ≥ 0.04" Precipitation[1]
2008	3.99	33	1.38
2007	3.78	32	1.33
2006	9.95	83	3.46
2005	11.28	100	4.17
2004	10.19	95	3.96
2003	9.43	74	3.08
2002	2.32	20	0.83
Geometric Mean	6.26	53.36	2.22

Notes:
Precipitation data from National Climactic Data Center (NCDC) Redmond (COOP 357062) rain gage (NCDC, 2011).
[1] conversion of hourly data to days for model use.

4.0 Groundwater Protectiveness Demonstration for UICs within Water Well Setbacks

The UIC WPCF Municipal Stormwater Permit Template (June 2011) requires that UICs be constructed and operated in a manner that protects groundwater quality. Horizontal setbacks between UICs and public water wells that are considered to be protective of groundwater are specified in the permit of water well. Specifically, the UIC WPCF Municipal Stormwater Permit Template requires that UICs be outside of the two-year Time-of-Travel and/or a of 500 feet setback radius from public or private wells. The City operates several UICs that are either within the 500 feet setback distance to a water well and/or are within the two-year Time-of-Travel. As such, the City is required to retrofit the UICs, close the UICs, or show that the UICs are protective of groundwater under Schedule A.8 of the UIC WPCF Permit Template. This section presents a Groundwater Protectiveness Demonstration as described in Schedule D.6 of the UIC WPCF Permit Template.

The Groundwater Protectiveness Demonstration is comprised of applying the Fate and Transport Tool to UICs in Redmond. Specifically, the Fate and Transport Tool was used to evaluate whether stormwater pollutant concentrations entering a UIC are attenuated to concentrations below the MRL (and that meet the groundwater protection requirements of OAR 340-040) at the point the infiltrated stormwater reaches groundwater.

Results from the average and reasonable maximum scenario of the unsaturated zone Fate and Transport Tool are presented in Table 13. Pollutant attenuation was simulated for UICs with a separation distance of greater than or equal to 5 feet. The model calculations for these scenarios are presented in Appendix C. The pollutant concentrations discharging to UICs used as input to the Fate and Transport Tool were equal to the existing EDLs (as listed in the UIC WPCF Municipal Stormwater Template) or 10 times the existing EDLs for ubiquitous pollutants based on stormwater sampling by other municipalities. Naphthalene, which does not have an EDL, was assigned an input concentration of about 0.05% of the pollutant solubility in water. As shown in Table 13, under the average scenario for unsaturated zone transport, copper, 2,4-D, and toluene concentrations in stormwater equal to the existing EDLs attenuate to below MRLs within 5 feet of transport. Under the average scenario for unsaturated zone transport, lead, benzo(a)pyrene, PCP, and DEHP concentrations in stormwater equal to 10 times the existing EDLs attenuate to below MRLs within 5 feet of transport. Under the average scenario for unsaturated zone transport, naphthalene concentrations in stormwater equal to 10 µg/L (i.e., 0.05% of the pollutant solubility in water) attenuate to below MRLs within 5 feet of transport. The simulated separation distances for these pollutants that are below the MRLs (or protective of the groundwater) are presented in Appendix D. **As such, the Fate and Transport Tool indicates that UICs within permit-required setback distances to water wells are protective of groundwater.**

The reasonable maximum scenario represents the worst-case pollutant transport conditions, and is characterized by compounding conservatism of input variables. The purpose of the reasonable maximum scenario is to evaluate model sensitivity, and it does not represent reasonably likely conditions. Under the reasonable maximum scenario for unsaturated zone transport, copper, lead, benzo(a)pyrene, naphthalene, PCP, and DEHP concentrations in stormwater equal to the input concentrations shown in Table 13 attenuate to below MRLs within 5 feet of transport. 2,4-D and toluene require greater than five (5) feet to attenuate to below the MRL under the reasonable maximum scenario. Under the reasonable maximum scenario of the Fate and Transport Tool, 2,4-D and toluene concentrations in stormwater equal to the existing EDLs attenuate to below MRLs within 14 feet of transport. The model calculations for this scenario are presented in Appendix E. Based on available separation distance data for the City's UICs, which accounts for about 85 percent of the City's UICs, the minimum separation distance between the bottom of the City UICs and the seasonal high groundwater is conservatively estimated to be greater than 100 feet. Therefore, under the worst-case pollutant transport conditions, 2,4-D and toluene attenuate to below the MRL before reaching groundwater. **As such, the Fate and Transport Tool indicates that UICs within permit-required setback distances to water wells are protective of groundwater.**

Table 13. Protectiveness Lookup Table - Pollutant Attenuation in the Unsaturated Zone under the Average and Reasonable Maximum Scenarios (UICs ≥ 5 Feet Separation Distance)
City of Redmond, Oregon

SEPARATION DISTANCE OF 5 FEET

				AVERAGE SCENARIO		*REASONABLE MAXIMUM SCENARIO*		
Pollutant	EDL (ug/L)	MRL (ug/L) [1]	Average Observed Concentration (ug/L) [2]	Input Concentration (ug/L) [3,5]	Output Concentration (ug/L) [4]	Input Concentration (ug/L) [3]	Output Concentration (ug/L) [4]	Ratio of Average Observed Concentration: Input Concentration
Copper	1,300	0.2	4.40	EDL	<MRL	EDL	<MRL	0.003
Lead	50	0.1	11.9	10xEDL	<MRL	10xEDL	<MRL	0.024
Benzo(a)pyrene	0.2	0.01	No Detections	10xEDL	<MRL	10xEDL	<MRL	NA
Naphthalene	NA	0.02	0.08	10 [6]	<MRL	10 [6]	<MRL	0.008
PCP	1.0	0.04	No Detections	10xEDL	<MRL	10xEDL	<MRL	NA
DEHP	6.0	1.0	No Detections	10xEDL	<MRL	10xEDL	<MRL	NA
2,4-D	70	0.1	NA	EDL	<MRL	EDL	39.2 [7]	NA
Toluene	1,000	0.5	No Detections	EDL	<MRL	EDL	313.6	NA

Notes:
MRL = method reporting limit
EDL = effluent discharge limit based on UIC WPCF Municipal Stormwater Template
NA = not available
µg/L = micrograms per liter
[1] Method Reporting Limit (MRL) based on typically achievable MRLs during stormwater monitoring in Oregon.
[2] Average observed concentration of pollutants in stormwater is based on Redmond stormwater sampling from 2007through 2010. Where data were non-detects, ½ the detection limit of the specific sample analysis was used for calculating the average.
[3] Input concentrations are the concentrations discharging from the end of pipe.
[4] Output concentrations are the concentrations below the UICs after 5 feet of transport.
[5] As requested by DEQ, the protectiveness demonstration uses input concentrations of 10 times the EDL for ubiquitous pollutants, and uses the EDL for other pollutants.
[6] The input concentration for naphthalene, which does not have an EDL in the UIC WPCF Municipal Stormwater Template, is about 0.05% of its solubility in water at 10.0 degrees Celsius (Bohon and Claussen, 1951).
[7] At a separation distance of 5 feet, infiltration time is shorter than 2.22 days because the maximum concentration immediately above the water table occurred before the maximum number of days that stormwater infiltrates into the UIC.

5.0 Proposed EDLs

The unsaturated zone Fate and Transport Tool was used to develop proposed EDLs for the City of Redmond's UIC WPCF Permit for lead, benzo(a)pyrene, PCP, and DEHP. DEQ recommended developing proposed EDLs for these four pollutants because they are considered more likely to be detected in municipal stormwater in Oregon based on Oregon ACWA studies (Kennedy/Jenks, 2009 and Kennedy/Jenks, 2011). The proposed EDLs were developed using the following assumptions:

- Proposed EDLs are limited to maximum concentrations of 10 times the EDLs in the UIC Permit Template,
- The separation distance between the bottom of the UICs and the seasonal high groundwater is 5 feet,
- The average scenario of the Fate and Transport Tool is used, and

- Groundwater is protected when pollutant concentrations just above the water table are at background levels (i.e., zero for synthetic organic compounds, as represented by the MRL).

Table 14 presents the proposed EDLs developed using the average transport scenario of the Fate and Transport Tool and a 5-foot separation distance between the bottom of the UIC and seasonal high groundwater. The calculations for proposed EDLs are provided in Appendix C. The proposed EDLs for lead, benzo(a)pyrene, PCP, and DEHP were limited to 10 times the EDLs in the UIC WPCF Municipal Stormwater Template.

Table 14. Proposed EDLs (UICs ≥ 5 Feet Separation Distance and Average Scenario)
City of Redmond, Oregon

Pollutant	MRL (ug/L) [1]	Average Observed Concentration (ug/L) [2]	Existing EDL (ug/L) [3]	Proposed EDL (ug/L) [4]	Output Concentration (ug/L) [5]
Lead	0.1	11.9	50	500	<MRL
Benzo(a)pyrene	0.01	No Detections	0.2	2.0	<MRL
PCP	0.04	No Detections	1.0	10.0	<MRL
DEHP	1.0	No Detections	6.0	60.0	<MRL

Notes:
μg/L = micrograms per liter
EDL = effluent discharge limit
MRL = method reporting limit
[1] Method Reporting Limit (MRL) based on typically achievable MRLs during stormwater monitoring in Oregon.
[2] Average observed concentration of pollutants is based on Redmond stormwater sampling from 2007 through 2010. Where data were non-detects, ½ the detection limit of the specific sample analysis was used for calculating the average concentration.
[3] Existing Effluent Discharge Limits based on the UIC WPCF Municipal Stormwater Template.
[4] Proposed EDLs based on the average transport scenario of the Fate and Transport Tool and the assumption that groundwater is protected when pollutant concentrations just above the water table are below the MRL.
[5] Output concentrations are the concentrations below the UICs after 5 feet of transport under the average transport scenario.

6.0 Groundwater Quality Data near Redmond

To further support the City of Redmond's Groundwater Protectiveness Demonstration, available groundwater quality data from SDWA sampling at municipal water supply wells were evaluated for the eight pollutants of interest. The City of Redmond samples 7 municipal wells for SDWA parameters. Many of the constituents analyzed under the SDWA have been analyzed for in urban stormwater (Kennedy/Jenks, 2009 and Kennedy/Jenks, 2011). As such, if UICs in the City of Redmond are not protective of groundwater, we would expect to find SDWA constituents in groundwater beneath and downgradient of the UICs.

As shown on Table 15, during the 25 years of SDWA sampling, only lead has been repeatedly detected in groundwater wells near the City of Redmond. Well locations are shown in Figure 7. The lead concentrations upgradient of the City's UICs (e.g., Well #3) are similar to concentrations downgradient of the UICs. This suggests that the lead concentrations observed in groundwater represent background conditions as opposed to contribution from UICs. DEHP and toluene were detected in a single sample at concentrations less than half of the maximum contaminant levels (DEHP was detected at a concentration of 0.0025 mg/L and toluene was detected at a concentration of 0.0005 mg/L, which is commonly the MRL). Because these are isolated detections and DEHP and toluene have not been detected in Redmond stormwater, it is unlikely that the DEHP and toluene concentrations observed in these two groundwater samples represent contribution from UICs. If UICs were adversely impacting groundwater, it is expected that pollutants would be ubiquitous downgradient of UICs. The lack of detections of representative stormwater pollutants in groundwater beneath the City of Redmond (i.e., PCP), and the low background-level concentrations of lead in groundwater suggest that the City's UICs are not adversely impacting groundwater. The lack of reoccurring high-level detections of stormwater pollutants in groundwater beneath the City of Redmond supports the Fate and Transport Tool conclusion that UICs are protective of groundwater.

7.0 Conclusions

The Fate and Transport Tool was used to 1) demonstrate groundwater protectiveness for stormwater discharged from UICs that are in the 500-foot well setback or the two-year Time-of-Travel from water wells and 2) propose EDLs for the City's UIC WPCF Permit that meet Oregon's groundwater protectiveness standards. Based on the Fate and Transport Tool results, UICs within permit-required setback distances to water wells are protective of groundwater. The Fate and Transport Tool simulation results indicated that concentrations of lead, benzo(a)pyrene, PCP, and DEHP could be 1000 times higher than the EDL while still being protective of groundwater. However, to be conservative, the City has selected 10 times the EDL as the proposed EDL.

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Figures

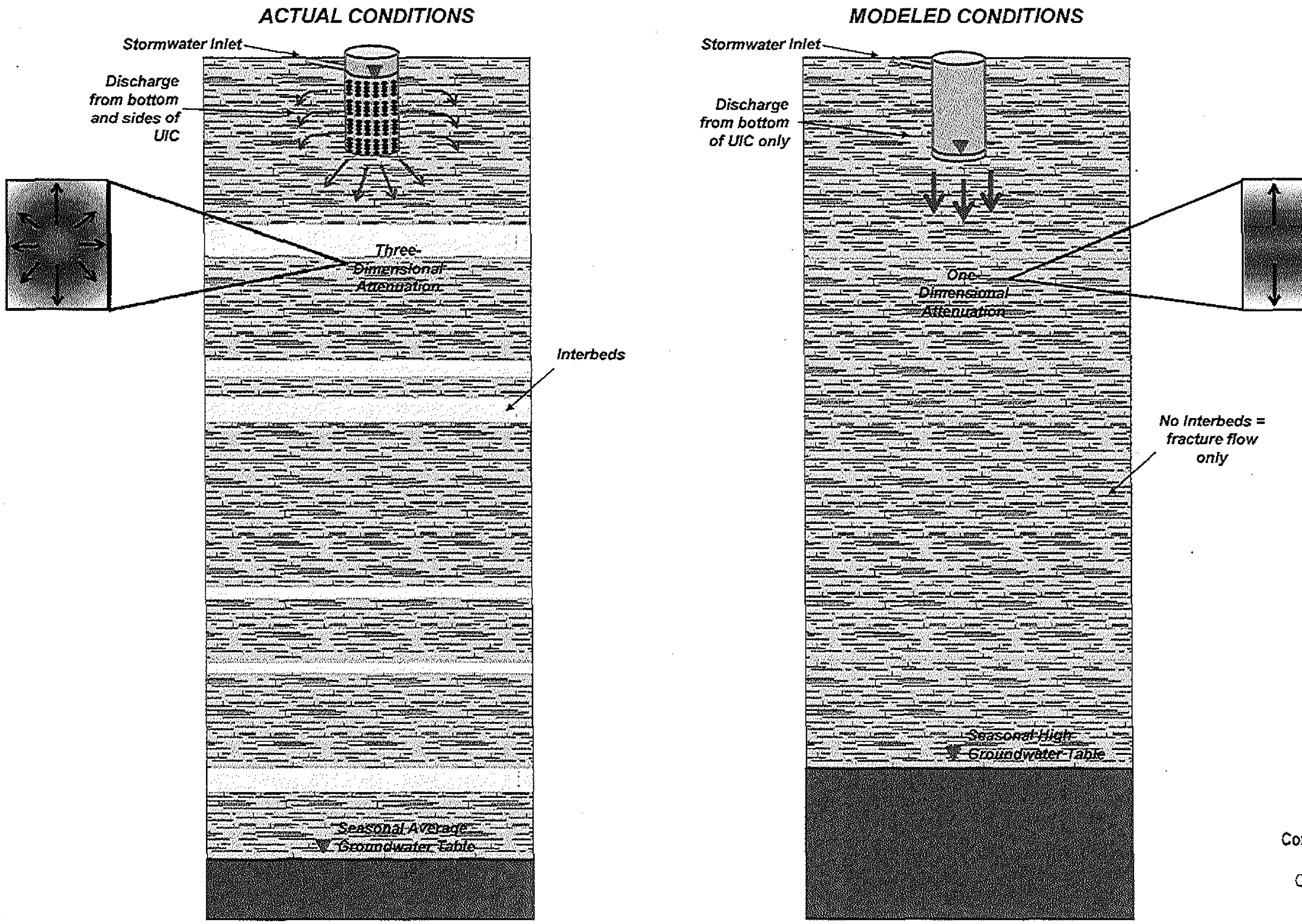
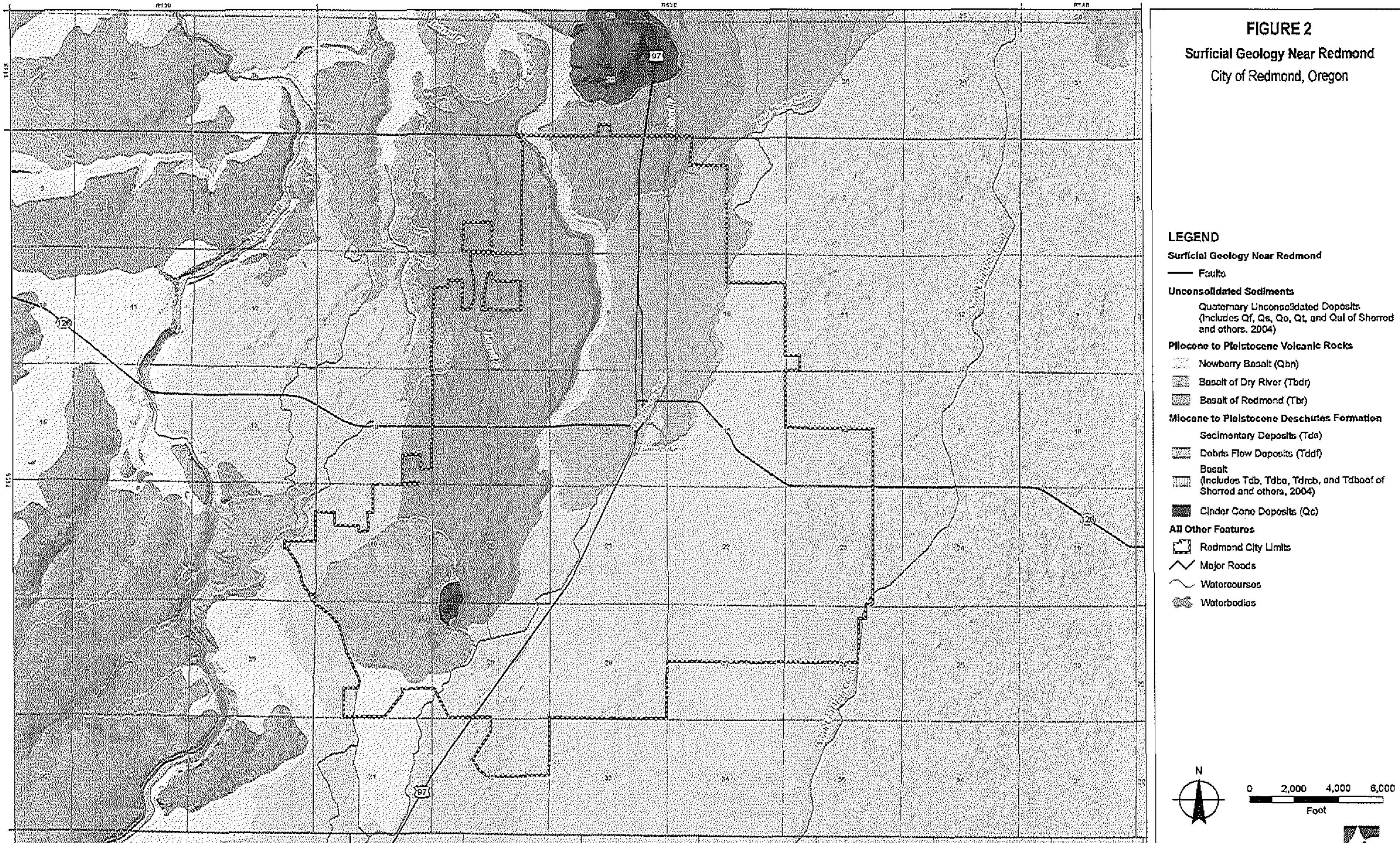


FIGURE 1
Conceptual Model for UIC Discharge in Redmond
City of Redmond, Oregon

GSI Water Solutions, Inc.

FIGURE 2
Surficial Geology Near Redmond
City of Redmond, Oregon



MAP NOTES:
Date: July 27, 2011
Data Sources: DOGAMI, USGS, OGIC, ESRI

GSI Water Solutions, Inc.

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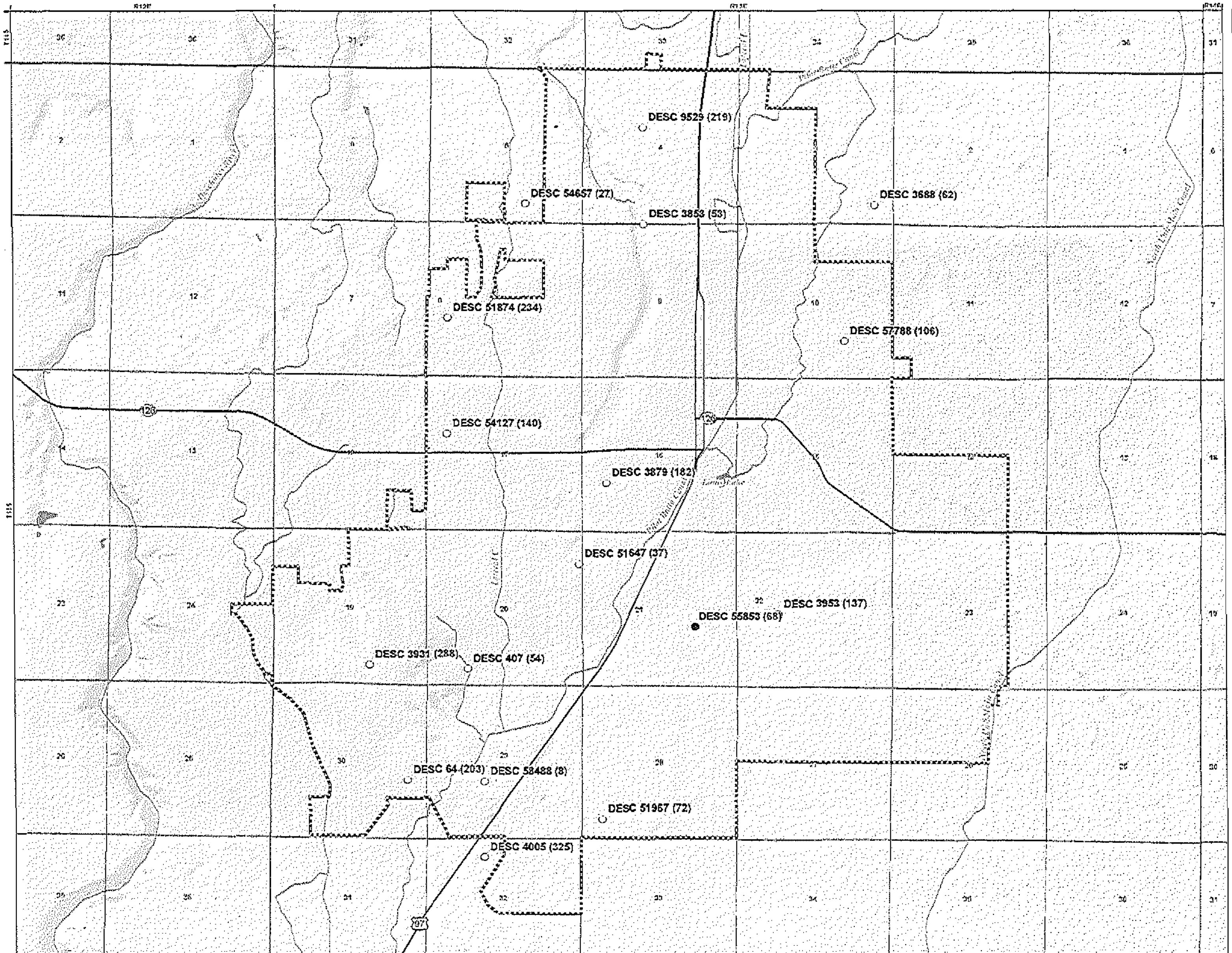

FIGURE 3

Redmond Interbed Thickness Above Water Table

City of Redmond, Oregon

LEGEND

Wells with Interbed Thickness

- Interbed Thickness Based on Driller's Log
- Interbed Thickness Based on Cuttings Log
- DESC XX Oregon Water Resource Department Well Log ID
- (5) Number in Parenthesis Equals Interbed Thickness Above Water Table (feet)

All Other Features

- Redmond City Limits
- Major Roads
- Watercourses
- Waterbodies

NOTES:
Interbeds include sand, sandstone, ash, tephra, pumice, tuff, and conglomerate as described in driller's log.

Depth to water table determined by driller's log.

0 0.25 0.5 0.75
Miles

MAP NOTES:
Date: June 27, 2011
Data Sources: OWRD, USGS, ODIC, ESRI

GSI Water Solutions, Inc.

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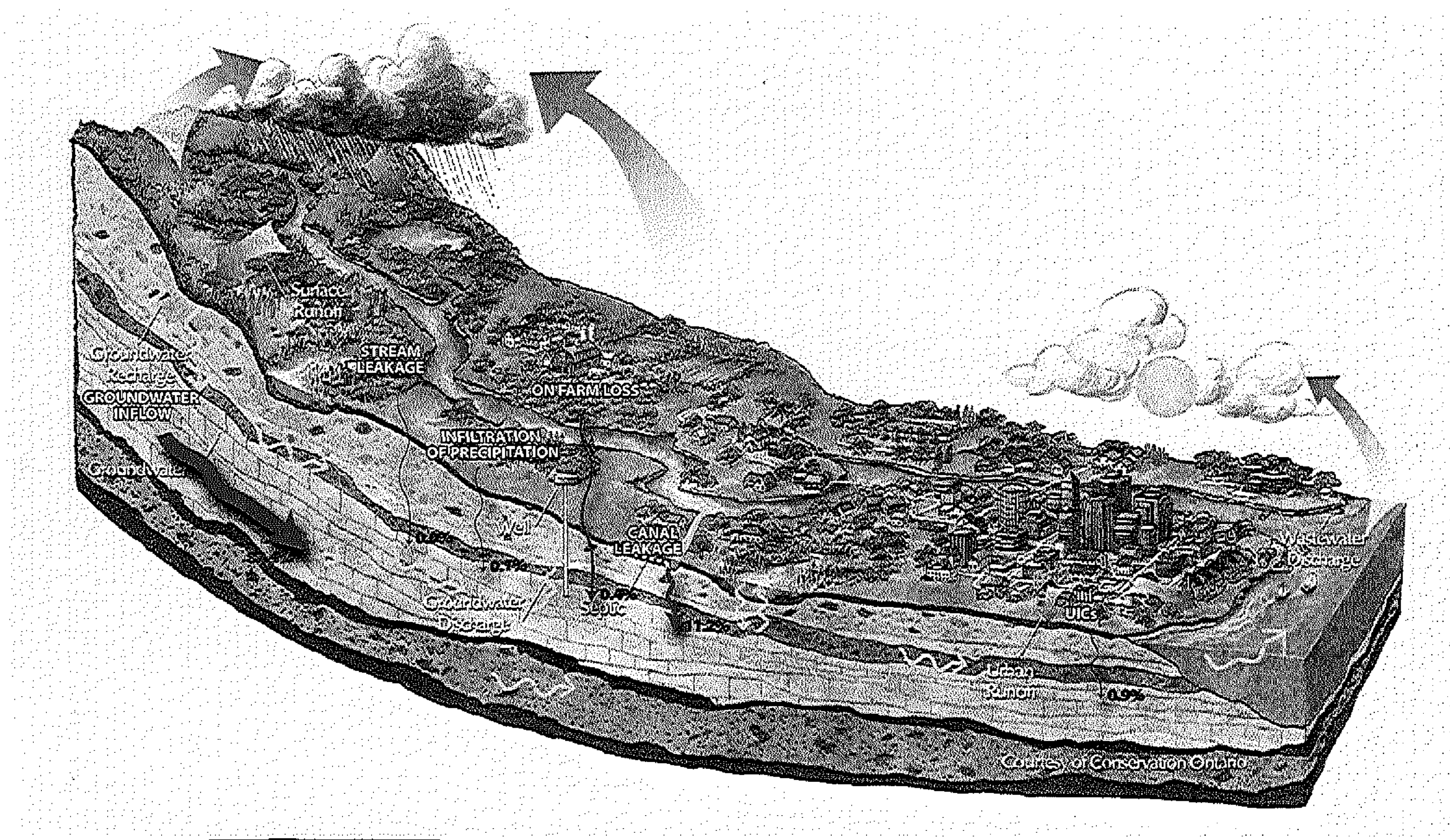
FIGURE 4

Sources of Recharge in Redmond

City of Redmond, Oregon



	Redmond		
	Recharge (ac-ft/yr)		Percent of Recharge in Redmond City Limits
UICs	4,045	(1)	0.9%
Infiltration of Precipitation	435	(2)	0.1%
Canal Leakage	48,892	(3)	11.2%
Stream Leakage	0		0.0%
On Farm Losses	1,949	(5)	0.4%
Groundwater Inflow	382,081	(6)	87.4%
Total	437,402		100.0%

LEGEND

Redmond Infiltration

GSI Water Solutions, Inc.

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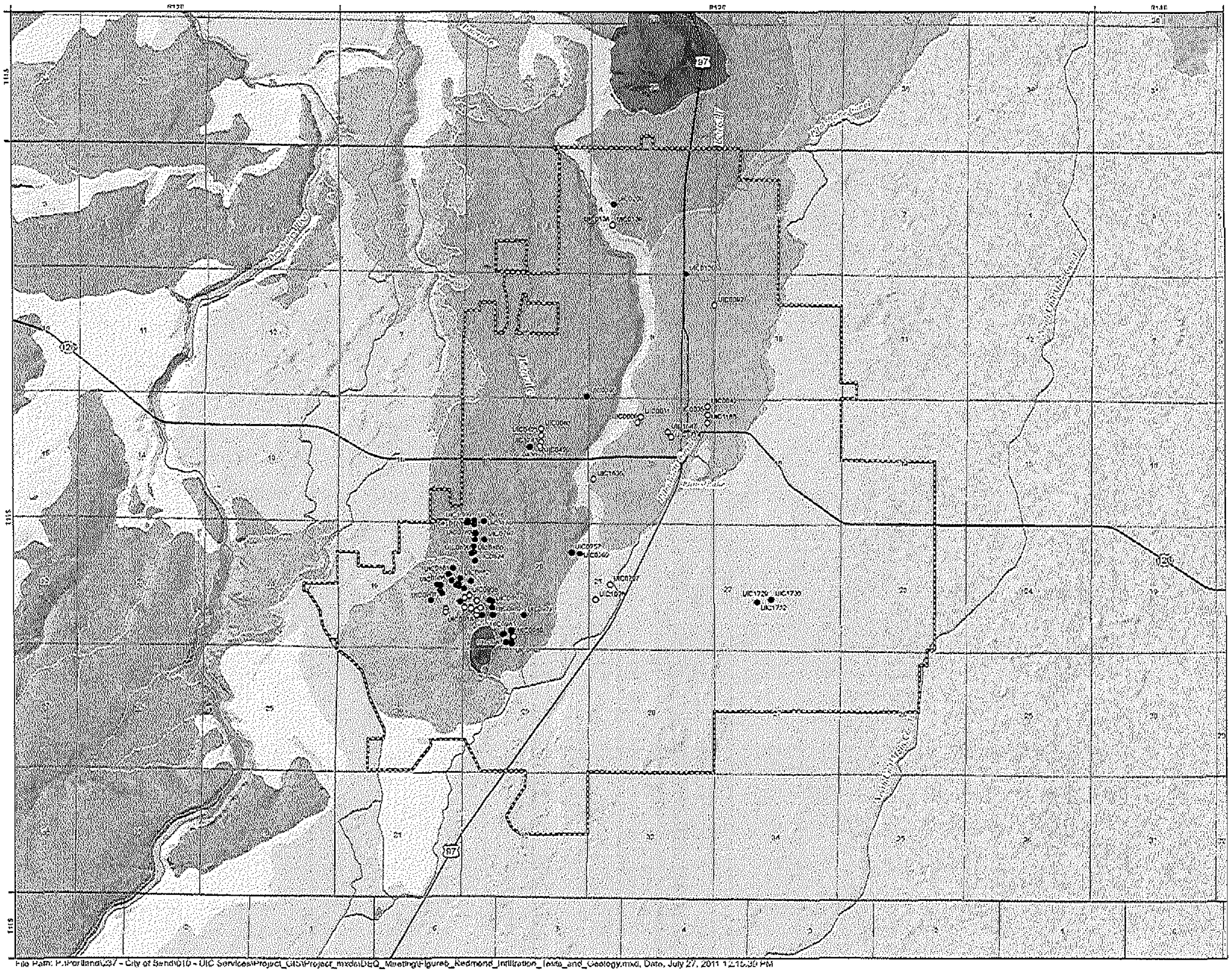
FIGURE 6

Infiltration Tests and Surficial Geology Near Redmond

City of Redmond, Oregon



LEGEND

City of Redmond UICs - Infiltration Tests

- Drill Holes
- Dry Wells

Surficial Geology Near Redmond

- Faults

Unconsolidated Sediments

- Quatemary Unconsolidated Deposits (Includes Qf, Qa, Qo, Qt, and Qal of Sherrod and others, 2004)

Pliocene to Pleistocene Volcanic Rocks

- Newberry Basalt (Qbn)
- Basalt of Dry River (Tbdr)
- Basalt of Redmond (Tbr)

Miocene to Pleistocene Deschutes Formation

- Sedimentary Deposits (Tds)
- Debris Flow Deposits (Tddf)
- Basalt (Includes Tdb, Tdba, Tdrcb, and Tdbaof of Sherrod and others, 2004)
- Cinder Cone Deposits (Qc)

All Other Features

- Redmond City Limits
- Major Roads
- Watercourses
- Waterbodies

N

0 2,000 4,000 6,000

Feet

MAP NOTES:

Date: July 27, 2011

Data Sources: City of Redmond, DOGAMI, USGS, OGIC, ESRI

GSI Water Solutions, Inc.

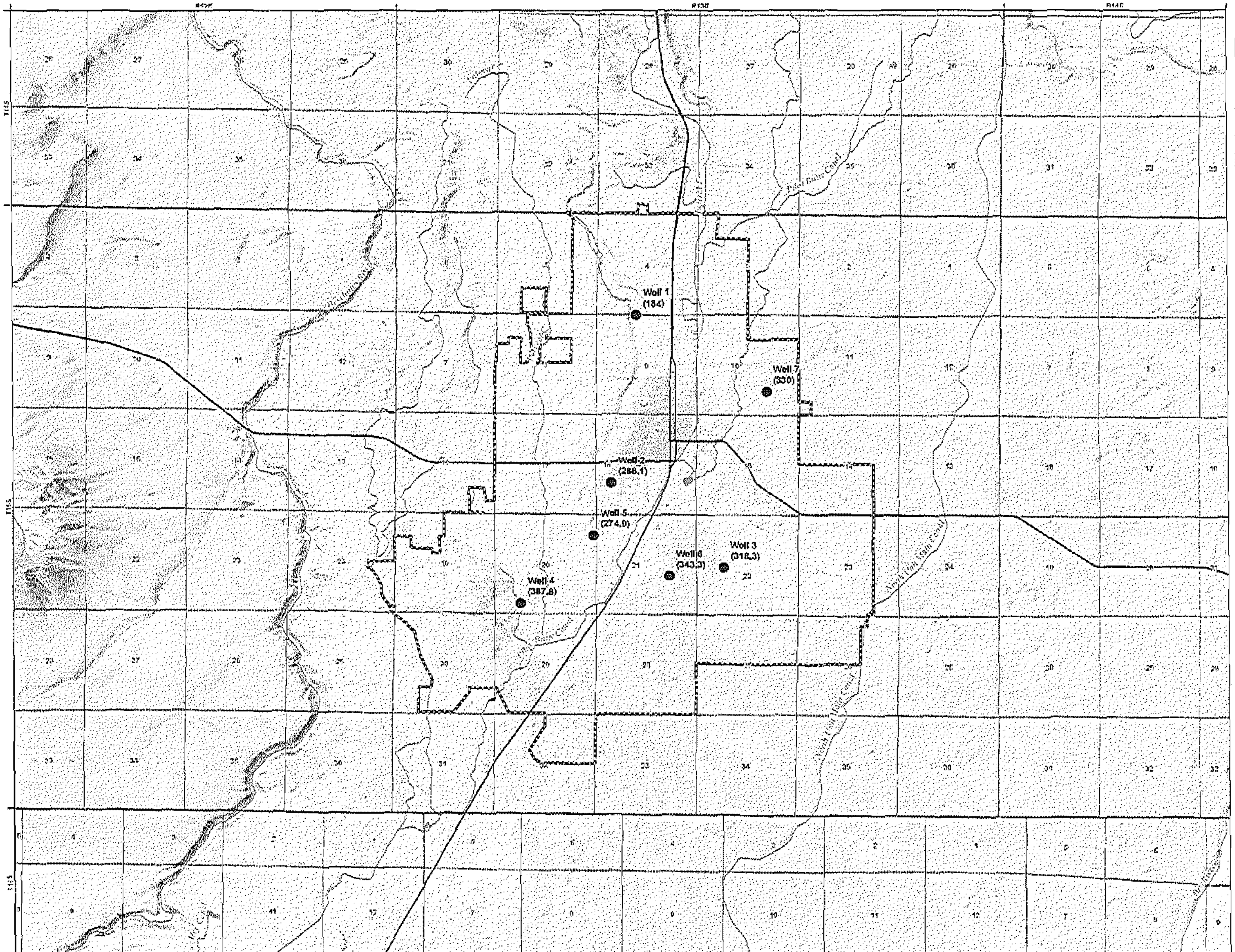


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FIGURE 7

Municipal Water Wells near Redmond and Analytical Groundwater Quality Data

City of Redmond, Oregon

LEGEND

- Municipal Water Wells with Available Analytical Data

All Other Features

- City Limits
- Major Roads
- Watercourses
- Waterbodies

NOTES:
Analytical data available on Oregon State Department of Human Services Drinking Water Program website
Number is parenthesis is Static Water Level
Static water level based on driller's log

0 0.5 1 1.5
Miles

MAP NOTES:
Date: July 27, 2011
Data Sources: City of Bend, DOGAMI, USGS, OGIC, ESRI

GSI Water Solutions, Inc.

Tables

ES Table 1 - City of Redmond - PROPOSED EDLs

City of Redmond, Oregon

Parameter	MRL (µg/L)	DEQ Municipal UIC WPCF Permit Template EDL (µg/L)	City of Redmond Proposed EDL (µg/L)
COMMON POLLUTANTS [1]			
Benzo(a)pyrene	0.01	0.2	***2***
Di(2-ethylhexyl)phthalate (DEHP)	1.0	6	***60***
Pentachlorophenol	0.04	1	***10***
Antimony(Total)		6	*same*
Arsenic(Total)		10	*same*
Cadmium(Total)		5	*same*
Copper	0.2	1300	*same*
Lead (Total)	0.1	50	***500***
Zinc (Total)		5,000	*same*
SCREENING POLLUTANTS [2]			
Barium (Total)		2000	*same*
Beryllium (Total)		4	*same*
Chromium(Total)		100	*same*
Cyanide (Total)		200	*same*
Mercury (Inorganic)		2	*same*
Selenium (Total)		50	*same*
Thallium (Total)		2	*same*
Total Nitrogen-N		10,000	*same*
Benzene		5	*same*
Toluene	0.5	1000	*same*
Ethylbenzene		700	*same*
Xylenes (Total)		10000	*same*
Diazinon		7	*same*
2,4 D	0.01	70	*same*
Dinoseb		7	*same*
Bis(2-chloroethyl) ether	0.1	0.3	*same*
Glyphosate		700	*same*

Notes:

1 = DEQ 2011 Permit Template Table A.5.1

2 = DEQ 2011 Permit Template Table A.5.2

MRL = laboratory method reporting limit

DEQ = Oregon Department of Environmental Quality

UIC WPCF = Underground injection control Water Pollution Control Facilities

EDLs = effluent discharge limits

(µg/L) = micrograms per liter

ES Table 2 - City of Redmond - Protectiveness Distance

City of Redmond, Oregon

Chemical Group/ Representative Chemical	MRL (µg/L)	City of Redmond Proposed EDLs Input Concentration *at the end of pipe* (µg/L)	Simulated Output Concentration [1] *at end of 5 feet of travel from UIC* (µg/L)	Simulated Distance to Protectiveness (< MRL) [1] (feet from base of UIC)
VOCs:				
Toluene	0.5	1000	< MRL	2.13
SVOCs:				
Di(2-ethylhexyl)phthalate (DEHP)	1	***60***	< MRL	0.024
Pentachlorophenol	0.04	***10***	< MRL	0.786
PAHs:				
Benzo(a)pyrene	0.01	***2***	< MRL	0.001
Metals:		0		
Copper	0.2	1300	< MRL	0.005
Lead (Total)	0.1	***500***	< MRL	0.001
Pesticides/Herbicides:				
2,4 D	0.01	70	< MRL	1.64
			minimum depth	0.001
			maximum depth	2.13
			average depth	0.655

City of Redmond's PROPOSED Separation Distance ≥ 5 Feet

Notes:
1 = values based on the average scenario simulation
MRL = laboratory method reporting limit
EDLs = effluent discharge limits
(µg/L) = micrograms per liter

Table 3: Properties of WPCF Permit Pollutants Used in Selection of Representative Indicator Pollutants
City of Redmond, Oregon

	EDL[1]	MCL[2]	DEQ RBCs for Groundwater[3]	Toxicity Ranking	Solubility (mg/L)[4]	EPA Mobility Ranking[5]	Mobility of Pollutant	Persistence (half-life [days])[6]	Persistence Ranking	Frequency of Detection in Redmond Stormwater (%)[7]	Frequency of Detection Ranking in Redmond Stormwater	Frequency of Exceedance in Redmond Stormwater (%)	Frequency of Detection in Oregon Stormwater (%)[8]	Frequency of Detection Ranking in Oregon Stormwater[8]	Frequency of Exceedance in Oregon Stormwater (%)[8]	Pollutant Category[9]
	μg/L	μg/L	μg/L													
Common Pollutants																
Benzo(a)pyrene	0.2	0.2	0.0029	High	0.0016	0.0001	Low	300	Medium	0	Low	0	25.1	Medium	0.3	PAH
Di(2-ethylhexyl)phthalate	6	6	4.1	High	0.34	0.0001	Low	14	Low	0	Low	0	58	Medium	4.7	SV
Pentachlorophenol	1	1	0.47	High	2000	1	High	100	Medium	0	Low	0	81.6	High	11.7	SV
Antimony (Total)	6	6	NR	High	170,000	0.01	Medium	Infinite	Infinite	54.5	High	0	46.3	Medium	0.3	M
Arsenic (Total)	10	10	0.038	High	120000	0.01	Medium	Infinite	Infinite	9	Low	0	82.8	High	0.2	M
Cadmium (Total)	5	5	18	High	1700	0.01	Medium	Infinite	Infinite	28.1	Medium	3.1	43.9	Medium	0.5	M
Copper (Total)	1300	1300	1400	Low	570	0.01	Medium	Infinite	Infinite	100	High	0	92.5	High	0	M
Lead (Total)	50	15	15	Medium	670	0.01	Medium	Infinite	Infinite	65.2	Medium	4.5	88.5	High	12.7	M
Zinc (Total)	5000	NR	NR	Low	1400	0.01	Medium	Infinite	Infinite	100	High	0	97.6	High	0.1	M
Screening Pollutants (From draft WPCF UIC Permit *and* additional pollutants of concern in stormwater)																
Barium (Total)	2000	2000	7300	Low	2,800	0.01	Medium	Infinite	Infinite	No data	No data	No data	97.6	High	0	M
Beryllium (Total)	4	4	73	High	84,000	0.01	Medium	Infinite	Infinite	No data	No data	No data	9.1	Low	0	M
Chromium VI	100	100	110	Medium	600000	0.01	Medium	Infinite	Infinite	No data	No data	No data	No data	No data	No data	M
Cyanide (Total)	200	200	730	Medium	NR	1.0	High	Infinite	Infinite	No data	No data	No data	2.4	Low	0	O
Mercury (Total, inorganic)	2	2	11	High	450	0.01	Medium	Infinite	Infinite	No data	No data	No data	37.6	Medium	0	M
Selenium (Total)	50	50	NR	Medium	2.60E+06	1.0	High	Infinite	Infinite	No data	No data	No data	6.3	Low	0	M
Thallium (Total)	2	2	NR	High	8600	0.01	Medium	Infinite	Infinite	No data	No data	No data	0.9	Low	0	M
Benzene	5	5	0.35	High	1800	1	High	10	Low	0	Low	0	0.6	Low	0	V
Toluene	1000	1000	2300	Low	530	1	High	0.5	Low	0	Low	0	25.2	Medium	0	V
Ethylbenzene	700	700	1300	Low	170	1	High	0.3	Low	1.3	Low	0	0.3	Low	0	V
Xylenes	10,000	10,000	210	Low	180	1	High	17.5	Low	1.3	Low	0	0	Low	0	V
Alachlor		2	NR	High	240	0.01	Medium	14	Low	No data	No data	No data	0	Low	0	P/H
Atrazine		3	NR	High	70	0.01	Medium	100	Medium	No data	No data	No data	0	Low	0	P/H
Carbofuran		40	NR	Medium	351	NR	Medium	110	Medium	No data	No data	No data	0	Low	0	P/H
Carbon Tetrachloride		5	0.17	High	790	1.0	High	265	Medium	0	Low	0	0	Low	0	V
Chlordane		2	0.16	High	0.056	0.01	Medium	812	High	No data	No data	No data	0	Low	0	P/H
Chlorobenzene		100	90	Medium	470	1.0	High	110	Medium	0	Low	0	0.5	Low	0	V
2,4-D[1,2]	70	70	370	Low	4500	NR	High	15	Low	No data	No data	No data	15.3	Low	0	P/H
Dalapon	200	200	NR	Low	800,000	NR	High	16	Low	No data	No data	No data	0	Low	0	P/H
Diazinon	7	NR	NR	NR	60	NR	Low	40	Low	No data	No data	No data	No data	No data	No data	P
o-Dichlorobenzene		600	50	Low	4000	1.0	High	Slow	High	0	Low	0	0	Low	0	V
p-Dichlorobenzene		75	0.48	Medium	79	1.0	High	104	Medium	0	Low	0	0	Low	0	V
1,3-Dichlorobenzene		NR	15	High	125	NR	High	42	Low	0	Low	0	0	Low	0	V
Bis(2-chloroisopropyl)ether		NR	NR	High	1,700	NR	Medium	100	Medium	No data	No data	No data	0	Low	0	SV
Bis(2-chloroethyl)ether	0.3	NR	NR	High	17,200	NR	Medium	100	Medium	No data	No data	No data	0	Low	0	SV

	EDL[1]	MCL[2]	DEQ RBCs for Groundwater[3]	Toxicity Ranking	Solubility (mg/L)[4]	EPA Mobility Ranking[5]	Mobility of Pollutant	Persistence (half-life [days])[6]	Persistence Ranking	Frequency of Detection in Redmond Stormwater (%)[7]	Frequency of Detection Ranking in Redmond Stormwater	Frequency of Exceedance in Redmond Stormwater (%)	Frequency of Detection in Oregon Stormwater (%)[8]	Frequency of Detection Ranking in Oregon Stormwater[8]	Frequency of Exceedance in Oregon Stormwater (%)[8]	Pollutant Category[9]
	μg/L	μg/L	μg/L													
Dinoseb	7	7	NR	High	52	NR	High	24	Low	No data	No data	No data	0.2	Low	0	P/H
Diquat		20	NR	Medium	700,000	NR	Low	Infinite	Infinite	No data	No data	No data	0	Low	0	P/H
Endothall		100	NR	Medium	100,000	NR	Medium	10	Low	No data	No data	No data	0	Low	0	P/H
Glyphosate	700	700	NR	Low	11,600	NR	Low	60	Medium	No data	No data	No data	0	Low	0	P/H
Lindane[HCH(gamma)]		0.2	0.044	High	7.3	1.0	High	980	High	No data	No data	No data	0	Low	0	P/H
Picloram		500	NR	Low	430	NR	Medium	100	Medium	No data	No data	No data	0	Low	0	P/H
1,2,4-Trichlorobenzene		70	12	Medium	35	1.0	High	104	Medium	0	Low	0	0	Low	0	V
Nitrate-nitrogen	10,000	10,000	NR	Low	High in soil & water	NR	High	Infinite	Infinite	100	High	3.3	84	High	0.3	O
Other Pollutants																
Naphthalene	N/A	NR	6.2	High	31	0.02	Low	10	Low	2.2	Low	N/A	No data	No data	No data	PAH

Table notes:

Pollutants shown in bold and orange highlighting were selected as indicator pollutants for the evaluation of separation distance.

[1] Effluent Discharge Limits (EDL) are based on Underground Injection Control (UIC) Water Pollution Control Facility (WPCF) Municipal Stormwater Template.

[2] Maximum contaminant level (MCL). U.S. EPA Drinking Water Contaminants. http://www.epa.gov/safewater/contaminants/index.html, Accessed July 5, 2011.

[3] Oregon DEQ Risk Based Concentrations (RBCs) for Groundwater Ingestion and Inhalation from Tapwater, Residential, 7/4/07. http://www.deq.state.or.us/lq/pubs/docs/RBDMTable.pdf (Accessed 5/19/08)

[4,5] U.S. EPA Superfund Chemical Data Matrix Methodology Report, Appendix A (2004). http://www.epa.gov/superfund/sites/npl/hrsres/tools/app_a_1.pdf (Accessed 12/07)USEPA (2006), Groundwater & Drinking Water Technical Factsheets. Available at: http://www.epa.gov/ogwdw/hfacts.html

[6] References for degradation rates:
a) Howard, Phillip; Robert S. Boethling; William F. Jarvis; William M. Moylan; and Edward M. Michalenko, 1991) Handbook of Environmental Degradation Rates, Lewis Publishers.
b) EPA Technical Fact Sheets

[7] Stormwater data from 2007 - 2010 City of Redmond stormwater sampling.

[8] Stormwater data comes from the Compilation and Evaluation of Existing Stormwater Quality Data from Oregon, Oregon Association of Clean Water Agencies report (1990-2008) unless otherwise noted (Kennedy/Jenks, 2009).

[9] Volatile organic compound (V), metal (M), polycyclic aromatic hydrocarbon (PAH), semi-volatile organic compound (SV), pesticide/herbicide (P/H), other (O)

Solubility = the maximum dissolved quantity of a pollutant in pure water at a given temperature.

Log K_{ow} = octanol/water partition coefficient is the ratio of a compounds concentration in the octanol phase to its concentration in the aqueous phase of a two-phase system. Low Kow values (<10) are considered hydrophilic and tend to have higher water solubility. High Kow values (>104) are very hydrophobic.

K_d = soil/water distribution coefficient. The amount of a chemical adsorbed by a sediment or soil (i.e., the solid phase) divided by the amount of test chemical in the solution phase, which is in equilibrium with the solid phase, at a fixed solid/solution ratio.

K_{oc} = soil/water distribution coefficient. Koc is a measure of the tendency for organic chemicals to be adsorbed to the soil. The higher the Koc value for each compound, the lower the mobility and the higher the adsorption.

Vapor Pressure = pressure exerted by a vapor in equilibrium with the solid or liquid phase of the same substance.

Mobility Ranking = from EPA's SCDM (reference 1). Value used where available; based on solubility and the soil/water distribution coefficient to determine the relative groundwater mobility factor.

Mobility of Pollutant = used in the UIC prioritization procedure to conservatively (assumes no dilution and/or degration) estimate the mobility of stormwater pollutants discharged to a UIC (i.e., through soil) to have adverse impacts on groundwater quality.

Table 15. Summary of Municipal Well Groundwater Analytical Data[1]

City of Redmond, Oregon

Analyte	Period of Record	No. Samples	No. Detections	MCL (mg/L)	Range (mg/L)	Comments
			City of Redmond Well #1			
PCP	1993 - 2008	10	0	0.001	--	--
Toluene	1993 - 2008	7	0	1	--	--
2,4-D	1984 - 2008	11	0	0.07	--	--
Lead	1985 - 2002	7	4	0.015	ND - 0.005	Detections occurred on 5/31/1985, 8/12/1986, 8/11/1988, and 8/21/1991
Naphthalene	--	--	--	--	--	--
Copper	1995	1	0	1.3	--	--
DEHP	1993 - 2008	10	0	0.006	--	--
Benzo(a)pyrene	1993 - 2008	10	0	0.0002	--	--
			City of Redmond Well #2			
PCP	1993 - 2008	10	0	0.001	--	--
Toluene	1993 - 2008	7	0	1	--	--
2,4-D	1993 - 2008	10	0	0.07	--	--
Lead	1988 - 2002	4	2	0.015	ND - 0.005	Detections occurred on 8/11/1988 and 8/21/1991
Naphthalene	--	--	--	--	--	--
Copper	--	--	--	--	--	--
DEHP	1993 - 2010	14	1	0.006	ND - 0.0025	Detection occurred on 10/14/2008
Benzo(a)pyrene	1993 - 2009	11	0	0.0002	--	--
			City of Redmond Well #3			
PCP	1993 - 2008	11	0	0.001	--	--
Toluene	1993 - 2008	8	0	1	--	--
2,4-D	1993 - 2008	11	0	0.07	--	--
Lead	1987 - 2002	4	1	0.015	ND - 0.002	Detection occurred on 8/3/1990
Naphthalene	--	--	--	--	--	--
Copper	1987 - 1990	2	0	1.3	--	--
DEHP	1993 - 2008	11	0	0.006	--	--
Benzo(a)pyrene	1993 - 2009	11	0	0.0002	--	--
			City of Redmond Well #4			
PCP	1993 - 2008	11	0	0.001	--	--
Toluene	1989 - 2008	9	1	1	ND - 0.0005	Detection occurred on 6/13/1989
2,4-D	1993 - 2008	11	0	0.07	--	--
Lead	1988 - 2002	4	1	0.015	ND - 0.005	Detection occurred on 8/11/1988
Naphthalene	--	--	--	--	--	--
Copper	--	--	--	--	--	--
DEHP	1993 - 2008	11	0	0.006	--	--
Benzo(a)pyrene	1993 - 2009	11	0	0.0002	--	--
			City of Redmond Well #5			
PCP	1998 - 2008	8	0	0.001	--	--
Toluene	1998 - 2008	5	0	1	--	--
2,4-D	1998 - 2008	8	0	0.07	--	--
Lead	1999 - 2002	2	0	0.015	--	--
Naphthalene	--	--	--	--	--	--
Copper	--	--	--	--	--	--
DEHP	1998 - 2008	8	0	0.006	--	--
Benzo(a)pyrene	1998 - 2008	8	0	0.0002	--	--
			City of Redmond Well #6			
PCP	2006 - 2008	3	0	0.001	--	--
Toluene	2006 - 2008	2	0	1	--	--
2,4-D	2006 - 2008	3	0	0.07	--	--
Lead	2006 - 2009	2	0	0.015	--	--
Naphthalene	--	--	--	--	--	--
Copper	--	--	--	--	--	--
DEHP	2006 - 2008	3	0	0.006	--	--
Benzo(a)pyrene	2006 - 2008	3	0	0.0002	--	--
			City of Redmond Well #7			
PCP	2006 - 2009	3	0	0.001	--	--
Toluene	2006 - 2009	2	0	1	--	--
2,4-D	2006 - 2009	3	0	0.07	--	--
Lead	2006 - 2009	2	0	0.015	--	--
Naphthalene	--	--	--	--	--	--
Copper	--	--	--	--	--	--
DEHP	2006 - 2009	3	0	0.006	--	--
Benzo(a)pyrene	2009 - 2008	3	0	0.0002	--	--

Notes

[1] Data source is Department of Human Services (DHS) SDWIS Data, http://170.104.63.9/namelook.php, accessed June 21, 2011.

MCL = maximum contaminant level

PCP = pentachlorophenol

DEHP = di(2-ethylhexyl)phthalate

mg/L = milligrams per liter

Appendices

Appendix A

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Technical Memorandum

Prepared for: GSI Water Solutions

Project Title: Cities of Bend and Redmond
Underground Injection Control (UIC) Risk Evaluation and System-Wide Assessment

Project No: 140776

Technical Memorandum

Subject: Annual Stormwater Runoff Recharge to UICs

Date: May 10, 2011

To: Matthew Kohlbecker, R.G., GSI Water Solutions, Inc.

From: Krista Reininga, P.E., Brown and Caldwell
Andy Thayumanavan, Brown and Caldwell

Introduction

To provide information to support GSI Water Solutions' (GSI) UIC Risk Evaluation for the cities of Bend and Redmond, Brown and Caldwell was tasked with developing estimates of the average annual recharge (i.e., stormwater runoff volumes) to city UICs. The purpose of this technical memorandum (TM) is to describe the data and methods used to develop the estimate. Varying levels of analysis can be used to estimate runoff volumes, from complex hydrologic models that incorporate detailed information regarding soil and temperature conditions, to more simple spreadsheets that calculate runoff based on rainfall, land use, runoff coefficients, and drainage areas. For this project, the latter simpler method was chosen. In addition, a decision was made to make conservative assumptions when choosing spreadsheet input parameters for these calculations. This TM provides a summary of spreadsheet input data used to estimate runoff volumes including rain gauge data, drainage areas by land use, and runoff coefficients for the cities of Bend and Redmond.

Study Area and Land Use

The study areas for this analysis include both the cities of Bend and Redmond. Bend encompasses an area of approximately 33 square miles and Redmond encompasses an area of approximately 16 square miles. Land use-based zoning data for both cities was provided by GSI. The zoning data were used to divide the total city into drainage areas of specific land uses. The drainage areas and associated land uses are summarized in Table 1 for Bend and Table 2 for Redmond. Using zoning data to estimate runoff volumes is a conservative assumption because vacant areas are represented in the calculations as they are zoned for future build-out.

Table 1. City of Bend Zoning

Zoning category	Area, acres
Central Business District	58.63
Commercial Convenience	107.35
Commercial General	831.27
Commercial Limited	655.07
Commercial Neighborhood	1.06
Industrial General	209.01
Industrial Light	1536.79
Industrial Park	37.68
Mixed Employment	121.00
Mixed Riverfront	274.63
Public Facilities	467.19
Professional Office	9.55
Professional Office/Residential Urban Medium Density/ Residential Suburban Standard Density	7.88
Residential Urban High Density	337.48
Residential Urban Low Density	2,185.45
Residential Urban Medium Density	1,552.31
Residential Urban Standard Density	12,361.69

Table 1. City of Bend Zoning	
Zoning category	Area, acres
Surface Mining	105.08
Residential Suburban Low Density	37.58
Urban Area Reserve	409.20
Total Area	21,306

Table 2. City of Redmond Zoning	
Zoning category	Area, acres
Airport	1,469.11
Strip Service Commercial	634.31
Central Business District Commercial	237.83
Special Service Commercial	74.08
Limited Service Commercial	62.94
Tourist Commercial	84.78
Fairgrounds	321.12
Light Industrial	1,122.27
Heavy Industrial	625.38
Open Space Park Reserve	1,014.94
Parks	125.02
Public Facility	320.76
Limited Residential	412.12
Limited Residential	863.21
Limited Residential	628.94
Limited Residential	1.17
General Residential	1,632.53
High Density Residential	432.78
Urban Holding	387.57
Total Area	10,450.86

Gauge Selection and Rainfall Records

Selection of a suitable rainfall gauge is a necessary step in the process of estimating runoff. Gauge selection often depends on the type of rainfall data (hourly, daily, etc.) required, period of record, and general proximity to the study area. Rainfall gauges found to be located within the study area were considered in order to estimate runoff volumes for the cities of Bend and Redmond. The focus of conducting the rain gauge review was on obtaining accurate estimates of average annual rainfall; therefore, an emphasis was placed on finding gauges with robust long-term historical summaries and less emphasis was placed on obtaining hourly data. Another important consideration in the selection of rain gauges was related to rainfall variability across the city due to possible orographic and other effects. Our evaluation indicated that gauges from the west side of Bend recorded higher average annual rainfall depths than those from the east side of Bend. However, the difference was relatively small at approximately 0.56 inches. Therefore, annual average precipitation from the west side gauge was selected to provide conservative representation of rainfall for the whole city. For the city of Redmond, the rainfall variability across the city was found to be very minimal (i.e., approximately 0.14 inches) and therefore had no effect on rain gauge selection. The source of information used to obtain rainfall data was the Western Regional Climate Center (WRCC). The WRCC is one of six regional climate centers in the U.S. administered by the National Oceanic and Atmospheric Administration (NOAA). Specific oversight is provided by the National Climatic Data Center of the National Environmental Satellite, Data, and Information Service. The mission of the WRCC is to disseminate high quality climate data and information pertaining to the western U.S.; foster better use of this information in decision-making; conduct applied research related to climate issues; and improve the coordination of climate-related activities at state, regional, and national scales. Given the recognized reliability of NOAA climate data, WRCC was considered to be an excellent source of statistical rain gauge summaries for areas within western U.S. Five of the WRCC gauges are located in Bend and Redmond and are summarized in Table 3.

Data in Table 3 show that for both Bend and Redmond there is not much difference among gauges within each city in terms of their locations and elevations. Therefore, gauge selections were based on two other important criteria: 1) which gauge had a longer period of record, and 2) which gauge had a higher average annual rainfall depth to get a conservative estimate of runoff volume.

Table 3. WRCC Rain Gauge Information for the Cities of Bend and Redmond

City	Rain gauge name (ID)	Elevation, feet	Latitude, ddmm	Longitude, dddmm	Average annual rainfall, inches	Maximum annual depth, inches	Period of record		Total years
							Start	End	
Bend	Bend (350694)	3,600	4404	12119	11.94	25.75	04/01/1901	12/31/2010	110
	Bend 7 NE (350699)	3,360	4407	12113	9.52	12.64	05/01/1991	01/01/2011	20
Redmond	Redmond 2W (357052)	3,010	4416	12113	8.28	13.99	04/07/1911	03/31/1980	69
	Redmond 1 SSE (357056)	3,020	4416	12110	10.36	13.44	05/01/1980	06/30/1989	9
	Redmond FAA AP (357062)	3,060	4416	12109	8.63	12.41	07/01/1948	12/31/2010	62

To select rainfall data for use in estimating average annual runoff to UICs, Bend gauge 350694 was chosen, given the length of the record and higher (conservative) rainfall depth. For Redmond, Redmond FAA AP 357062 was selected because it has a comparable period of record with Redmond 2W 357052 and it provides the more conservative estimate of average annual rainfall. Based on these gauge selections, an average annual rainfall of 11.94 inches was used to calculate runoff volumes for Bend and an average annual rainfall of 8.63 inches was used to calculate runoff volumes for Redmond in order to estimate annual recharge to the cities' UICs.

Additionally, maximum annual depths were obtained for each city from the WRCC. These are provided in Table 3.

Runoff Coefficient Estimates

To estimate runoff into UICs, runoff coefficients are needed to estimate the amount/portion of rainfall that actually runs over land (i.e., does not evaporate or infiltrate into the ground) into UICs. The following U.S. Environmental Protection Agency runoff coefficient formula was used to estimate runoff coefficients for each land use:

$$Rc = 0.9 * \%IMP + 0.05$$

where:

Rc = runoff coefficient
%IMP = average percent imperviousness for a specific land use

The average percent impervious values for different land use categories were obtained from the *Central Oregon Stormwater Manual (COSM)* (Central Oregon Intergovernmental Council, 2007) and are provided in Table 4.

Table 4. Land Use Categories and Average Percent Imperviousness

Land use	Percent impervious
Commercial	85
Industrial	72
High Density Residential	65
Medium Density Residential	38
Low Density Residential	25
Open Space/Parks	15

Source: COSM

The land use categories in Tables 1 and 2 were each sorted and grouped according to the general land use categories identified in Table 4 to estimate their average percent imperviousness and hence their runoff coefficients using the equation above (see Tables 5 and 6 for resulting runoff coefficients).

Stormwater Runoff Volumes

The average annual stormwater runoff volume (i.e., recharge to UICs) was calculated for each land use category using the rational method according to the following formula:

$$V = Rc*I*A$$

Where:

V = average annual runoff volume
Rc = runoff coefficient
I = average annual precipitation depth
A = drainage area

Using the rainfall, drainage area, and runoff coefficient information from the previous sections, stormwater runoff volume estimates for the cities of Bend and Redmond were calculated using this formula and are provided in Tables 5 and 6, respectively.

Table 5. City of Bend Average and Maximum Annual Runoff Volume by Land Use			
Zoning category	Runoff coefficient	Average annual runoff volume, acre-feet	Maximum annual runoff volume, acre-feet
Central Business District	0.82	47.50	102.50
Commercial Convenience	0.82	87.10	187.70
Commercial General	0.82	674.10	1453.80
Commercial Limited	0.82	531.20	1145.60
Commercial Neighborhood	0.82	0.90	1.90
Industrial General	0.70	145.20	313.10
Industrial Light	0.70	1067.32	2301.79
Industrial Park	0.70	26.20	56.40
Mixed Employment	0.82	98.10	211.60
Mixed Riverfront	0.82	222.70	480.30
Public Facilities	0.82	378.90	817.00
Professional Office	0.82	7.70	16.70
Professional Office/Residential Urban Medium Density/ Residential Suburban Standard Density	0.39	3.10	6.60
Residential Urban High Density	0.64	213.20	459.90
Residential Urban Low Density	0.28	598.00	1289.60
Residential Urban Medium Density	0.39	605.50	1305.80
Residential Urban Standard Density	0.39	4821.60	10398.20
Surface Mining	0.70	73.00	157.40
Residential Suburban Low Density	0.28	10.30	22.20
Urban Area Reserve	0.19	75.30	162.40
Total		**9687**	**20891**

Table 6. City of Redmond Average and Maximum Annual Runoff Volume by Land Use			
Zoning Category	Runoff coefficient	Average annual runoff volume, acre-feet	Maximum annual runoff volume, acre-feet
Airport	0.82	861.1	1238.2
Strip Service Commercial	0.82	371.8	534.6
Central Business District Commercial	0.82	139.4	200.5
Special Service Commercial	0.82	43.4	62.4
Limited Service Commercial	0.82	36.9	53.0
Tourist Commercial	0.82	49.7	71.5
Fairgrounds	0.82	188.2	270.7
Light Industrial	0.70	563.4	810.1

Table 6. City of Redmond Average and Maximum Annual Runoff Volume by Land Use			
Zoning Category	Runoff coefficient	Average annual runoff volume, acre-feet	Maximum annual runoff volume, acre-feet
Heavy Industrial	0.70	313.9	451.4
Open Space Park Reserve	0.19	135.0	194.2
Parks	0.19	16.6	23.9
Public Facility	0.28	63.4	91.2
Limited Residential	0.28	81.5	117.2
Limited Residential	0.28	170.7	245.5
Limited Residential	0.28	124.4	178.9
Limited Residential	0.28	0.2	0.3
General Residential	0.39	460.2	661.8
High Density Residential	0.64	197.6	284.2
Urban Holding	0.82	227.2	326.7
Total		**4045**	**5816**

The estimates of average annual runoff volumes in Tables 5 and 6 provide an estimate of the average annual recharge to UICs in Bend and Redmond. In summary, these estimates are conservative based on the following assumptions:

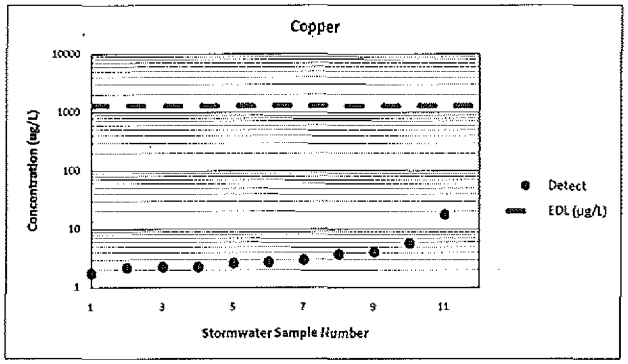
- WRCC rain gauges with the highest estimates of average annual rainfall were used to estimate runoff.
- Runoff coefficients are estimated to be conservative for Bend and Redmond given the porous soils and high evaporation rates.
- Land uses are based on zoning (future build-out) and do not account for the more pervious vacant areas that exist.
- An assumption was made that all areas of the cities drain to UICs when some smaller areas are know to be piped to drain directly to the Deschutes River. In addition, some runoff drains to private as opposed to public UICs.

References

OTAK, *Central Oregon Stormwater Manual*, May 2007

Western Regional Climate Center, http://www.wrcc.dri.edu/summary/Climsmor.html

Appendix B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1000
100
10
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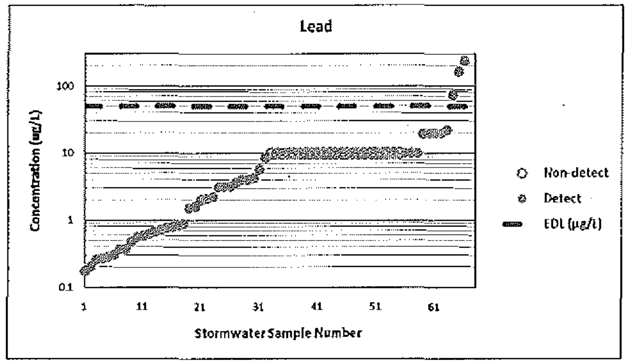
1
3
5
7
9
11
Stormwater Sample Number
Detect
EDL (µg/L)


Lead
Concentration (ug/L)
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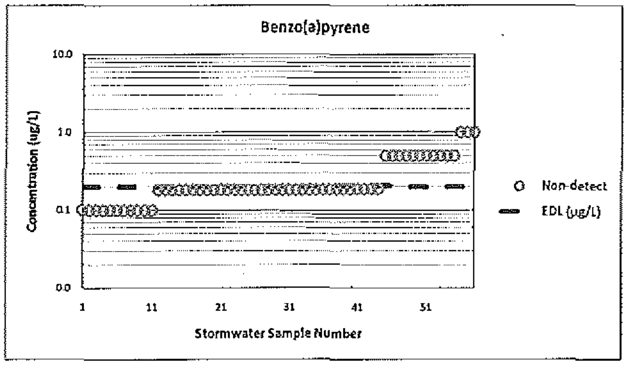
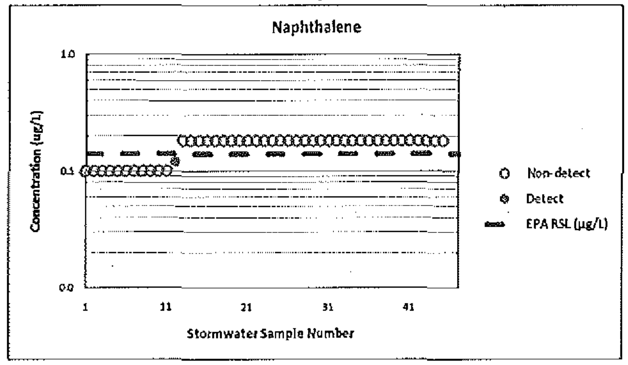
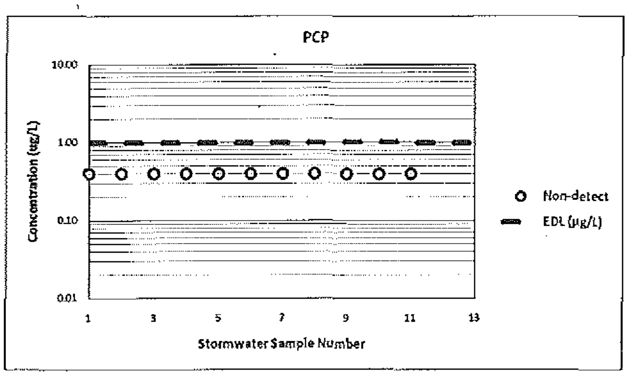
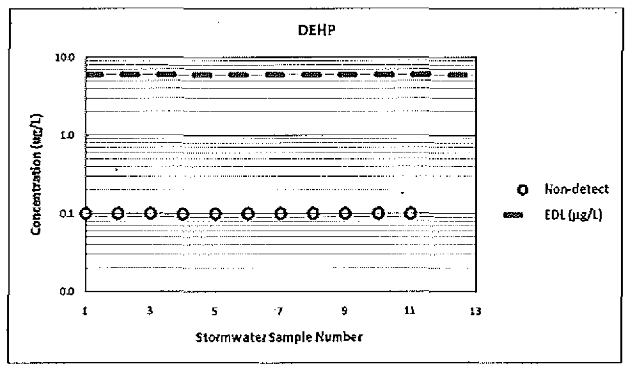
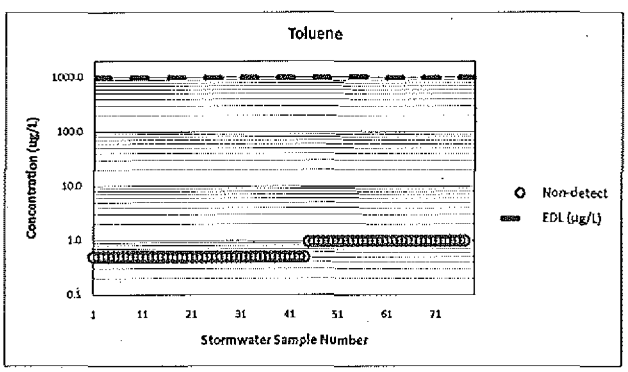
10
1
0.1
1
11
21
31
41
51
61
Stormwater Sample Number
Non-detect
Detect
EDL (µg/L)


Benzo(a)pyrene
Concentration (ug/L)
10.0
1.0
0.1
0.0
1
11
21
31
41
51
Stormwater Sample Number
Non-detect
EDL (µg/L)


Naphthalene
Concentration (ug/L)
1.0
0.1
0.0
1
11
21
31
41
Stormwater Sample Number
Non-detect
Detect
EPA RSL (µg/L)


PCP
Concentration (ug/L)
10.00
1.00
0.10
0.01
1
3
5
7
9
11
13
Stormwater Sample Number
Non-detect
EDL (µg/L)


DEHP
Concentration (ug/L)
10.0
1.0
0.1
0.0
1
3
5
7
9
11
13
Stormwater Sample Number
Non-detect
EDL (µg/L)


Toluene
Concentration (ug/L)
1000.0
100.0
10.0
1.0
0.1
1
11
21
31
41
51
61
71
Stormwater Sample Number
Non-detect
EDL (µg/L)

Appendix C

Appendix C
Pollutant Fate and Transport
Pollutant Attenuation After 5 Feet of Transport - City of Redmond

	Parameter	Symbol	Units	Metals				PAHs				SVOCs				Pesticides/ Herbicides		VOCs	
				Copper		Lead		Benzo(a)pyrene		Naphthalene		PCP		di-(2-ethylhexyl) phthalate		2,4-D		Toluene	
				Average Scenario	Reasonable Maximum Scenario	Average Scenario	Reasonable Maximum Scenario	Average Scenario	Reasonable Maximum Scenario	Average Scenario	Reasonable Maximum Scenario	Average Scenario	Reasonable Maximum Scenario	Average Scenario	Reasonable Maximum Scenario	Average Scenario	Reasonable Maximum Scenario	Average Scenario	Reasonable Maximum Scenario
UIC Properties	Distance Needed to Reach MRLs	y	m	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52
		y	ft	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
	Concentration	C_0	mg/L	1.30E+00 [1]	1.30E+00 [1]	5.00E-01 [2]	5.00E-01 [2]	2.00E-03 [2]	2.00E-03 [2]	1.00E-02 [3]	1.00E-02 [3]	1.00E-02 [2]	1.00E-02 [2]	6.00E-02 [2]	6.00E-02 [2]	7.00E-02 [1]	7.00E-02 [1]	1.00E+00 [1]	1.00E+00 [1]
	Infiltration Time	t	d	222 [4]	222 [4]	222 [4]	222 [4]	2.22 [5]	2.22 [5]	2.22 [5]	2.22 [5]	2.22 [5]	2.22 [5]	2.22 [5]	2.22 [5]	2.22 [5]	2.181 [6]	2.22 [5]	2.22 [5]
Chemical Properties	First-Order Rate Constant	k	d^{-1}					1.30E-03 [7]	2.60E-04 [8]	7.50E-02 [7]	2.50E-02 [8]	2.21E-02 [9]	1.39E-02 [10]	1.50E-02 [7]	1.00E-02 [8]	5.30E-03 [7]	2.20E-03 [8]	3.30E-01 [7]	8.20E-02 [8]
	Half-Life	h	d					533.2 [11]	2666.0 [11]	9.2 [11]	27.7 [11]	31.4 [11]	49.9 [11]	46.2 [11]	69.3 [11]	130.8 [11]	315.1 [11]	2.1 [11]	8.5 [11]
Physical and Chemical Soil Properties	Soil Porosity	η	-	0.375 [12]	0.375 [12]	0.375 [12]	0.375 [12]	0.375 [12]	0.375 [12]	0.375 [12]	0.375 [12]	0.375 [12]	0.375 [12]	0.375 [12]	0.375 [12]	0.375 [12]	0.375 [12]	0.375 [12]	0.375 [12]
	Soil Bulk density	ρ_b	g/cm³	1.66 [13]	1.66 [13]	1.66 [13]	1.66 [13]	1.66 [13]	1.66 [13]	1.66 [13]	1.66 [13]	1.66 [13]	1.66 [13]	1.66 [13]	1.66 [13]	1.66 [13]	1.66 [13]	1.66 [13]	1.66 [13]
	Fraction Organic Carbon	f_{oc}	-					0.007110 [14]	0.003568 [15]	0.007110 [14]	0.003568 [15]	0.007110 [14]	0.003568 [15]	0.007110 [14]	0.003568 [15]	0.007110 [14]	0.003568 [15]	0.007110 [14]	0.003568 [15]
	Organic Carbon Partition Coefficient	K_{oc}	L/kg					282,185 [16]	282,185 [16, 17]	1,300 [16]	830 [18]	410 [19]	410 [19]	12,200 [16]	12,200 [16, 17]	201 [20]	20 [21]	162 [22]	37 [23]
	Distribution Coefficient	K_d	L/kg	71,300 [24]	58,000 [25]	230,000 [24]	157,000 [25]	2,006 [26]	1,007 [26]	9.2 [26]	3.0 [26]	2.9 [26]	1.5 [26]	86.7 [26]	43.5 [26]	1.4 [26]	0.070 [26]	1.2 [26]	0.13 [26]
	Pore Water Velocity	v	m/d	0.64 [27]	0.91 [28]	0.64 [27]	0.91 [28]	0.64 [27]	0.91 [28]	0.64 [27]	0.91 [28]	0.64 [27]	0.91 [28]	0.64 [27]	0.91 [28]	0.64 [27]	0.91 [28]	0.64 [27]	0.91 [28]
Calculations	Retardation Factor	R	-	314,909	256,168	1,015,834	693,418	8,862	4,448	42	14.1	13.9	7.5	384	193	7.3	1.3	6.1	1.6
	Dispersion Coefficient	D	m²/d	4.88E-02	6.96E-02	4.88E-02	6.96E-02	4.88E-02	6.96E-02	4.88E-02	6.96E-02	4.88E-02	6.96E-02	4.88E-02	6.96E-02	4.88E-02	6.96E-02	4.88E-02	6.96E-02
	Normalized Dispersion	D'	m²/d	1.55E-07	2.72E-07	4.80E-08	1.00E-07	5.50E-06	1.57E-05	1.17E-03	4.95E-03	3.51E-03	9.33E-03	1.27E-04	3.60E-04	6.67E-03	5.32E-02	8.01E-03	4.40E-02
	Normalized Velocity	V'	m/d	2.03E-06	3.57E-06	6.30E-07	1.32E-06	7.22E-05	2.05E-04	1.53E-02	6.49E-02	4.61E-02	1.23E-01	1.67E-03	4.73E-03	8.75E-02	6.98E-01	1.05E-01	5.77E-01
	Normalized Degradation	K'	d^{-1}	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.47E-07	5.85E-08	1.79E-03	1.78E-03	1.59E-03	1.86E-03	3.91E-05	5.17E-05	7.25E-04	1.68E-03	5.42E-02	5.18E-02
	A_1	-	-	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-3.00E-03	-4.33E-04	-1.77E-01	-4.16E-02	-6.25E-02	-2.31E-02	-3.57E-02	-1.67E-02	-1.26E-02	-3.67E-03	-7.57E-01	-1.36E-01
	A_2	-	-	1.30E+02	9.80E+01	2.33E+02	1.61E+02	2.18E+02	1.29E+02	1.40E+01	6.58E+00	8.04E+00	4.35E+00	4.53E+01	2.68E+01	5.46E+00	4.73E-04	4.77E+00	3.60E-01
	e^{A1}	-	-	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.97E-01	1.00E+00	8.38E-01	9.59E-01	9.49E-01	9.77E-01	9.65E-01	9.83E-01	9.87E-01	9.96E-01	4.69E-01	8.73E-01
	$erfc(A_2)$	-	-	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.91E-10	0.00E+00	0.00E+00	1.12E-14	9.99E-01	1.49E-11	6.11E-01
	B_1	-	-	2.00E+01	2.00E+01	2.00E+01	2.00E+01	2.00E+01	2.00E+01	2.02E+01	2.00E+01	2.01E+01	2.00E+01	2.00E+01	2.00E+01	2.00E+01	2.00E+01	2.08E+01	2.01E+01
	B_2	-	-	1.30E+02	9.81E+01	2.33E+02	1.61E+02	2.18E+02	1.29E+02	1.53E+01	7.96E+00	9.21E+00	6.24E+00	4.55E+01	2.71E+01	7.06E+00	4.47E+00	6.65E+00	4.52E+00
	e^{B1}	-	-	4.85E+08	4.85E+08	4.85E+08	4.85E+08	4.87E+08	4.85E+08	5.79E+08	5.06E+08	5.11E+08	4.97E+08	5.03E+08	4.93E+08	4.91E+08	4.87E+08	1.03E+00	5.56E+08
	$erfc(B_2)$	-	-	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.52E-10	0.00E+00	1.68E-10
	Concentration at Distance	C	mg/L	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.87E-12	0.00E+00	0.00E+00	3.88E-16	3.01E-02	3.49E-12	3.14E-01
Regulatory Standards	MRLs		mg/L	2.00E-04 [29]		1.00E-04 [29]		1.00E-05 [29]		2.00E-05 [29]		4.00E-05 [29]		1.00E-03 [29]		1.00E-04 [29]		5.00E-04 [29]	
	EDLs		mg/L	1.30E+00 [30]		5.00E-02 [30]		2.00E-04 [30]		NA		1.00E-03 [30]		6.00E-03 [30]		7.00E-02 [30]		1.00E+00 [30]	
Observed Concentration [31]		C	mg/L	4.40E-03		1.19E-02		No Detections		8.16E-05		No Detections		No Detections		No Available Data		No Detections	
Ratio of Observed Concentration : Input Concentration		-	-	0.0034		0.0238		No Detections		0.0082		No Detections		No Detections		No Available Data		No Detections	

NOTES
[1] Input concentration equal to the effluent discharge limit (EDL) in the Underground Injection Control (UIC) Water Pollution Control Facility (WPCF) Municipal Stormwater Template.
[2] Input concentration equal to 10 times the effluent discharge limit (EDL) in the Underground Injection Control (UIC) Water Pollution Control Facility (WPCF) Municipal Stormwater Template.
[3] The input concentration for naphthalene, which does not have an EDL in the UIC WPCF Municipal Stormwater Template, is about 0.05% of its solubility in water at 10.0 degrees Celsius (Bohon and Claussen, 1951).
[4] In Redmond, water infiltrates into UICs for a total of 2.22 days (see note 5). Because metals do not degrade over time, the metals' infiltration time allows for 100 years of metals transport. Specifically, 2.22 days of infiltration per year * 100 years = 222 days of infiltration.
[5] In Redmond, water is assumed to infiltrate into UICs for a total of 2.22 days. This infiltration time was determined by assuming that infiltration occurs when precipitation rate is equal to or exceeds 0.04 inches per hour, and summing the total hours in the year that precipitation rate is equal to or exceeded 0.04 inches per hour based on data from 2002 and 2008 (Redmond rain gage 357062). The geometric mean infiltration time from 2002 through 2008 of 53 hours (2.22 days) was used in the model.
[6] Infiltration time is shorter than 2.22 days because the maximum pollutant concentration immediately above the water table occurred prior to the maximum number of days that stormwater infiltrates into the UIC (reaches steady-state).
[7] Median biodegradation rate from a review of scientific literature (see text for references).
[8] 25th percentile biodegradation rate from a review of scientific literature (see text for references).
[9] 10 percent of the average biodegradation rate of PCP under aerobic conditions from studies by Schmidt et al. (1999) and D'Angelo and Reddy (2000).
[10] 10 percent of the minimum biodegradation rate of PCP under aerobic conditions from studies by Schmidt et al. (1999) and D'Angelo and Reddy (2000).
[11] Calculated from the following formula: $C_t = C_0 e^{-kt}$, where C_t is concentration at time t, C_0 is initial concentration, t is time, and k is biodegradation rate.
[12] Porosity of material infilling fractured rock beneath the UIC. Because typical fracture widths in basalt are 0.14 mm (Lindberg, 1989, measurements from the Columbia River Basalt Group), we assume that the infilling material would be fine sand-sized (0.075 mm to 0.42 mm, Table 4.2, pg. 84 of Fetter, 1994). Therefore, typical
[13] Calculated by formula 8.26 in Freeze and Cherry (1979): $\rho_b = 2.65(1-\eta)$.
[14] Estimate of f_{oc} based on accumulation of TOC in stormwater around the UIC; see text for description.
[15] Reasonable maximum scenario is conservatively 1/2 of the average scenario estimate of f_{oc} based on accumulation of TOC in stormwater around the UIC; see text for description.
[16] Calculated from the equation of Roy and Griffin (1985), which relates K_{oc} to water solubility and K_{ow}, as presented in Fetter (1994).
[17] Because the K_{oc}s reported in field studies were all higher than K_{oc}s calculated from K_{ow} (i.e., field-study K_{oc}s were less conservative), the reasonable maximum scenario uses the K_{oc} calculated by Roy and Griffin (1985)
[18] The lowest K_{oc} reported for Naphthalene in the EPA (1996) review of n = 20 Naphthalene K_{oc}s from field-testing. The range of K_{oc} was 830 L/kg - 1,950 L/kg.

[19] The K_{oc} for Pentachlorophenol is pH-dependent. Soil and groundwater pH are in equilibrium; therefore, soil pH can be estimated from groundwater pH. pH has been measured at City of Redmond municipal wells 4,5 and 6 (the shallowest city wells), and ranged from 7.93 to 8.17. The average groundwater pH in Redmond is 8.01, which corresponds with a Koc of 410 L/kg.

[20] Calculated from equation (71) in EPA (1996), which relates Koc to Kow for certain chlorinated pesticides. The Kow was taken from EPA (2008a).

[21] The lowest K_{oc} reported for 2,4-D acid in EPA (2010a). The range of K_{oc} is 20.0 to 109.1 L/kg.

[22] Calculated from equation (71) in EPA (1996), which relates Koc to Kow for VOCs, chlorobenzenes, and certain chlorinated pesticides. The log Kow for Toluene (2.69) was taken from EPA (2010c)

[23] The lowest K_{oc} reported for Toluene in EPA (2010c). The range of K_{oc} was 37 - 178 L/kg.

[24] Median K_d for copper or lead, calculated using site-specific data and an equation from Brickner (1998), based on City of Bend 2011 stormwater sampling.

[25] Minimum K_d for copper or lead, calculated using site-specific data and an equation from Brickner (1998), based on City of Bend 2011 stormwater sampling.

[26] K_d calculated from the following equation: $Kd = (f_{oc})(K_{oc})$ (e.g., Watts, pg. 279, 1998). We conservatively assume that sorption only occurs on the sedimentary material infilling the fractures, and no sorption occurs on fracture faces.

[27] Hydraulic conductivity calculated using the pump-in method at 90 UICs in the City of Redmond. The pump-in method is outlined in USDI (pgs. 83 - 95, 1993), and is discussed in more detail in the text. The median hydraulic conductivity of the Quaternary Basalt and Andesite geologic unit (i.e., the most permeable geologic unit that UICs and drillholes are completed in) was conservatively used.

[28] Hydraulic conductivity calculated using the pump-in method at 90 UICs in the City of Redmond. The pump-in method is outlined in USDI (pgs. 83 - 95, 1993), and is discussed in more detail in the text. The hydraulic conductivity of the Quaternary Basalt and Andesite geologic unit (i.e., the most permeable geologic unit that UICs and drillholes are completed in) was conservatively used. The 95% UCL on the mean is typically used for the reasonable maximum transport scenario, but the maximum was used because only 5 pump-in tests were conducted in the Quaternary Basalt and Andesite, which is not a large enough sample size to calculate a 95% UCL on the mean.

[29] MRLs based on typically achieveable method reporting limits during storm water sampling in Oregon. Samples analyzed were collected during 2007-2011.

[30] EDLs from the UIC WPCF Municipal Stormwater Template.

[31] Average observed concentration of stormwater data collected during the Redmond 2007 – 2010 stormwater sampling event. Where data were non-detects, ½ the detection limit of the specific sample analysis was used for calculating the average.

ABBREVIATIONS

PAHs = Polynuclear Aromatic Hydrocarbons	USGS = United States Geological Survey	MRL = Method Reporting Limit	m = meters
SVOCs = Semi-Volatile Organic Compounds	EPA = Environmental Protection Agency	TOC = Total Organic Carbon	m/d = meters per day
VOCs = Volatile Organic Compounds	UIC = Underground Injection Control	d = days	m^2/d = square meters per day
PCP = Pentachlorophenol	UCL = Upper Confidence Level	g/cm^3 = grams per cubic centimeter	mg/L = milligrams per liter

Appendix D

APPENDIX D

Separation Distance Necessary to Meet MRLs

City of Redmond, Oregon

Pollutant	MRL (ug/L)	COMPUTED DISTANCE TO MEET MRLs								
		Input Concentration = Average of Stormwater Data			Input Concentration = EDL			Input Concentration = Redmond Proposed EDLs		
		Input Concentration (ug/L)	Distance Under Average Scenario (feet)	Distance Under Reasonable Maximum Scenario (feet)	Input Concentration (ug/L)	Distance Under Average Scenario (feet)	Distance Under Reasonable Maximum Scenario (feet)	Input Concentration (ug/L)	Distance Under Average Scenario (feet)	Distance Under Reasonable Maximum Scenario (feet)
Copper	0.2	4.40	0.0026	0.0046	1,300	0.005	0.008	1,300	0.005	0.008
Lead	0.1	11.89	0.0010	0.0021	50	0.001	0.002	500	0.001	0.003
Benzo(a)pyrene	0.01	No Detections			0.2	0.001	0.003	2	0.001	0.003
PCP (pH=8.01)	0.04	No Detections			1	0.604	1.603	10	0.786	2.088
DEHP	1.0	No Detections			6	0.017	0.049	60	0.024	0.069
2,4-D	0.1	No Available Data			70	1.639	13.075	70	1.639	13.075
Toluene	0.5	No Detections			1,000	2.126	11.682	1,000	2.126	11.682

ASSUMPTIONS

1) 100 years of pollutant transport simulated for metals. In Bend, UICs discharge water into the subsurface 3.9 days each year for 100 years = 390 days of transport. In Redmond, UICs discharge water into the subsurface 2.2 days each year for 100 years = 222 days of transport.

2) Input concentrations are equal to the average concentration of stormwater data collected by each City, the EDL, or 10x the EDL. Where there were non detects, 1/2 the detection limit was used for calculating the average. Because naphthalene does not have an EDL in the draft UIC WPCF Permit, the EPA Regional Screening Level was used.

3) All input parameters based on data from the City of Bend and City of Redmond (with the exception of metals transport parameters, which are based on Portland data).

4) Median vertical hydraulic conductivity of the Quaternary basalt and andesite is used for velocity.

Appendix E

Appendix E
Pollutant Fate and Transport
Pollutant Attenuation After 14 Feet of Transport - City of Redmond

	Parameter	Symbol	Units	Pesticides/ Herbicides		VOCs	
				2,4-D		Toluene	
				Average Scenario	Reasonable Maximum Scenario	Average Scenario	Reasonable Maximum Scenario
UIC Properties	Distance Needed to Reach	y	m	4.27	4.27	4.27	4.27
	MRLs	y	ft	14.00	14.00	14.00	14.00
	Concentration	C_0	mg/L	7.00E-02 [1]	7.00E-02 [1]	1.00E+00 [1]	1.00E+00 [1]
	Infiltration Time	t	d	2.22 [2]	2.22 [2]	2.22 [2]	2.22 [2]
Chemical Properties	First-Order Rate Constant	k	d^{-1}	5.30E-03 [3]	2.20E-03 [4]	3.30E-01 [3]	8.20E-02 [4]
	Half-Life	h	d	130.8 [5]	315.1 [5]	2.1 [5]	8.5 [5]
Physical and Chemical Soil Properties	Soil Porosity	n	-	0.375 [6]	0.375 [6]	0.375 [6]	0.375 [6]
	Soil Bulk density	ρ_b	g/cm^3	1.66 [7]	1.66 [7]	1.66 [7]	1.66 [7]
	Fraction Organic Carbon	f_{oc}	-	0.007110 [8]	0.003555 [9]	0.007110 [8]	0.003555 [9]
	Organic Carbon Partition Coefficient	K_{oc}	L/kg	201 [10]	20 [11]	162 [12]	37 [13]
	Distribution Coefficient	K_d	L/kg	1.4 [14]	0.070 [14]	1.2 [14]	0.13 [14]
	Pore Water Velocity	v	m/d	0.64 [15]	0.91 [15]	0.64 [15]	0.91 [15]
Calculations	Retardation Factor	R	-	7.3	1.3	6.1	1.6
	Dispersion Coefficient	D	m^2/d	1.37E-01	1.95E-01	1.37E-01	1.95E-01
	Normalized Dispersion	D'	m^2/d	1.87E-02	1.49E-01	2.24E-02	1.23E-01
	Normalized Velocity	v'	m/d	8.75E-02	6.98E-01	1.05E-01	5.77E-01
	Normalized Degradation	k'	d^{-1}	7.25E-04	1.68E-03	5.42E-02	5.18E-02
	A_1	-	-	-3.53E-02	-1.03E-02	-2.00E+00	-3.76E-01
	A_2	-	-	1.00E+01	2.30E+00	8.93E+00	2.61E+00
	e^{A1}	-	-	9.65E-01	9.90E-01	1.35E-01	6.87E-01
	$erfc(A_2)$	-	-	0.00E+00	8.43E-04	0.00E+00	7.14E-05
	B_1	-	-	2.00E+01	2.00E+01	2.20E+01	2.04E+01
	B_2	-	-	1.10E+01	5.06E+00	1.02E+01	5.35E+00
	e^{B1}	-	-	5.03E+08	4.90E+08	3.59E+09	7.06E+08
	$erfc(B_2)$	-	-	0.00E+00	8.41E-13	0.00E+00	3.79E-14
	Concentration at Distance	C	mg/L	0.00E+00	4.36E-05	0.00E+00	3.79E-05
Regulatory Standards	MRLs		mg/L	1.00E-04 [17]		5.00E-04 [17]	
	EDLs		mg/L	7.00E-02 [18]		1.00E+00 [18]	
Observed Concentration [19]		C	mg/L	No Available Data		No Detections	
Ratio of Observed Concentration : Input Concentration		-	-	No Available Data		No Detections	

NOTES

[1] Input concentration equal to the effluent discharge limit (EDL) in the Underground Injection Control (UIC) Water Pollution Control Facility (WPCF) Municipal Stormwater Template.

[2] In Redmond, water is assumed to infiltrate into UICs for a total of 2.22 days. This infiltration time was determined by assuming that infiltration occurs when precipitation rate is equal to or exceeds 0.04 inches per hour, and summing the total hours in the year that precipitation rate is equal to or exceeded 0.04 inches per hour based on data from 2002 and 2008 (Redmond rain gage 357062). The geometric mean infiltration time from 2002 through 2008 of 53 hours (2.22 days) was used in the model.

[3] Median biodegradation rate from a review of scientific literature (see text for references).

[4] 25th percentile biodegradation rate from a review of scientific literature (see text for references).

[5] Calculated from the following formula: $C_t = C_0e^{-kt}$, where C_t is concentration at time t, C_0 is initial concentration, t is time, and k is biodegradation rate.

[6] Porosity of material infilling fractured rock beneath the UIC. Because typical fracture widths in basalt are 0.14 mm (Lindborg, 1989, measurements from the Columbia River Basalt Group), we assume that the infilling material would be fine sand-sized (0.075 mm to 0.42 mm, Table 4.2, pg. 84 of Fetter, 1994). Therefore, typical porosity of a sand (0.375) from Freeze and Cherry (1979), page 37, Table 2.4 is used in this analysis.

[7] Calculated by formula 8.26 in Freeze and Cherry (1979): $\rho_b = 2.65(1-n)$.

[8] Estimate of f_{oc} based on accumulation of TOC in stormwater around the UIC; see text for description .

[9] Reasonable maximum scenario is conservatively 1/2 of the average scenario estimate of f_{oc} based on accumulation of TOC in stormwater around the UIC; see text for description .

[10] Calculated from the equation of Roy and Griffin (1985), which relates K_{oc} to water solubility and K_{ow}, as presented in Fetter (1994).

[11] Because the K_{oc}s reported in field studies were all higher than K_{oc}s calculated from K_{ow} (i.e., field-study K_{oc}s were less conservative), the reasonable maximum scenario uses the K_{oc} calculated by Roy and Griffin (1985)

[12] The lowest K_{oc} reported for Naphthalene in the EPA (1996) review of n = 20 Naphthalene K_{oc}s from field-testing. The range of K_{oc} was 830 L/kg - 1,950 L/kg.

[13] The K_{oc} for Pentachlorophenol is pH-dependent. Soil and groundwater pH are in equilibrium; therefore, soil pH can be estimated from groundwater pH. pH has been measured at city of Redmond municipal wells 4,5 and 6 (the shallowest city wells), and ranged from 7.93 to 8.17. The average groundwater pH in Redmond is 8.01, which corresponds with a Koc of 410 L/kg.

[14] K_d calculated from the following equation: $Kd = (f_{oc})(K_{oc})$ (e.g., Watts, pg. 279, 1998). We conservatively assume that sorption only occurs on the sedimentary material infilling the fractures, and no sorption occurs on fracture faces.

[15] Hydraulic conductivity calculated using the pump-in method at 90 UICs in the City of Redmond. The pump-in method is outlined in USDI (pgs. 83 - 95, 1993), and is discussed in more detail in the text. The hydraulic conductivity of the Quaternary Basalt and Andesite geologic unit (i.e., the most permeable geologic unit that UICs and drillholes are completed in) was conservatively used.

[16] Hydraulic conductivity calculated using the pump-in method at 90 UICs in the City of Redmond. The pump-in method is outlined in USDI (pgs. 83 - 95, 1993), and is discussed in more detail in the text. The hydraulic conductivity of the Quaternary Basalt and Andesite geologic unit (i.e., the most permeable geologic unit that UICs and drillholes are completed in) was conservatively used. (The 95% UCL on the mean is typically used for the reasonable maximum transport scenario, but the maximum was used because only 5 pump in tests were conducted in the Quaternary Basalt and Andesite, which is not a large enough sample size to calculate a 95% UCL on the mean).

[17] MRLs based on typically achievable method reporting limits during storm water sampling in Oregon. Samples analyzed were collected during 2007-2011.

[18] EDLs from the UIC WPCF Municipal Stormwater Template.

[19] Average observed concentration of stormwater data collected during the Redmond 2007 – 2010 stormwater sampling event. Where data were non-detects, ½ the detection limit of the specific sample analysis was used for calculating the average.

ABBREVIATIONS

PAHs = Polynuclear Aromatic Hydrocarbons	USGS = United States Geological Survey	MRL = Method Reporting Limit	m = meters
SVOCs = Semi-Volatile Organic Compounds	EPA = Environmental Protection Agency	TOC = Total Organic Carbon	m/d = meters per day
VOCs = Volatile Organic Compounds	UIC = Underground Injection Control	d = days	m^2/d = square meters per day
PCP = Pentachlorophenol	UCL = Upper Confidence Level	g/cm^3 = grams per cubic centimeter	mg/L = milligrams per liter

City of Redmond UICs within 500' Radius or 2 yr Time of Travel

UIC Number	UIC Type
UIC0108	Drillhole
UIC0109	Drillhole
UIC0118	Drillhole
UIC0120	Drywell
UIC0121	Drywell
UIC0122	Drywell
UIC0122c	Drillhole
UIC0136	Drywell
UIC0160	Drywell
UIC0163	Drywell
UIC0166	Drywell
UIC0166c	Drillhole
UIC0167	Drywell
UIC0168	Drywell
UIC0169	Drywell
UIC0170	Drywell
UIC0171	Drywell
UIC0174	Drywell
UIC0182	Drywell
UIC0187	Drywell
UIC0188	Drywell
UIC0189	Drywell
UIC0194	Drywell
UIC0195	Drywell
UIC0196	Drywell
UIC0197	Drywell
UIC0198	Drywell
UIC0199	Drywell
UIC0200	Drywell
UIC0201	Drywell
UIC0202	Drywell
UIC0255	Drywell
UIC0292	Drywell
UIC0297	Drywell
UIC0300	Drywell
UIC0301	Drywell
UIC0302	Drywell
UIC0303	Drywell
UIC0304	Drywell
UIC0305	Drywell
UIC0306	Drywell
UIC0307	Drywell
UIC0308	Drywell
UIC0309	Drywell
UIC0310	Drywell
UIC0311	Drywell

City of Redmond UICs within 500' Radius or 2 yr Time of Travel

UIC Number	UIC Type
UIC0312	Drywell
UIC0313	Drywell
UIC0315	Drywell
UIC0316	Drywell
UIC0317	Drywell
UIC0320	Drywell
UIC0321	Drywell
UIC0322	Drywell
UIC0323	Drywell
UIC0385	Drywell
UIC0386	Drywell
UIC0390	Drywell
UIC0391	Drywell
UIC0392	Drywell
UIC0393	Drywell
UIC0398	Drywell
UIC0403	Drywell
UIC0404	Drywell
UIC0405	Drywell
UIC0412	Drywell
UIC0427	Drillhole
UIC0433	Drywell
UIC0434	Drywell
UIC0435	Drywell
UIC0464	Drywell
UIC0474	Drywell
UIC0475	Drywell
UIC0476	Drywell
UIC0477	Drywell
UIC0483	Drywell
UIC0484	Drywell
UIC0485	Drywell
UIC0493	Drywell
UIC0494	Drywell
UIC0496	Drywell
UIC0524	Drywell
UIC0543	Drywell
UIC0544	Drywell
UIC0545	Drywell
UIC0546	Drywell
UIC0547	Drywell
UIC0548	Drywell
UIC0549	Drywell
UIC0550	Drywell
UIC0551	Drywell
UIC0552	Drywell

September 22, 2011

City of Redmond UICs within 500' Radius or 2 yr Time of Travel

UIC Number	UIC Type
UIC0553	Drywell
UIC0619	Drywell
UIC0653	Drywell
UIC0654	Drywell
UIC0655	Drywell
UIC0656	Drywell
UIC0657	Drywell
UIC0658	Drywell
UIC0676	Drywell
UIC0679	Drywell
UIC0689	Drillhole
UIC0707	Drywell
UIC0708	Drywell
UIC0709	Drywell
UIC0712	Drywell
UIC0713	Drywell
UIC0714	Drywell
UIC0715	Drywell
UIC0716	Drywell
UIC0717	Drywell
UIC0718	Drywell
UIC0719	Drywell
UIC0720	Drywell
UIC0721	Drywell
UIC0722	Drywell
UIC0723	Drillhole
UIC0724	Drillhole
UIC0725	Drillhole
UIC0737	Drywell
UIC0738	Drywell
UIC0739	Drillhole
UIC0755	Drywell
UIC0799	Drywell
UIC0821	Drywell
UIC0865	Drywell
UIC0866	Drywell
UIC0869	Drywell
UIC0870	Drywell
UIC0871	Drywell
UIC0873	Drywell
UIC0874	Drywell
UIC0876	Drywell
UIC0877	Drywell
UIC0894	Drywell
UIC0896	Drywell
UIC0900	Drywell

September 22, 2011

City of Redmond UICs within 500' Radius or 2 yr Time of Travel

UIC Number	UIC Type
UIC0903	Drywell
UIC0924	Drywell
UIC0925	Drywell
UIC0926	Drywell
UIC0973	Drywell
UIC0983	Drywell
UIC0984	Drywell
UIC0985	Drywell
UIC0986	Drywell
UIC0987	Drywell
UIC0988	Drywell
UIC0989	Drillhole
UIC0990	Drillhole
UIC0991	Drillhole
UIC0992	Drillhole
UIC0993	Drillhole
UIC0994	Drywell
UIC0995	Drywell
UIC0996	Drillhole
UIC0997	Drillhole
UIC0998	Drillhole
UIC0999	Drillhole
UIC1020	Drywell
UIC1021	Drywell
UIC1022	Drywell
UIC1023	Drywell
UIC1024	Drywell
UIC1025	Drywell
UIC1041	Drywell
UIC1042	Drywell
UIC1043	Drywell
UIC1044	Drywell
UIC1052	Drywell
UIC1053	Drywell
UIC1054	Drywell
UIC1055	Drywell
UIC1060	Drywell
UIC1061	Drywell
UIC1062	Drywell
UIC1065	Drywell
UIC1066	Drywell
UIC1067	Drywell
UIC1068	Drywell
UIC1069	Drywell
UIC1070	Drywell
UIC1085	Drywell

City of Redmond UICs within 500' Radius or 2 yr Time of Travel

UIC Number	UIC Type
UIC1091	Drywell
UIC1092	Drywell
UIC1096	Drywell
UIC1097	Drywell
UIC1098	Drywell
UIC1099	Drywell
UIC1100	Drywell
UIC1101	Drywell
UIC1102	Drywell
UIC1103	Drywell
UIC1104	Drywell
UIC1105	Drywell
UIC1106	Drywell
UIC1107	Drywell
UIC1108	Drywell
UIC1109	Drywell
UIC1110	Drywell
UIC1111	Drywell
UIC1112	Drywell
UIC1117	Drywell
UIC1118	Drywell
UIC1119	Drywell
UIC1120	Drywell
UIC1121	Drywell
UIC1122	Drywell
UIC1123	Drywell
UIC1126	Drywell
UIC1135	Drywell
UIC1136	Drywell
UIC1146	Drywell
UIC1149	Drywell
UIC1190	Drywell
UIC1197	Drywell
UIC1198	Drywell
UIC1217	Drywell
UIC1218	Drywell
UIC1220	Drywell
UIC1223	Drywell
UIC1241	Drywell
UIC1242	Drywell
UIC1245	Drywell
UIC1255	French drain
UIC1263	Drywell
UIC1264	Drywell
UIC1273	Drywell
UIC1274	Drywell

September 22, 2011

City of Redmond UICs within 500' Radius or 2 yr Time of Travel

UIC Number	UIC Type
UIC1300	Drywell
UIC1323	Drywell
UIC1324	Drywell
UIC1325	Drywell
UIC1331	Drywell
UIC1334	Drywell
UIC1335	Drywell
UIC1383	Drywell
UIC1389	Drywell
UIC1392	Drywell
UIC1480	Drywell
UIC1481	Drywell
UIC1482	Drywell
UIC1484	Drywell
UIC1485	Drywell
UIC1486	Drywell
UIC1488	Drywell
UIC1510	Drywell
UIC1513	Drywell
UIC1518	Drywell
UIC1529	Drywell
UIC1530	Drywell
UIC1533	Drywell
UIC1535	Drywell
UIC1536	Drywell
UIC1539	Drywell
UIC1541	Drywell
UIC1542	Drywell
UIC1560	Drywell
UIC1561	Drywell
UIC1562	Drywell
UIC1593	Drywell
UIC1594	Drywell
UIC1595	Drywell
UIC1596	Drywell
UIC1597	Drywell
UIC1598	Drywell
UIC1599	Drywell
UIC1600	Drywell
UIC1602	Drywell
UIC1604	Drywell
UIC1628	Drywell
UIC1629	Drywell
UIC1636	Drywell
UIC1646	Drywell
UIC1665	Drywell

September 22, 2011

City of Redmond UICs within 500' Radius or 2 yr Time of Travel

UIC Number	UIC Type
UIC1722	Drywell
UIC1729	Drywell
UIC1730	Drywell
UIC1731	Drywell
UIC1732	Drywell
UIC1733	Drywell
UIC1734	Drywell
UIC1735	Drywell
UIC1736	Drywell
UIC1737	Drywell
UIC1744	Drywell
UIC1747	Drywell
UIC1749	Drywell
UIC1757	Drywell
UIC1841	Drywell
UIC1854	Drywell
UIC1855	French drain

City of Redmond UICs within 500' Radius or 2 yr Time of Travel

UIC Number	UIC Type
UIC0108	Drillhole
UIC0109	Drillhole
UIC0118	Drillhole
UIC0120	Drywell
UIC0121	Drywell
UIC0122	Drywell
UIC0122c	Drillhole
UIC0136	Drywell
UIC0160	Drywell
UIC0163	Drywell
UIC0166	Drywell
UIC0166c	Drillhole
UIC0167	Drywell
UIC0168	Drywell
UIC0169	Drywell
UIC0170	Drywell
UIC0171	Drywell
UIC0174	Drywell
UIC0182	Drywell
UIC0187	Drywell
UIC0188	Drywell
UIC0189	Drywell
UIC0194	Drywell
UIC0195	Drywell
UIC0196	Drywell
UIC0197	Drywell
UIC0198	Drywell
UIC0199	Drywell
UIC0200	Drywell
UIC0201	Drywell
UIC0202	Drywell
UIC0255	Drywell
UIC0292	Drywell
UIC0297	Drywell
UIC0300	Drywell
UIC0301	Drywell
UIC0302	Drywell
UIC0303	Drywell
UIC0304	Drywell
UIC0305	Drywell
UIC0306	Drywell
UIC0307	Drywell
UIC0308	Drywell
UIC0309	Drywell
UIC0310	Drywell
UIC0311	Drywell

September 22, 2011

City of Redmond UICs within 500' Radius or 2 yr Time of Travel

UIC Number	UIC Type
UIC0312	Drywell
UIC0313	Drywell
UIC0315	Drywell
UIC0316	Drywell
UIC0317	Drywell
UIC0320	Drywell
UIC0321	Drywell
UIC0322	Drywell
UIC0323	Drywell
UIC0385	Drywell
UIC0386	Drywell
UIC0390	Drywell
UIC0391	Drywell
UIC0392	Drywell
UIC0393	Drywell
UIC0398	Drywell
UIC0403	Drywell
UIC0404	Drywell
UIC0405	Drywell
UIC0412	Drywell
UIC0427	Drillhole
UIC0433	Drywell
UIC0434	Drywell
UIC0435	Drywell
UIC0464	Drywell
UIC0474	Drywell
UIC0475	Drywell
UIC0476	Drywell
UIC0477	Drywell
UIC0483	Drywell
UIC0484	Drywell
UIC0485	Drywell
UIC0493	Drywell
UIC0494	Drywell
UIC0496	Drywell
UIC0524	Drywell
UIC0543	Drywell
UIC0544	Drywell
UIC0545	Drywell
UIC0546	Drywell
UIC0547	Drywell
UIC0548	Drywell
UIC0549	Drywell
UIC0550	Drywell
UIC0551	Drywell
UIC0552	Drywell

September 22, 2011

City of Redmond UICs within 500' Radius or 2 yr Time of Travel

UIC Number	UIC Type
UIC0553	Drywell
UIC0619	Drywell
UIC0653	Drywell
UIC0654	Drywell
UIC0655	Drywell
UIC0656	Drywell
UIC0657	Drywell
UIC0658	Drywell
UIC0676	Drywell
UIC0679	Drywell
UIC0689	Drillhole
UIC0707	Drywell
UIC0708	Drywell
UIC0709	Drywell
UIC0712	Drywell
UIC0713	Drywell
UIC0714	Drywell
UIC0715	Drywell
UIC0716	Drywell
UIC0717	Drywell
UIC0718	Drywell
UIC0719	Drywell
UIC0720	Drywell
UIC0721	Drywell
UIC0722	Drywell
UIC0723	Drillhole
UIC0724	Drillhole
UIC0725	Drillhole
UIC0737	Drywell
UIC0738	Drywell
UIC0739	Drillhole
UIC0755	Drywell
UIC0799	Drywell
UIC0821	Drywell
UIC0865	Drywell
UIC0866	Drywell
UIC0869	Drywell
UIC0870	Drywell
UIC0871	Drywell
UIC0873	Drywell
UIC0874	Drywell
UIC0876	Drywell
UIC0877	Drywell
UIC0894	Drywell
UIC0896	Drywell
UIC0900	Drywell

City of Redmond UICs within 500' Radius or 2 yr Time of Travel

UIC Number	UIC Type
UIC0903	Drywell
UIC0924	Drywell
UIC0925	Drywell
UIC0926	Drywell
UIC0973	Drywell
UIC0983	Drywell
UIC0984	Drywell
UIC0985	Drywell
UIC0986	Drywell
UIC0987	Drywell
UIC0988	Drywell
UIC0989	Drillhole
UIC0990	Drillhole
UIC0991	Drillhole
UIC0992	Drillhole
UIC0993	Drillhole
UIC0994	Drywell
UIC0995	Drywell
UIC0996	Drillhole
UIC0997	Drillhole
UIC0998	Drillhole
UIC0999	Drillhole
UIC1020	Drywell
UIC1021	Drywell
UIC1022	Drywell
UIC1023	Drywell
UIC1024	Drywell
UIC1025	Drywell
UIC1041	Drywell
UIC1042	Drywell
UIC1043	Drywell
UIC1044	Drywell
UIC1052	Drywell
UIC1053	Drywell
UIC1054	Drywell
UIC1055	Drywell
UIC1060	Drywell
UIC1061	Drywell
UIC1062	Drywell
UIC1065	Drywell
UIC1066	Drywell
UIC1067	Drywell
UIC1068	Drywell
UIC1069	Drywell
UIC1070	Drywell
UIC1085	Drywell

September 22, 2011

City of Redmond UICs within 500' Radius or 2 yr Time of Travel

UIC Number	UIC Type
UIC1091	Drywell
UIC1092	Drywell
UIC1096	Drywell
UIC1097	Drywell
UIC1098	Drywell
UIC1099	Drywell
UIC1100	Drywell
UIC1101	Drywell
UIC1102	Drywell
UIC1103	Drywell
UIC1104	Drywell
UIC1105	Drywell
UIC1106	Drywell
UIC1107	Drywell
UIC1108	Drywell
UIC1109	Drywell
UIC1110	Drywell
UIC1111	Drywell
UIC1112	Drywell
UIC1117	Drywell
UIC1118	Drywell
UIC1119	Drywell
UIC1120	Drywell
UIC1121	Drywell
UIC1122	Drywell
UIC1123	Drywell
UIC1126	Drywell
UIC1135	Drywell
UIC1136	Drywell
UIC1146	Drywell
UIC1149	Drywell
UIC1190	Drywell
UIC1197	Drywell
UIC1198	Drywell
UIC1217	Drywell
UIC1218	Drywell
UIC1220	Drywell
UIC1223	Drywell
UIC1241	Drywell
UIC1242	Drywell
UIC1245	Drywell
UIC1255	French drain
UIC1263	Drywell
UIC1264	Drywell
UIC1273	Drywell
UIC1274	Drywell

City of Redmond UICs within 500' Radius or 2 yr Time of Travel

UIC Number	UIC Type
UIC1300	Drywell
UIC1323	Drywell
UIC1324	Drywell
UIC1325	Drywell
UIC1331	Drywell
UIC1334	Drywell
UIC1335	Drywell
UIC1383	Drywell
UIC1389	Drywell
UIC1392	Drywell
UIC1480	Drywell
UIC1481	Drywell
UIC1482	Drywell
UIC1484	Drywell
UIC1485	Drywell
UIC1486	Drywell
UIC1488	Drywell
UIC1510	Drywell
UIC1513	Drywell
UIC1518	Drywell
UIC1529	Drywell
UIC1530	Drywell
UIC1533	Drywell
UIC1535	Drywell
UIC1536	Drywell
UIC1539	Drywell
UIC1541	Drywell
UIC1542	Drywell
UIC1560	Drywell
UIC1561	Drywell
UIC1562	Drywell
UIC1593	Drywell
UIC1594	Drywell
UIC1595	Drywell
UIC1596	Drywell
UIC1597	Drywell
UIC1598	Drywell
UIC1599	Drywell
UIC1600	Drywell
UIC1602	Drywell
UIC1604	Drywell
UIC1628	Drywell
UIC1629	Drywell
UIC1636	Drywell
UIC1646	Drywell
UIC1665	Drywell

September 22, 2011

City of Redmond UICs within 500' Radius or 2 yr Time of Travel

UIC Number	UIC Type
UIC1722	Drywell
UIC1729	Drywell
UIC1730	Drywell
UIC1731	Drywell
UIC1732	Drywell
UIC1733	Drywell
UIC1734	Drywell
UIC1735	Drywell
UIC1736	Drywell
UIC1737	Drywell
UIC1744	Drywell
UIC1747	Drywell
UIC1749	Drywell
UIC1757	Drywell
UIC1841	Drywell
UIC1854	Drywell
UIC1855	French drain