Appendix D

Guide for Assessing Potential Impacts of Highway Stormwater Infiltration on Water Balance and Groundwater Quality in Roadway Environments

and

User's Guide for the Groundwater Quality Assessment Tool

This appendix is accompanied by a Groundwater Quality Assessment Tool. The User Tool can be downloaded from the TRB website (www.trb.org); search for "*NCHRP Research Report 922*". This appendix includes a User's Manual for the Groundwater Quality Assessment Tool.

Appendix D

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1 Introduction 1

2 Potential Impacts of Stormwater Infiltration on Water Balance 2

2.1 Potential Changes in the Water Balance 4

2.2 Potential Benefits and Impacts Associated with Increases in Deeper Infiltration 5

2.3 Resources for Evaluating Risks 7

3 Potential Impacts of Stormwater Infiltration on Groundwater Quality 7

3.1 Sources, Fates, and Transport of Groundwater Contaminants of Concern in Roadway Runoff . 7

3.2 Potential for Groundwater Impacts Associated with Existing Soil and Groundwater Contamination 19

3.3 Potential Risks to Groundwater Quality from Roadway Contaminant Spills 20

4 Assessing and Mitigating Potential Stormwater Infiltration Impacts on Water Balance and Groundwater Quality 21

4.1 Localized Groundwater Mounding 22

4.2 Water Balance Impacts on Stream Flows 22

4.3 Pollutants in Stormwater Runoff 23

4.4 Existing Soil and Groundwater Contamination 25

4.5 Wellhead and Spring Protection 27

4.6 Contaminant Spills 30

4.7 Special Considerations for Karst Topography 31

5 Consultation with Local, State, and Federal Agencies 32

5.1 Local Groundwater Suppliers 32

5.2 Water Resources Protection Agencies 32

5.3 EPA Underground Injection Control (UIC) Program 33
5.4 EPA Sole Source Aquifer Program 33
5.5 Sanitation Districts and Other Underground Utilities 33
6 Summary 34
7 User's Guide for the Groundwater Quality Assessment Tool 34
7.1 Introduction 34
7.2 General Use of Tool 35
7.3 Tool Inputs 37
7.4 Simulation Results 41
7.5 Technical Approach 43
7.6 Results Interpretation and Known Limitations 44
8 References 46

1 Introduction

Infiltration of stormwater from urban highways has many potential benefits, but also has the potential to result in environmental and infrastructure impacts associated with the volume of water infiltrated (i.e., water balance impacts) and the introduction and/or mobilization of pollutants into groundwater (i.e., groundwater quality impacts). The purpose of this Guide is to provide guidance for identifying potential impacts related to these factors, particularly in the urban roadway environment, and provide recommendations for project planners and designers with respect to assessing and avoiding and/or mitigating these potential impacts. Two key factors should guide the user's interpretation and application of this material:

First, it is critical to balance the benefits of stormwater infiltration with its risks. This Guide is intended as resource for understanding a wide range of potential issues. Not all the issues identified would necessarily apply to a given site. In many cases, the groundwater-related risks associated with stormwater infiltration can be mitigated or avoided once they are identified and given careful consideration. Yet, under some conditions, the risks posed by stormwater infiltration cannot be mitigated and represent a clear limit to stormwater infiltration.

Second, it is important to consider the watershed-scale context of potential issues. Some of the potential issues identified in this Guide would be of limited concern for stormwater infiltration at isolated sites, but cumulative effects could lead to a significant issue. The most effective way to mitigate these issues and balance benefits of stormwater infiltration may be the watershed and regional planning scale. Groundwater management agencies may develop regional groundwater protection criteria. The authors also recommend that these factors should be considered, and appropriate studies done, as part of developing stormwater regulations that would mandate stormwater infiltration.

The remainder of this Guide is organized as follows:

- **Section 2** introduces and identifies potential impacts related to changes in the natural water balance.
- **Section 3** introduces and identifies potential impacts related to groundwater quality.
- **Section 4** discusses the factors for project teams to considered in evaluating whether infiltration of roadway runoff is infeasible or undesirable from the perspective of site water balance or groundwater quality. This section also provides recommendations for classifying the relative risk that a given project poses and determining how impacts can be potentially avoided and/or mitigated as part of the project development process.
- **Section 5** provides guidance for consulting with local agencies, such as water suppliers and resource agencies, with respect to potential water balance or groundwater quality impacts associated with stormwater infiltration.
- **Section 6** provides a brief summary of this Guide.
- **Section 7** serves as a user's guide for the Groundwater Quality Assessment Tool which can be used to evaluate the acute effect of deicing salts on groundwater quality.

This Guide is based on a synthesis of published literature, experiences of the research team, and selected stormwater guidance documents. This Guide is not intended to provide a comprehensive set of criteria for evaluating infiltration feasibility that are applicable in all cases. Project planning and design professionals

should exercise appropriate judgment in considering potential water balance and groundwater quality impacts associated with infiltration of stormwater from highways.

2 Potential Impacts of Stormwater Infiltration on Water Balance

Water balance refers to the fate of precipitation that falls on a given area of land over a given period. The major components of the water balance include (1) direct runoff to surface waters, (2) evapotranspiration (ET), and (3) deeper infiltration, including water that recharges a groundwater aquifer and/or discharges as baseflow to stream channels (Gobel et al. 2004). In the context of highway project development, the water balance at a site-scale or small watershed-scale is typically the most meaningful, as a project may have the greatest potential to cause negative impacts at this scale. The term "watershed" refers to the land area that drains to a water body of interest. Impacts can be most acute in smaller watersheds, such the area draining to a small headwaters stream. However, the effects of widespread stormwater infiltration could have effects on larger watersheds, such as regional streams.

Analysis at the scale of days or weeks is most appropriate for assessing acute impacts such as localized groundwater mounding, while analysis of long-term averages (i.e., years, decades) is most appropriate timescale for evaluating long term changes in watershed hydrologic regime, such as changes in baseflow or long-term subsurface soil wetting, that may result in chronic or acute issues. Typically, water balance impacts are most acute at the scale of smaller watersheds.

The "natural" or "undeveloped" water balance varies greatly by region, watershed conditions, and the scale of the system that is being considered. To illustrate this variability, the authors compared annual fluxes in water balance components between several case studies of mostly undeveloped watersheds throughout the United States (Table 1). In several studies, ET represents the largest component of the water balance, ranging from 30 to more than 90 percent. This trend is especially prevalent in warmer and drier locations (e.g., California, Texas). In colder and wetter areas, ET tends to make up a smaller fraction of the water balance than arid areas. At a site level, water balance may differ substantially from regional averages as a function of soil properties, local surface geology and hydrogeology, vegetation properties, presence of impervious surfaces, relative magnitudes and patterns of potential ET and rainfall, and other factors.

Table 1. Evaluation of Variability in Undeveloped Water Balance by Region based on Selected Studies

Source:	Location:	Annual Fluxes (as percent of precipitation):
Church et al. 1995	North Eastern US	Runoff and Baseflow = 55% ET and Recharge = 45%
Jefferson et. al. 2008	Northwest (Cascade Mountains); The two study watersheds adjoin each other in the upper McKenzie River watershed on the west side of the Oregon Cascades	Runoff and Baseflow = 70%; ET = 30%; Water Storage Change = 0%
Milly 1994	East of the Rocky Mountains	Runoff and Baseflow = 27%; ET = 73%; Water Storage Change = 0%
Mohseni & Stefan 2001	The Baptism River watershed in northern Minnesota. The watershed is heavily timbered with both deciduous and coniferous trees.	Runoff and Baseflow = 55% ET and Recharge = 45%
Mohseni & Stefan 2001	The Little Washita River watershed in Oklahoma. One third of the watershed is cultivated and the rest is either pasture or wooded pasture.	Runoff and Baseflow = 7% ET and Recharge = 93%
Najjar 1999	Susquehanna River Basin	Runoff and Baseflow = 49%

Source:	Location:	Annual Fluxes (as percent of precipitation):
		ET = 51% Water Storage Change = 0%
Ng & Miller 1980	Southern California Chaparral (average of two years of monitoring)	South facing: Runoff and Baseflow = 3%; ET = 97%, Storage change negligible. North facing: Runoff and Baseflow = 9%, ET = 83% and storage change = 8%.
Rose 2009	South Eastern US: five-state study area (Georgia, South Carolina, North Carolina, Virginia, and Maryland)	Runoff and Baseflow = 37% ET and Recharge = 63%
Ward 1993	Texas	Runoff = 12.5 %; ET = 86 %; Recharge = 1.5%

Sanford and Selnick (2013) estimated the estimated long-term fraction of precipitation lost to evapotranspiration at the county scale for the conterminous United States (Figure 1). This graphic illustrates the variability in the relative proportions of different fluxes in of the water balance. It also demonstrates that ET is at or above 40 percent of the long-term fraction of precipitation for most of the United States. Given that the post-development ET fraction is approximately proportional to the amount of vegetation remaining, the ET fraction could be reduced to less than 10 to 20 percent for moderate to dense development. With this change in ET, the potential to impact water balance is significant for both runoff and infiltration approaches.

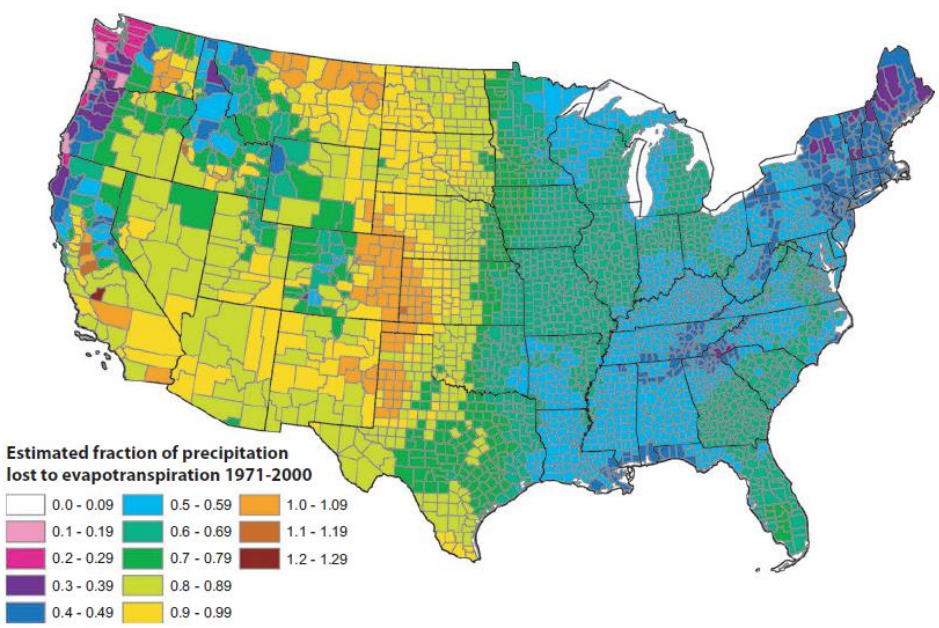

Figure 1. Estimated Long Term Fraction of Precipitation Lost to Evapotranspiration (Sanford and Selnick, 2013). Areas with ET fractions greater than 1.0 contain significant density of irrigated agriculture.

2.1 Potential Changes in the Water Balance

Project activities have the potential to alter the water balance of a site (and smaller watersheds) because of changes in land cover (i.e., addition of impervious surface, compaction of pervious areas) and/or because of the addition of stormwater controls (i.e., infiltration systems). Project changes together with other watershed developments may impact overall watershed characteristics and should be considered in concert with cumulative impact analyses.

In what ways can stormwater infiltration result in changes in the water balance?

How are roadways unique in their impacts on the water balance?

Many transportation improvements include the addition of impervious surfaces, either as a result of construction of a new roadway or the addition of lanes. In addition, adjacent roadside unpaved right-of-way is compacted. An increase in impervious surface (and compacted soils) typically results in an increase in the surface runoff component of the water balance and tends to decrease the amount of water that enters the ground, resulting in reductions in deeper infiltration (groundwater recharge and/or baseflow). Where vegetation is removed and replaced by impervious surface, ET is also generally lower due to a reduction in the amount of rainfall intercepted in plant leaves and in the upper soil layer that contains plant roots (i.e., the root zone) and mulches – these storage elements hold water during a rain storm and make it available for subsequent ET. While evaporation occurs from residual ponded water on impervious surfaces as well, the relative storage provided from ponding on impervious surfaces tends to be significantly less than the storage provided in the root zone below vegetated areas (Gobel et al. 2004) or even in unvegetated soils. The result is that project development, without stormwater controls, tends to result in an increase in surface runoff with corresponding decreases in both ET and deeper infiltration.

Stormwater regulations are increasingly emphasizing management approaches based on "mimicking pre-development hydrology". By "hydrology", the regulations typically refer to only surface runoff hydrology (i.e. groundwater and ET components of hydrology are not addressed). This goal is generally accomplished by using volume reduction practices that rely on infiltration, ET, or consumptive uses to reduce the amount of runoff discharged directly to surface waters (Dietz 2007; USEPA 2010). In most cases, compliance with these regulations is demonstrated based on the volume of direct surface runoff, without reference to or direct consideration of the other elements of the water balance or overall hydrology (SARWQCB 2009; WADOE 2012; USEPA 2012c). Infiltration BMPs can be effective in mitigating increases in direct surface runoff volume and the corresponding reductions in the amount of water infiltrated. However, infiltration BMPs may result in proportions of ET and deeper infiltration that are different than natural conditions. When surface runoff volume is held fixed between natural and proposed conditions and ET is reduced (as discussed above), an increase in deeper infiltration elements of the water balance (recharge and/or baseflow) must occur.

A study conducted in Recklinghausen, Germany demonstrated that an "average density" development without infiltration caused the area-averaged groundwater recharge to decrease from 221 mm per year (28 percent of rainfall) in the natural condition to 163 mm year (20 percent of rainfall) in the developed condition. When runoff from the developed impervious area was infiltrated, the area-averaged groundwater recharge nearly doubled from the proposed condition without controls (163 mm per year) to the proposed condition with controls (245 mm per year, 31 percent of rainfall), which also exceeded the natural condition recharge of 221 mm per year (Gobel et al. 2004). In semi-arid climates, natural recharge may be significantly less than this study, which could result in a more substantial change in groundwater recharge because of the use of infiltration BMPs. For example, Ng and Miller (1980) found that in Southern

California chaparral, ET made up 83 to 97 percent of the water balance, and deeper infiltration was less than 10 percent. This is consistent with the estimates made by Sanford and Selnick (2013) shown in Figure 1. When infiltration is used in Southern California, deeper infiltration has been estimated to increase by as much as three times over pre-project conditions when stormwater is infiltrated to meet water quality design requirements (Strecker and Poresky, 2009). Also, sites that develop with a greater impervious cover (such as roadways), tend to result in a greater reduction in ET and therefore a more substantial shift toward increased infiltration when project goals include matching pre-development volume to the post-project volume of direct surface discharge.

The proportional split between deeper infiltration and ET that occurs in a BMP is a function of the underlying infiltration rate of site soils, soil moisture retention properties, vegetative cover, transpiration rates of vegetation, plant root depths, rainfall intensity, and facility design characteristics, specifically the footprint and the depth of the BMP (Clark et al. 2006). When shallow BMPs with larger surface areas are used, the level of ET tends to increase due to the additional retained moisture content in the top layer of soils in closer contact with the atmosphere (Strecker and Poresky, 2009). In contrast, when deeper BMPs with smaller footprints are used, or when BMPs do not contain amended soil and vegetation elements a greater portion of the water balance is associated with deeper infiltration; ET plays a more minor role.

Roadway environments, particularly in urban areas, represent a unique category of developed areas because of the typically high degree of "connectedness" of impervious area with hardened drainage systems and relatively small footprints that are typically available for infiltration BMPs. Directly connected impervious areas (DCIAs) have been shown to generate a significant amount of the total runoff from developed areas (Lee and Heaney 2003). The level of connectedness is important for water balance, as runoff from DCIAs, by definition, is not routed across pervious surfaces before being routed to the stormwater drainage system, which limits opportunities for ET and infiltration. Limited space in typical roadway environments also limits the amount of ET that may occur from BMPs. While relatively small footprints may be sufficient to achieve infiltration where soil conditions allow (i.e., infiltration rates are high, other constraints do not exist), ET is typically proportional to surface area, so the ET element of the water balance generally decreases as the BMP footprint decreases. As a result, where infiltration is used in the roadway environment to mimic pre-development surface runoff volumes, a substantial increase in deeper infiltration compared to natural conditions would be expected; this change may be particularly acute in semi-arid and arid areas where deeper infiltration tends to be a smaller element of the water balance in the natural condition and ET a larger element in the natural condition.

2.2 Potential Benefits and Impacts Associated with Increases in Deeper Infiltration

When considering potential impacts of stormwater infiltration on water balance, the most significant consideration is the increase in deeper infiltration that may occur as part of projects that are designed to mimic natural surface water discharge (as introduced in Section 2.1). An increase in deeper infiltration may have both positive and negative impacts.

How do the changes in the water balance express themselves in terms of positive and negative impacts?

Potential benefits. In regions where aquifers are actively managed for water supply, an increase in infiltration may be desirable and even encouraged. For example, the Los Angeles (CA) region is underlain by several productive aquifers that are actively managed for water supply. Centralized stormwater capture facilities currently provide approximately 30,000 acre-feet per year of recharge. The Los Angeles

Department of Water and Power Stormwater Capture Master Plan (2016) estimated that stormwater capture (including centralized and distributed) could provide an additional potential of 114,000 acre-feet per year of recharge, which amounts to approximately $125 million in new water supply for a region that continually faces water supply challenges. The plan identified a range of other benefits associated with infiltration in these conditions. In some areas including the Central Valley in California and the Ogallala aquifer in South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas, where groundwater elevations have been severely reduced, such augmentation over natural infiltration recharge rates may be beneficial for supply, assuming that water quality in the aquifer can be maintained or improved.

In regions where streams are perennial, urbanization has often been found to result in a reduction in baseflow and associated water quality issues during dry weather (for example, Spinello and Simmons 1992). Note that in some locations with wastewater discharges or significant irrigation return flows this is not the case. Implementing stormwater measures that increase deeper infiltration compared to natural conditions in selected locations may be an important part of regional strategies to augment baseflow and address dry weather water quality considerations. Where localized increases in infiltration volume do not cause negative impacts (such as those discussed below), this localized increase in infiltration may help contribute to regional improvements in watershed health by offsetting regional decreases in infiltration volume caused by historic urbanization.

Another potential positive impact of increased infiltration volume is the potential to improve groundwater quality through dilution of groundwater contaminants, provided that the stormwater itself does not result in water quality impacts (as discussed in Section 3). In some cases, dilution of contaminants is not desirable, as groundwater contamination plumes can be more efficiently addressed if they remain localized and concentrated. However, in some cases, dilution of groundwater contaminants is an acceptable management strategy that can be supported through practices that result in an increased infiltration component of the water balance (Fischer et al. 2003). Nightingale (1987) found that infiltration of stormwater in the Fresno, California, area was diluting nitrate levels in groundwater that were elevated due in large part to surrounding agricultural activities.

Potential negative consequences. Potential negative consequences of increases in deeper infiltration are generally most acute in areas where local subsurface conditions have limited ability to accept additional infiltrated volumes or where minor changes in hydrogeologic conditions would result in potential impacts.

On a sub-watershed scale, an increase in deeper infiltration volume has the potential to change the local hydrogeologic regime, which can have significant adverse impacts on streams. For example, in the arid southwest, many channels are naturally ephemeral, meaning that they flow during and after storm events or for some period during the wet season, but are normally dry for much of the year. The riparian ecosystems in these areas are specifically adapted for these conditions. An increase in deeper infiltration in these areas has the potential to extend the duration of surface baseflows which can result in a “type change” of the stream from ephemeral to intermittent or perennial channels. This can result in colonization of the channel with different vegetative and terrestrial species, changes in hydrologic regime, and other changes that threaten the functions and values of a riparian area as well as the species present therein. As a specific example, environmental clearance documents for the Rancho Mission Viejo planned community in Orange County, California (California FEIR No 589) identified potential adverse impacts to the endangered Arroyo Toad (which prefers dry wash habitats) if the baseflow regime of ephemeral intermittent creeks within the project were significantly altered as a result of development. This project included stormwater management features designed to manage the overall water balance of the site to avoid significant changes in deeper infiltration so that natural stream baseflows were maintained.

On a more localized basis, the volume of infiltrated water can result in groundwater "mounding" – localized increases in the elevation of the groundwater table below infiltration BMPs, as discussed in Appendix C. Infiltration may also increase the risk of geotechnical hazards such as subsidence, liquefaction, slope instabilities, foundation and subbase issues, and infrastructure damage associated with expansive clays (OCPW 2013; Strecker et al., 2015).

2.3 Resources for Evaluating Risks

Section 4 of this Guide provides guidance for assessing the potential for water balance impacts recommended measures to help mitigate these potential impacts. **Appendix C** provides resources for estimating the development of mounded conditions, including potential impacts to the roadway prism and reduction in effective infiltration rates resulting from mounding. Appendix E provides more information regarding potential geotechnical impacts and hazards related to stormwater infiltration.

3 Potential Impacts of Stormwater Infiltration on Groundwater Quality

While infiltration of stormwater has the potential for improvements in surface water quality, it also has the potential for unintended consequences for groundwater quality (Clark et al. 2006, Weiss et al. 2008). Infiltration of stormwater has the potential to impact groundwater quality as a result of an influx of pollutants contained in stormwater and/or mobilization of pollutants that are present in soils or groundwater. This section identifies the groundwater contaminants of concern that are typically encountered in runoff from urban roadways and discusses their fate and transport relative to potential impacts on groundwater quality (Section 3.1). It also discusses the potential for stormwater infiltration to mobilize and spread soil and groundwater contaminants (Section 3.2) and the potential for contaminant spills to impair groundwater quality (Section 3.3).

3.1 Sources, Fates, and Transport of Groundwater Contaminants of Concern in Roadway Runoff

Potential for stormwater infiltration to contaminate groundwater has been studied extensively (Weiss et al. 2008). Pitt et al. (1999) and Pitt and Clark (2007) have characterized the risk of groundwater contamination from infiltration of stormwater as a function of the following factors:

- Pollutant mobility – pollutants that are more mobile in the vadose zone (the unsaturated zone between the groundwater table and the ground surface) have a higher potential to contaminate groundwater than those which do not move through the vadose zone as readily.
- Pollutant abundance – pollutants that are highly abundant in terms of concentration and detection frequency in stormwater have higher potential to impact groundwater quality. Abundance should be assessed relative to applicable groundwater quality standards.
- Pollutant partitioning – pollutants that are present primarily in soluble fractions tend to have a higher potential to contaminate groundwater.

This section identifies the main categories of contaminants which may potentially pose a risk to groundwater quality resulting from stormwater infiltration.

What are the most common contaminants of concern for groundwater in roadway environments?

How are roadways unique in their impacts on groundwater quality?

In what ways can stormwater infiltration impact groundwater quality?

The fate and transport of individual groundwater contaminants varies significantly depending on the pollutant, characteristics of water and soil, treatment facility type, and other factors. Although the composition and concentration of pollutants found in stormwater runoff are highly site-specific, the following categories of pollutants have been frequently detected in urban stormwater runoff and may pose concerns for groundwater quality:

- Nutrients
- Pesticides
- Organic compounds
- Pathogenic microorganisms
- Heavy metals
- Salts

Note that particulates and particulate-bound pollutants are not included on this list because infiltration BMPs are generally highly effective at removing particulates from stormwater prior to stormwater reaching groundwater. Except for conditions with direct connections between surface water and groundwater (such as karst topography, discussed in Section 4.7 or injection wells with little or no pretreatment), there is limited potential for particulates and particulate-bound pollutants to migrate to groundwater and impair groundwater resources.

The sections below provide a discussion of the potential for groundwater contamination for the six primary pollutants categories listed above based on a synthesis of literature sources and evaluation of unit processes provided in stormwater BMPs. Table 2, at the end of this section, provides a summary of the pollutants of concern and the relative risk to groundwater quality that each is believed to pose.

Detection vs. Contamination. It is important to note that some studies only evaluated whether certain contaminants were detected in groundwater and if detected, the studies may have concluded that groundwater contamination is a concern. Detection only determines if a pollutant could be measured. Contamination is typically determined by whether the contaminant concentrations exceed applicable water quality criteria.

3.1.1 Nutrients

The two nutrients with the most significant potential to contaminate groundwater are nitrogen and phosphorus. Nitrogen compounds, specifically nitrate, are the most commonly encountered nutrient contaminants in groundwater due to their application as fertilizers on developed landscaped areas and agricultural land uses and the deposition of vehicular exhaust on roadways and surrounding soils (Pitt et al. 1994, 1996); they also occur from the breakdown of organic debris. Naturally occurring sources of nitrogen, the atmosphere and soils also lead to groundwater contamination if environmental conditions are conducive. Compost amendments in shoulder treatments and/or stormwater controls can also be sources of nutrients at levels of concern if not appropriately specified and sourced. Some DOTs, such as Colorado DOT, limit use of fertilizers to only the post-construction phase for re-establishing plants and they do not use fertilizers on an ongoing basis after this phase (personal communication, Holly Huyck). This reduces both nitrogen and phosphorous in stormwater runoff.

Nitrogen compounds in stormwater may be removed through processes such as uptake by plants and microbes, microbially-mediated nitrification/denitrification, and volatilization, which are highly dependent

on soil composition and hydrologic properties (Weiss et al. 2008). Nitrate is the nitrogen species of greatest concern for groundwater quality because it is highly mobile in the vadose zone and groundwater. It is also not readily converted to other nitrogen species, except where biological processes are active and cyclical changes in redox conditions occur (Pitt et al. 1994, 1996). The leaching of nitrogen into groundwater and soils is most common during cool, wet seasons because lower temperatures reduce the rates of denitrification, ammonia volatilization, microbial immobilization, and plant uptake. An accumulation of nitrate in groundwater may result in health risks associated with groundwater consumption and may contribute to detrimental nutrient loadings in surface waters that receive inputs from contaminated groundwater. Nitrite and ammonia are also mobile in soils but tend to be present in relative low levels because in most cases, they undergo oxidation to nitrate relatively rapidly in the aerobic vadose zone. Fertilizer sources of nitrate can be controlled by limited and careful application of fertilizers.

Phosphorus is also of concern for groundwater contamination in some cases. Sources of phosphorus in the urban highway environment include detergents in gasoline, motor oil, fertilizer, bird droppings, animal remains, and compost amendments. The most common form of dissolved, mobile phosphorus present in stormwater, orthophosphate, can be removed from infiltrating water through precipitation or chemical adsorption onto soils (Weiss et al. 2008). The relative phosphorus saturation of native soils can be used as an indicator of the level of potential removal of dissolved phosphorus that will result as water percolates through the soil. Soils that have been historically used for agricultural purposes may contain relatively high levels of phosphorus and may provide relatively little capacity to sorb additional phosphorus or may contribute to phosphorus loadings. Like nitrate, elevated dissolved phosphorus levels in groundwater may contribute to detrimental nutrient loadings in surface waters that receive groundwater discharges.

Summary: Overall, nutrients in highway runoff pose relatively limited potential to impact groundwater quality due to relatively low concentrations in urban stormwater in comparison to groundwater concentrations and groundwater quality objectives (Pitt et al. 1999). Risks are elevated when stormwater includes runoff from industrial and/or agricultural land uses that may periodically contain very high levels of nutrients or where aquifers or receiving waters have limited capacity for additional nutrients.

3.1.2 Pesticides

Pesticide sources in the urban highway environment may include roadside maintenance of landscaping, medians, and other landscaped or managed areas. Concentrations of pesticides found in groundwater vary significantly based on pesticide usage (quantity and type), underlying soil texture, total organic carbon of the soil, contaminant persistence, and the depth to groundwater (Pitt et al. 1994, 1996, 1999). Pesticides with high solubility and low affinity for organic matter (low partitioning coefficients) tend to pose the greatest risk. Pesticides tend to have the highest mobility in coarse-grained or sandy soils without a hardpan layer, with low clay and organic matter content and high permeability.

Decomposition is possible in both soil media and water, but the time frame can range between days and years depending on the conditions and the specific compounds (Pitt et al. 1994, 1996). Studies conducted on the half-life of most pesticides are generally applicable to surface and near-surface conditions and do not generally account for the reduced microbial activity deeper in the vadose zone.

Recent research in California related to stormwater drywells (Nelson et al., 2016) found that hydrophobic pesticides posed negligible risk to groundwater quality, but water-soluble pesticides such as neonicotinoids and fipronil could reach the groundwater table with limited processes for sorption of these pollutants regardless of soil properties. There are currently no drinking water quality standards for these pesticides

(however, these may be developed). Invertebrate aquatic species can be very sensitive to pesticides. Stormwater quality monitoring has shown that fipronil is present above levels associated with chronic aquatic toxicity (SFEI, 2013).

Summary: Where there is concern regarding pesticide contamination, risks can generally be mitigated by careful selection and application of pesticides. Pesticides with low solubility and high affinity for organic matter tend to pose limited risk of groundwater contamination. Neonicotinoids and fipronil should be avoided, particularly where infiltrated water has connectivity to surface waters. Where soils are coarse and have limited organic matter, the use of amended media in an infiltration BMP has the potential to limit transport of some pesticides.

3.1.3 Organic Compounds

Some organic compounds in groundwater are naturally occurring, such as those originating from decomposing animal wastes, leaf litter, vegetation, and organisms in the soil; many others are man-made and originate from sources like landfills, sewage systems, agricultural runoff, and urban stormwater runoff, including highway runoff (Pitt et al. 1999). The most common organics detected in groundwater are phthalate esters, such as bis(2-ethylhexyl) phthalate, and phenolic compounds, such as phenol and 2,4-dimethyl phenol. Volatile organic compounds, such as benzene, chloroform, methylene chloride, trichloroethylene (TCE), tetrachloroethylene, toluene, and xylene, are also detected in groundwater. Finally, polycyclic aromatic hydrocarbons (PAHs, a class of semi-volatile organic compounds), such as fluoranthene and pyrene, are commonly detected in urban stormwater, particularly from roadway and parking lot runoff due to their production via combustion processes. Uncombusted petroleum products (oils, lubricants, etc.) are also sources of some types of PAHs.

PAHs and other organic compounds have been detected in groundwater (Pitt et al. 1999, Weiss et al. 2008, Fischer et al. 2003, Pitt et al., 2012; Talebi and Pitt, 2014; Wilson et al., 1989), particularly in sites with high permeability subsurface soils, especially those with coarse-grained alluvium, sand, and gravel. For example, testing in New Jersey demonstrated that groundwater receiving runoff from roadways and parking lots contained elevated concentrations of petroleum hydrocarbons, such as benzene and toluene, when compared to background groundwater levels (Fischer et al. 2003). Study of the risks posed by stormwater infiltration (NAS, 2016) identified PAH contamination, particularly in sandy soils with little separation to groundwater, as one of the most important risks related to drinking water standards.

Organic compounds are typically removed via volatilization, sorption and degradation to levels that would not affect groundwater quality. Treatment processes found in organically active and aerobic soils (sorption, microbial degradation) generally trap hydrocarbons within the first few centimeters of soil and do not allow them to percolate far enough to contaminate groundwater (Weiss et al. 2008). PAHs have been successfully removed from infiltrating stormwater through degradation by naturally developed microbial communities where there is a prolonged aerobic, sulfate reducing, and denitrifying environment (Miklas and Grabowiecki 2007, Dallman and Spongberg, 2012). The rate of volatilization for many hydrocarbons decreases with lower temperatures, resulting in higher detectable rates in colder months (Fischer et al. 2003). The presence of sandy soils and a high-water table have been found to be correlated with greater prevalence of groundwater contamination by organic compounds (Pitt et al. 1994, 1996).

Brody-Heine et al. (2011) conducted a one-dimensional modeling study of fate and transport below drywells in Bend, OR. The study found that for climate conditions in Bend (semi-arid, high desert), the organic pollutants benzo(a)pyrene, naphthalene, pentachlorophenol (PCP), di-2-ehylhexyl phthalate

(DEHP), 2,4-dichlorophenoxyacetic acid (2,4-D), and toluene were attenuated to below detection limits within 5 feet of transport under average condition. Under a "worst-case" scenario all pollutants were attenuated within 37 feet. This one-dimensional model did not consider lateral advection/dispersion, therefore is somewhat conservative.

Chlorinated solvents (e.g., tricloroethane, TCE) and methyl tertiary-butyl ether (MTBE) are mobile in soils, degrade slowly, and are hazardous to human health. However, these contaminants are not commonly detected at levels of concern in stormwater. They are commonly associated with historical soil and groundwater contamination (See Section 3.2) and they also could be of concern related to contaminant spills in roadways (See Section 3.3).

Summary: While roadways are a known source of organic compounds, particularly petroleum hydrocarbons and combustion by-products, the risk posed by infiltration of organic compounds in stormwater is relatively low due to relatively low stormwater concentrations and relatively low mobility of most organic compounds in the vadose zone. There is an elevated level of contamination risk where specific sources of organic compounds are present, where there is a shallow depth to mounded groundwater, where soils are sandy, and where sub-surface injection/infiltration is used – each of these factors reduces the effectiveness of removal processes in the vadose zone that would protect groundwater quality. These risks can be mitigated using soil amendments to improve treatment, observing criteria for separation to the groundwater table, and evaluating mounding to assess whether there would be prolonged periods with reduced groundwater separation.

Chlorinated solvents, MTBE, and similar soluble compounds can be of concern related to existing soil/water contamination and/or contaminant spills. See Section 3.2 and 3.3 for guidance on assessing and mitigating these risks.

3.1.4 Pathogenic Microorganisms

Pathogens, including bacteria and viruses, are ubiquitous in urban stormwater runoff. They originate from anthropogenic sources, such as human waste, dog waste, and failing septic systems, as well as natural sources, such as bird and animal droppings. Pathogenic contamination of groundwater has been linked to stormwater infiltration. For example, some studies suggest that pathogens are more commonly detected in groundwater in areas with a high groundwater table and near MS4 outfalls (Pitt et al. 1999). Contamination depends on several site-specific environmental factors and pathogen characteristics, but it is believed that infiltration through BMPs may create a pathway for groundwater contamination (Weiss et al. 2008).

The survival and persistence of pathogens in the vadose done and in groundwater is sensitive to several factors, including pH, interactions with soil microflora, moisture content, temperature, dissolved oxygen content, and concentrations of organic matter. Viral pathogens, specifically enteroviruses have a high likelihood for groundwater contamination if they are present in the stormwater runoff as they are highly mobile and are less sensitive to environmental factors than bacterial pathogens (Pitt et al. 1999). Bacterial pathogens are often removed through sedimentation or sorption to soils during percolation through the upper layer of soils. The pathogens that are successfully filtered and sorbed are inactivated and killed as soil dries and necessary survival factors are eliminated (Pitt et al. 1999). For pathogens reaching the groundwater table, the distribution and movement of pathogens in groundwater is controlled by convection, sorption, and dispersion in the liquid phase.

Summary: Pathogen contamination from stormwater infiltration, particularly by enteroviruses, may be of significant concern for groundwater quality in many urban roadway areas due to the potential for elevated loadings from human waste, pet waste, and garbage. Like other contaminants, the risk of pathogen contamination is elevated where soils are coarser and depth to groundwater is less. However, where groundwater is not used for human consumption or where groundwater is disinfected prior to use, the practical consequences of bacterial contamination may be limited. Additionally, for controlled access facilities, such as limited access highways and freeways, the source of human pathogens would be very limited, with associated reduced concern for groundwater contamination. When highways include runoff from adjacent areas, there is more potential for human pathogen sources.

3.1.5 Heavy Metals

Heavy metals, such as copper, lead, and zinc, are commonly found in stormwater runoff. Sources of heavy metals in urban runoff include automobile parts, building materials, exposed metal products, fertilizers, fungicides, atmospheric deposition from industrial and vehicle exhausts and other sources. In the roadway environment, specific sources included brake pads and treated woods (copper), tires (zinc), and galvanized guardrails (zinc). Leaded gasoline was historically a major source of lead and arsenic loading, however allowable levels of lead have been greatly reduced in gasoline in the United States and, in the last 20 years, lead is not commonly detected in runoff at levels of concern. Lead may still be a concern as a legacy pollutant in roadside soils in some case and/or if there are sensitive receptors that could be impacted by lead at low levels.

During the infiltration process, when infiltrated through soils, metals are typically removed via filtration of particulate-bound metals, adsorption of dissolved metals to soil particles, chemical precipitation, diffusion into solid particles, and biological uptake (Weiss et al. 2008, Hamad et al., 2016), decreasing their likelihood of groundwater contamination. However, metals are of increased concern when infiltration facilities are in sand or gravels or when infiltration occurs in close proximity to sites with elevated stormwater concentrations, such as industrial sites and maintenance yards. This can be particularly concerning if infiltration occurs close aquatic habitat Among the heavy metals of potential concern to groundwater quality, zinc has the highest solubility in stormwater and tends to be the most mobile in the vadose zone (Pitt et al. 1999). Soils that have at least moderate cation exchange capacity and organic content tend to provide greater potential for removing heavy metals through sorption and other processes, however metals have been found to be well retained in systems without organic content, such as permeable pavements (Dierkes et al. undated).

Summary: While roadways are recognized to be an elevated source of metals, concentrations in urban runoff tend to be much less than drinking water standards, therefore risks of human health issues from metals in infiltrated stormwater are minor. Where drinking water standards apply, metals are typically not of concern. However, where groundwater discharges to sensitive aquatic habitat, metals may be of concern because some species exhibit detrimental responses to heavy metals at relatively low concentrations. Long-term loading of highway runoff on sandy soils can lead to eventual increase in groundwater concentrations that could exceed surface water toxicity criteria. The use of organic materials in soil media for infiltration systems can improve the retention of heavy metals. Periodic removal of surficial soils can help reduce the potential for breakthrough.

3.1.6 Constituents of Emerging Concern

Constituents of emerging concern (CECs) include those that have not received adequate study to characterize sources and/or acceptable exposure limits, but which pose potential risks. SFEI (2013) identified fipronil, Perfluoroalkyl Substances (PFASs), nonylphenol and nonylphenol ethoxylates, and polybrominated diphenyl ethers (PBDEs) as the highest level of concern among CECs. Among these, fipronil and PFASs have the highest mobility and potential to impact groundwater quality.

PFASs are used in a variety of manufactured products including non-stick coatings and aqueous film-forming foams (AFFF) used for firefighting, as well as some fabrics/textiles and paper products. Their mobility varies based on properties specific to the compound. PFASs with longer perfluoroalkyl tails tend to have more sorption and retardation than those with shorter tails (ITRC, 2018). All the studies regarding PFASs that were reviewed as part of this project detected this class of compounds in stormwater samples from urban areas with various land use types (Ahrens, 2011; Houtz, 2013; ITRC, 2018; Lin et al., 2018; Nguyen et al., 2011; Procopio et al., 2017; Xiao et al., 2012). Studies indicated that perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) were the most common PFASs detected (Procopio et al., 2017; Xiao et al., 2012). The US EPA has established health advisory (HA) levels of 70 parts per trillion (ppt) for both PFOS and PFOA. PFOS and PFOA were detected at residential sites below the health advisory level and concentrations at industrial/commercial sites were significantly higher than at the residential sites, with PFOS concentrations exceeding the health advisory level and reaching up to 156 ppt (Xiao et al., 2012). In addition to being present in stormwater, two sources found that PFAS in soils leached into the groundwater (Ahrens, 2011; ITRC, 2018). The authors did not identify studies on PFASs in the highway environment, however firefighting foams have been used in the highway environment.

Summary. Stormwater infiltration may have the potential to transport PFASs to groundwater if either the stormwater or the soils contain elevated PFAS concentrations; however, it is unknown whether contamination (i.e., exceedance of health risk-based thresholds) is likely to occur. Extensive research is ongoing on PFOA/PFOA. In areas covered by local groundwater protection criteria, spill containment requirements may be adequate to control potential spills.

As discussed earlier, neonicotinoids and fipronil appear to pose the greatest risk to aquatic toxicity. However, this risk can be best controlled via source control via appropriate selection and application of pesticides. This class of pollutants is not removed by any conventional stormwater treatment approach, therefore discharge of treated runoff to streams could have similar risks as discharge of contaminated groundwater to streams, though these pathways would have different concentrations and durations of exposure.

Other CECs, such as pharmaceuticals and endocrine disruptors, have similar properties. They are not removed by migration through soil or by stormwater treatment processes. Therefore, the key management question is whether these can be allowed to discharge to water via groundwater discharge (longer duration, more attenuated concentration) or via surface runoff (shorter duration, but potentially less attenuated concentration).

3.1.7 Salts and Dissolved Minerals

Inorganic dissolved minerals, including chloride, sulfate, and sodium, are commonly detected in groundwater at concentrations of concern in areas that include extensive agriculture and/or use of deicing

salts (Pitt et al. 1999, Mullaney et al., 2009, Kunze and Sroka, 2004, Watson et al., 2002). Sources of salts in groundwater include natural salts in soils, addition of fertilizers to agricultural fields, evaporation of irrigation water (leaving salts behind), addition of salts to waste streams through consumptive uses (e.g., water softening), and application of salts to roads and other surfaces during cold weather. Among stormwater-related sources, road salting is the most significant source of salt loading and has been found to significantly affect chloride content and salinity of groundwater (Pitt et al. 1994, 1996; Mullaney et al., 2009, Kunze and Sroka, 2004, Watson et al., 2002). The potential for long term accumulation of salts in groundwater is a function of the nature of the aquifer and the loading of saline water versus fresh water – aquifers that exist in closed or relatively closed basins are more susceptible to long term increases in salts. Reclaimed water (treated wastewater) is also a source of salts and may be a consideration in areas where reclaimed water is used to irrigate roadside vegetation or other landscaping tributary to roadway systems. Deicing salt in runoff to surface waters can also cause severe issues (Corsi, et al., 2010, Mullaney et al., 2009).

Summary: Roadway runoff in cold climates, where salt is used, has a high potential for contaminating groundwater because salts are water soluble, non-filterable, not readily sorbed to solids, and can leach into groundwater as infiltration occurs (Weiss et al. 2008; Pitt et al. 1994, 1996, Ostendorf et al. 2009). Because conventional treatment methods are not effective at removing salts, the potential for salt contamination of soil and groundwater can be an overriding factor in determining the feasibility of stormwater infiltration.

Salt impacts can be categorized into chronic impacts – i.e., long term accumulation of salts from various sources affecting regional water quality, and acute impacts – i.e., localized salt plumes potentially impacting water wells near stormwater infiltration systems.

The key factors in determining whether salts contamination precludes stormwater infiltration are:

- The loading rate of salts
- The distance between infiltration BMPs and points of use (i.e., drinking water wells)
- Local hydrogeologic contexts, such at the flow-through rate of the groundwater
- Local salt and nutrient management plan criteria (where applicable)

The Groundwater Quality Assessment Tool (See Section 7) is intended to help assess acute salt plumes.

In areas where salts are not applied to roadways, the infiltration of stormwater tends improve groundwater quality through dilution, as stormwater typically has relatively low dissolved mineral concentrations (Pitt et al. 1994, 1996). Arid climates often experience elevated dissolved solids levels due to high levels of evapotranspiration.

3.1.8 Summary of Stormwater Contaminants of Concern for Groundwater Quality Impacts

Table 2 provides a summary of the potential risks to groundwater quality posed by the stormwater contaminants. This table identifies the level of risk posed by each category of contaminant and the degree to which risks can potentially be addressed through mitigation measures such source controls, pretreatment, and separation to groundwater. Risks are discussed in the context of water supply water beneficial uses (including drinking water and agricultural beneficial uses) and ecological beneficial uses of surface waters. Note that depending on the local conditions, one or both beneficial uses may not apply, so national, state,

and local groundwater regulations should be reviewed. Specific mitigation measures are identified in Section 4.

It is important to note that the theoretical potential to contaminate groundwater should also be weighed with the types and sources of contamination that have been observed. Edwards et al. (2016) conducted an extensive review of groundwater contamination potential, particularly focused on drywells, which are identified to be among the highest potential for groundwater contamination because of injection below the ground surface. The authors reviewed the findings from 13 studies of groundwater contamination potential from drywells. This study provided the following summary:

> *"Although contaminants were detected in stormwater samples in all of the examined drywell studies, the conclusion of the majority of studies is that when conducted properly and allowing for a sufficient separation distance and subsurface pollutant attenuation, drywell infiltration of stormwater does not pose a threat to groundwater and drinking water sources. Although some contaminants were detected in stormwater samples above regulatory levels [based on drinking water criteria], these contaminants were rarely detected in groundwater at similar levels. Even in Modesto, California, where drywells have been used for more than half a century, no contaminants detected in downgradient groundwater monitoring wells exceeded regulatory values. Studies that showed insufficient pollutant attenuation in the drywell or underlying vadose zone sediment concluded that incorporating pretreatment into the drywell design would reduce influent contaminant concentrations."*

This is not intended to imply that drywells are inherently safe and effective. Like any infiltration BMP, if installed in an unsuitable location (i.e., karst, unconfined shallow aquifer) or without adequate consideration for pretreatment and O&M, they have the potential to contribute to groundwater quality impacts. Additionally, where groundwater quality criteria are based on aquatic life standards, limits can be much lower.

Table 2. Summary of Potential Stormwater Contaminants of Concern for Groundwater Quality

Constituent	Roadway-related Sources	Relative Abundance in Roadway Stormwater Runoff in Soluble Phase	Mobility through Vadose Zone	Relative Stormwater-Related Contamination Risk	Potential for Remaining Risk after Mitigation Measures (See Section 4.4)
Nitrogen	• Fertilizers • Vehicle exhaust • Petroleum products • Plant materials • Animal droppings and remains • Compost amendments	Low	Moderate to High, as nitrate Greatest during cooler weather	**Drinking water.** ***Low.*** While nitrate has high mobility in groundwater, relatively low concentrations are typically observed in stormwater runoff which tend to be well below drinking water quality objectives. **Surface water/ecological.** ***Low.*** If streams receiving groundwater flow and are impaired for nitrogen species, then infiltration may provide less attenuation of nitrogen loads than other approaches. However, increased baseflow from infiltration can reduce the sensitivity of streams to nitrogen loads by reducing conditions that contribute to eutrophication (i.e., low flow, stagnation, elevated temperature). Overall, this risk is typically low.	Limited risk, except where groundwater is very sensitive to nitrogen inputs, or where natural sources of nitrogen exist in soils that may be mobilized by stormwater infiltration.
Phosphorus	• Fertilizers • Detergents in gasoline • Motor oil • Plant materials • Animal droppings and remains • Compost amendments	Low	Low to Moderate Greatest where soils have limited potential to sorb dissolved phosphorus.	**Drinking water.** ***Not applicable.*** There are not phosphorus standards for drinking water. **Surface water/ecological.** ***Low.*** Phosphorus concentrations tend to be relatively low in highway runoff and mobility in sub-surface environments tends to be limited. Infiltration is among the most effective processes and also supports improved baseflow, which can reduce conditions that contribute to eutrophication (i.e., low flow, stagnation, elevated temperature). **Exceptions.** Where soils contain elevated phosphorus concentrations (such as historical agriculture uses), risks may be elevated if infiltration water mobilizes phosphorus in the soil that would have otherwise not been mobilized.	Limited risk, except where soils have received historic phosphorus loadings and may be a source of phosphorus. Compost-based soil media should be avoided in BMPs in areas where surface waters are sensitive to phosphorus as these media have been observed to leach phosphorus.

Constituent	Roadway-related Sources	Relative Abundance in Roadway Stormwater Runoff in Soluble Phase	Mobility through Vadose Zone	Relative Stormwater-Related Contamination Risk	Potential for Remaining Risk after Mitigation Measures (See Section 4.4)
Pesticides	• Pesticide use in landscaped areas	Low to Moderate	Low to High Greatest in sandy soils, high water table, and pesticides with high solubility and low affinity for organic matter. Neonicotinoids and fipronil have high mobility.	**Drinking water.** ***Not applicable.*** Currently, there are not drinking water standards for the critical water soluble pesticides. However, these could be established. **Surface water/ecological.** ***Low.*** Concentrations in highway stormwater runoff tend to be low, and pesticide concentrations can be managed through product selection and application. There is limited incremental risk posed by infiltration as alternative treatment processes do not provide better attenuation.	Limited risk with appropriate mitigation measures, including: • DOTs using infiltration should avoid water soluble pesticides. • Agricultural runoff should not be routed into DOT infiltration practices. Note that both fipronil and neonicotinoids are used to control insects. Fipronil is common in residential land around buildings. Neonicotinoids are common in agricultural land. Neither application applies to most DOT right of way projects.
Organic Compounds	• Oils, gasoline • Asphalt, coal tar • Agricultural runoff • Other	Moderate to High	Low to Moderate Greatest in sandy soils and where there is a high water table.	**Drinking water.** ***Moderate.*** Particularly in sandy soils or high groundwater table. The most critical contaminants are certain PAH compounds that are detected in stormwater runoff and can pass through soils, particularly under cooler conditions, with less separation to groundwater, and less organic soil. MTBE and PCE/TCE are both highly mobile, however, current sources are limited, so the relative risk from stormwater infiltration is low. **Surface water/ecological.** ***Low.*** PAHs are primarily an issue in the environment if they accumulate in sediments. Water that has been infiltrated does not carry particulates that would be settleable in surface waters.	Limited risk with appropriate mitigation measures, including: • Maintain appropriate separation to groundwater • For sandy soils, amend surface layer to increase organic content and promote biological activity While some elevated PAH levels have been found below infiltration BMPs, contamination of water supply wells with PAHs from stormwater BMPs has not been reported, indicating effects are likely localized.
Pathogens	• Human waste • Animal droppings and remains • Septic systems	Highly variable; may be highest in urban areas due to human waste and pet waste	Low for bacterial pathogens Moderate to High for enteroviruses	**Drinking water.** ***Moderate.*** Pathogens are commonly present in stormwater runoff. While roadways do not have elevated risks compared to other land uses, pathogens may be present at elevated levels. Enteroviruses are highly mobile and have a high risk of groundwater contamination if infiltrated. The relevance of this risk depends on whether groundwater is used without treatment. **Surface water/ecological.** ***Low.*** If there is direct connectivity to surface waters that support recreational uses, then infiltration may continue to pose a risk. However, this risk is lower than the risk of direct discharge**.**	Limited risk for bacterial pathogens with appropriate separation to groundwater. Enteroviruses may pose an unavoidable risk where they are present, and groundwater is used without treatment. This is strongly influenced by proximity to drinking water wells and whether water is treated after extraction.

Constituent	Roadway-related Sources	Relative Abundance in Roadway Stormwater Runoff in Soluble Phase	Mobility through Vadose Zone	Relative Stormwater-Related Contamination Risk	Potential for Remaining Risk after Mitigation Measures (See Section 4.4)
Metals (copper, zinc, lead	• Vehicles • Roadway debris • Roadway paint • Roadway materials	Moderate to High relative to surface water toxicity criteria Generally Low relative to drinking water criteria	Low, removed through sorption and filtration	**Drinking water.** ***Low.*** Metals are generally removed through sedimentation, filtration, sorption and precipitation prior to reaching groundwater. Additionally, stormwater concentrations are typically much lower than drinking water standards. **Surface water/ecological.** ***Low.*** If there is direct connectivity to surface waters that support biological uses, then infiltrated water could still discharge above chronic toxicity criteria. However, this risk is lower than the risk of direct discharge.	Limited risk with appropriate mitigation measures, including: • Maintain appropriate separation to groundwater • For sandy soils, amend surface layer to increase organic content and promote sorption With these mitigation measures, the risk posed to surface water ecological receptors can be minimized.
Emerging Contaminants	• Fire fighting foams • Pharmaceuticals • Soluble pesticides • Endocrine disruptors	Generally low, but not well characterized. Potential for spills or releases.	CECs of interest are those that have high mobility.	**Drinking water.** ***Unknown, potentially high*****.** This category includes a range of contaminants that could be mobile, persistent, and have health effects. **Surface water/ecological.** ***Low.*** Risks posed by infiltration pathways are lower than the risk of direct discharge,	Data are not available to assess the incremental risk posed by releases of compounds. Discontinuing use of PFOS/PFOA should reduce the potential risk posed by infiltration of highway runoff in the future.
Salts	• Roadway salting • Fertilizers • Natural mineral leaching • Reclaimed water irrigation	Seasonally High	High	**Drinking water.** ***Moderate to high.*** Where salt is used, it is likely to have moderate to major effect on groundwater quality relative to drinking water and irrigation beneficial uses. The severity of this effect depends on the proximity to drinking water wells, hydrogeologic conditions, and other factors. **Surface water/ecological.** ***Moderate to high.*** Risks posed by infiltration pathways are lower than the risk of direct discharge, however, long-term accumulation could result in chronically elevated salt concentrations in nearby receiving waters rather than shorter pulses of surface runoff.	Risks of salt loadings may be difficult to mitigate, except where it is feasible to: (1) place BMPs in areas that pose lower risks to drinking water wells, (2) divert runoff from infiltration BMPs during winter months, (3) avoid using salt (risks of alternative approaches should be evaluated), or (4) coordinate stormwater management approach with a local salt management plan.

3.2 Potential for Groundwater Impacts Associated with Existing Soil and Groundwater Contamination

Legacy contamination of soil and groundwater is common in areas that have previously been used for urban development or agricultural uses. The most common constituents of concern are volatile organic compounds; especially chlorinated solvents like PCE and TCE, and the gasoline oxygenate MTBE. These compounds have been observed to persist in groundwater and have been detected in aquifers throughout the United States (Moran, et al. 2006). Subsurface contamination may also originate from septic systems, cemeteries, mining tailings disposal areas, industrial slag deposits, and informal municipal solid waste disposal sites, with similar considerations.

In the highway environment, DOT project teams should be aware of historic fill, particularly in old DOT fill sections and in older urban environments. These fills may contain a wide range of waste, including both municipal and industrial waste. Additionally, project teams should investigate whether previous fill materials included beneficial reuse material, such as fly ash, foundry sand, cinders, others from industrial sources. These materials can be considered safe for use as fill material, however contaminants in the materials could be mobilized by stormwater infiltration. Records of fill materials could be found in state records or historic plan sets. Historic fill materials can also be characterized via a geotechnical investigation.

Where soil or groundwater contamination exists below a project site or in the project vicinity, stormwater infiltration may have several negative consequences that should be carefully evaluated (Gobel et al. 2004):

1. Infiltration of stormwater can mobilize pollutants in contaminated soils and provide a mechanism to transport these pollutants to groundwater. This can threaten groundwater quality and complicate soil cleanup efforts.
2. Infiltration of stormwater can influence the behavior of existing groundwater pollutant plumes through the addition and/or concentration of infiltrating water over current conditions. This can result in a plume shifting its direction of movement, accelerating movement and/or spreading and becoming more diffuse. Where cleanup efforts are underway, this can complicate these efforts and make isolation of the plume from groundwater sources more challenging. Where cleanup activities have not started, the spreading of a plume generally makes cleanup efforts more challenging and costly and may threaten drinking water supplies.
3. Where stormwater infiltration results in a localized increase in groundwater table, there may be potential for the water table to intersect with contaminated soil and/or utilities that would otherwise be “high and dry”. Finally, infiltration may also disrupt the natural degradation process of contaminants in soil or groundwater by introducing additional waters, nutrients, or limiting reagents to the environment.

Soil and groundwater contaminants are not solely anthropogenic. In some cases, historic geologic deposits may contain elevated levels of natural contaminants such as selenium and arsenic which can be mobilized through stormwater infiltration. For example, the central portion of Orange County (California) is underlain by a selenium plume that originated from selenium contained in natural sediments deposited over geologic time, which has been released because of changes in water table with agricultural development and urbanization. Infiltration of stormwater in this vicinity has the potential to further mobilize selenium from soils as well as increase the volume of contaminated groundwater discharged to creeks.

It is possible that in some cases, stormwater infiltration could be used as part of a solution to address groundwater or soil contamination, either through dilution or by strategically influencing the movement of a plume. Such an approach should generally be implemented in close coordination with groundwater

management and/or cleanup authorities. Soil and groundwater contamination are highly site-specific considerations that should be evaluated carefully for each project site where historical data suggests that contamination is present or may be present.

3.3 Potential Risks to Groundwater Quality from Roadway Contaminant Spills

The U.S.DOT estimates that seven percent of all trucks travelling the nation's roadways are carrying hazardous material (FHWA 2009). As such, contaminant spills are a constant risk in the roadway environment, with the potential to deposit high concentrations and volumes of pollutants onto the roadway and into the roadway drainage system within a short period of time. While most state DOTs have procedures defined for reporting and handling spills, contaminants may begin to infiltrate before responders are able to contain and remove the source. Infiltration of spilled contaminants may occur whether there are infiltration BMPs present or not; however, in theory, the use of infiltration BMPs may accelerate the rate at which the contaminants are able to percolate into groundwater and may also concentrate these contaminants into small areas such that the natural ability of soils to attenuate and remove contaminants are more limited. Conversely, the presence of infiltration BMPs may help prevent spilled pollutants from draining to surface waters where they may have impacts on the downstream environment and receiving waters. Much of the spill may be contained within the infiltration system if runoff is not present at the time of the spill.

Based on a review of 10 years of roadway spill records in Alabama, Becker et al. (2001) found that hydrocarbons (including diesel oil, road tar, gasoline, fuel oil, asphalt, liquefied petroleum gas, jet fuel, hydraulic oil, and creosote) were the most commonly spilled constituents in highway incidents by a large margin and were also released in the greatest volumes. Ammonia and ammonium nitrate were also released, but at much less frequency and lower quantities. Other types of spills are possible; however, data suggests that spills other than petroleum hydrocarbons tend to be quite rare.

Per the discussion in Section 3.1.3, petroleum hydrocarbons (organic compounds) are generally retained within a relatively thin layer of surficial soils and would not be expected to pose a significant risk to groundwater quality in most cases where infiltration occurs through soils and/or media. BMPs that are underlain by a thick layer of soil or that have amended media filtration processes would theoretically provide a high level of control for petroleum hydrocarbon spills and limit the potential for groundwater contamination. Higher risk of contamination may occur when there is limited separation to groundwater and soils are sandy or gravelly with limited organic content. Where these conditions prevail, it may be desirable to include BMP design components isolate groundwater contamination pathways such as including a containment vault with isolation valves upstream of underground infiltration systems to contain inflow of contaminants. However, the general measures that are used to address potential impacts from chronic stormwater loadings in sandy soils and high groundwater conditions (e.g., pretreatment and amended soils) would also tend to be effective for controlling and containing most spills.

Miklas and Grabowiecki (2007) evaluated the potential for permeable pavements to capture and degrade petroleum hydrocarbons and concluded that relatively large hydrocarbon spills can be contained in permeable pavement systems. They found that the gravel, sand, and soil that make up permeable pavements function as hydrocarbon traps and in-situ bioreactors under some conditions. Similar findings would likely apply to bioretention areas and similar systems that have amended soils and plant roots. In the event of any significant spills, the systems would need to be remediated to remove contaminated soil and media.

Literature was not identified that specifically considered the potential risks posed by spills of solvents or other mobile contaminants. However, these types of spills are believed to be very uncommon and highway

designs may not be able to provide risk mitigation measures for very infrequent and unpredictable occurrences.

Even though very rare, a chlorinated solvent spill or PFOA/PFOS spill could carry high risks to groundwater supply and require very costly cleanup. Local groundwater protection requirements may specify spill containment requirements to reduce the potential for these types of spills to reach groundwater. For example, the City of Portland Water Bureau has defined a wellhead protection zone related to its Columbia South Shore Well Field. Within the wellhead protection zone, minimum spill containment measures must be included in all stormwater management BMPs receiving runoff from highways and major arterials in this area. Containment approaches are based on capturing dense non-aqueous phase liquids, such as TCE and PCE (mobile, heavy solvents) that could rapidly migrate into the aquifer if allowed to pool on permeable soils. Common containment approaches include water tight sumps upstream of BMPs and/or chambers with isolation valves. Containment volumes are focused on the volume of solvent spills that could occur. The Water Bureau allows infiltration in this area if spill containment is provided.

4 Assessing and Mitigating Potential Stormwater Infiltration Impacts on Water Balance and Groundwater Quality

This section is intended to provide guidance for assessing the potential for impacts of stormwater infiltration related to water balance and groundwater quality. This section also provides recommendations for mitigating these potential impacts to potentially improve the level of infiltration that can safely be achieved in the highway environment.

What and how should factors be considered in evaluating whether infiltration of roadway runoff is infeasible or undesirable related to site water balance and groundwater quality?

How can potential impacts be mitigated to reduce risks and improve feasibility and desirability of infiltration?

This section is divided into seven key factors that should be considered in assessing the feasibility and desirability of infiltration related to water balance and groundwater quality:

- Localized groundwater mounding,
- Water balance impacts on streamflow,
- Contamination from stormwater runoff pollutants,
- Soil and groundwater contamination,
- Wellhead and spring protection,
- Special considerations for karst aquifers, and
- Local groundwater management objectives and criteria.

Key to summary tables in this section: The summary tables included within each subsection below contain guidance for evaluating the potential level of risk associated with each feasibility factor and provides recommendations for additional analysis and mitigation measures where site-specific factors suggest that risks may be elevated. The intent of these tables is to help users develop planning level classifications of potential risk. Each of these factors may warrant more extensive analysis than described in this planning level document, but the tables and guidance here will assist in project planning by focusing attention where the potential for impacts is greatest. Where elevated risk indicators are not present, a simplified assessment may be adequate. The greater number of elevated risk indicators present for a given

site indicates a higher level of risk, which may require a more extensive assessment to demonstrate that infiltration can be safely done or may represent a technical basis for infiltration to be considered infeasible. These tables are intended for planning level screening only -- the final determination of whether to implement infiltration in an urban roadway environment should be based on site specific information and analysis, coordination with other applicable agencies, and best professional judgment.

4.1 Localized Groundwater Mounding

The use of infiltration BMPs has the potential to result in elevated local groundwater tables that exceed the natural seasonal high groundwater table or extend the duration of ponding at a site. The mounding potential beneath a BMP is a function of the facility design, the infiltration rate, the precipitation rate, and the hydrogeologic conditions at the site. It is critical for project teams to understand the hydrologic conditions at the site in order to assess mounding and determine the separation to groundwater.

Refer to **Appendix C** for guidance on evaluating risk of groundwater mounding, including an electronic tool that can be used to estimate risks for specific combinations of site conditions.

4.2 Water Balance Impacts on Stream Flows

As discussed in Section 2.2, the use of infiltration systems to reduce surface water discharge volumes may result in additional volume of deeper infiltration compared to natural conditions, which may result in impacts to receiving channels associated with change in dry weather flow regimes. This is a function of the local climate, but also the local hydrogeologic conditions. To assist in project planning, several indicators may be used to help evaluate the potential for impacts, as summarized in Table 3. A relatively simple survey of hydrogeologic data (piezometer measurements, boring logs, regional groundwater maps) and downstream receiving water characteristics is generally adequate to determine whether there is potential for impacts and whether a more rigorous assessment is needed. Since linear highway projects typically make up a relatively minor portion of any watershed, a single project is unlikely to significantly change the overall watershed water balance. More typically, the practical question is whether infiltration of highway runoff would exacerbate an existing water balance condition rather than necessarily create a new condition of concern. A review of local watershed conditions may be adequate to determine if this factor warrants further considerations. If water balance concerns do exist in the watershed, or if extensive infiltration is planned, it may be most appropriate to follow the lead of local jurisdictions in terms of watershed-scale priorities and approaches. Where water balance conditions appear to be sensitive to development impacts and there is an elevated risk of impacts, a computational analysis may be warranted to evaluate the feasibility/desirability of infiltration.

Table 3. Risk Factors and Mitigation Measures for Water Balance Impacts on Stream Flows

	Lower Risk Indicators	↔	Elevated Risk Indicators
Risk Factors	• Actively managed aquifer with adequate capacity for additional infiltrated volume • Perennial streams in vicinity that naturally receive base flow from groundwater discharge year round • Relatively simple geology; predictable vertical migration of water • Higher order (larger) streams • Less arid environments. • Proposed BMPs provide substantial ET losses (e.g., filter strips)		• Perched groundwater or shallow, local aquifer • Lower order (smaller) streams • Streams are ephemeral or intermittent. • More complex geology; e.g., sloping strata with potential for lateral migration to channel banks • More arid environments. • Future development is projected over a significant proportion of watershed (potential for cumulative effects)
Potential Additional Studies and Risk Mitigation Measures for Sites with Elevated Risk	• Conduct more detailed investigation of hydrogeology and water fluxes. • Conduct computational analysis of water balance on a long-term basis. • Select BMPs that provide partial infiltration such that there is a more natural balance between infiltration and ET. • Develop a stormwater management strategy involving less infiltration and more treated discharge. • If cumulative development impacts are of concern, potentially collaborate with local jurisdictions to evaluate potential water balance impacts or adhere to findings of studies prepared by local jurisdictions.		

4.3 Pollutants in Stormwater Runoff

As discussed in Section 3.1, the concentration of stormwater pollutants is highly dependent on the land uses and activities present in the area tributary to an infiltration BMP. Likewise, the potential for groundwater contamination is a function of pollutant abundance, speciation of pollutants in soluble forms, and the mobility of the pollutant in the subsurface soils. To assist in project planning, Table 4 provides risk indicators to help evaluate the potential for impacts and identify pollutants that may warrant expanded analysis. This table also provides potential mitigation measures to help reduce risks – these include general mitigation measures, as well as pollutant-specific mitigation measures.

Table 4. Risk Factors and Mitigation Measures for Contamination from Stormwater Runoff Pollutants

	Lower Risk Indicators	↔	Elevated Risk Indicators
Risk Factors	• No roadway salting • Lower traffic volumes, lower heavy truck traffic and contaminant sources[1] • Soils have substantial pollutant attenuation capacity[1] • Depth to mounded seasonal high groundwater exceeds 10 feet • Anthropogenic sources of pathogens are limited in tributary area or groundwater is disinfected before use.		• Significant roadway salting • Higher traffic volumes and contaminant sources[1] • Soils have limited pollutant attenuation capacity[1] • Depth to mounded seasonal high groundwater is less than 10 feet • Sources of anthropogenic pathogens are present in tributary area • Karst topography (see Section 4.7)

Potential Additional Studies and Risk Mitigation Measures for Sites with Elevated Risk	• Determine beneficial uses and water quality standards that apply to groundwater.
	• Evaluate expected stormwater quality vs. local groundwater quality objectives.
	• Characterize depth to groundwater and conduct groundwater mounding analyses (**Appendix C**) to determine risk level.
	• Utilize BMPs that provide treatment to runoff prior to deeper infiltration to address pollutants of concern, such as amended soil media to augment removal capacity of native soil – effective for metals, many organics and bacterial pathogens; some pesticide.
	• Utilize pollutant-specific source controls, as applicable:
	  ○ Pesticides - limit application of water soluble pesticides; utilize pesticides with lower mobility and shorter half-life.
	  ○ Pathogens – provide sanitary facilities; provide animal waste disposal; implement program to clean up animal remains; identify location of drinking water wells and avoid infiltration near wells.
	  ○ Salts – limit application, consider alternative methods, and potentially divert runoff from salted roadways in cold weather.
	• Identify expected high source areas, such as maintenance yards and gas stations, and design drainage system to hydrologically isolate these areas from infiltration BMPs.
	• Develop a stormwater management strategy involving less or no infiltration in cases where potential contamination cannot be mitigated.		

1 – Indicators of loading and soil pollutant attenuation capacity are included in the following bullet lists.

The following list includes indicators of elevated sources that may be applicable in the urban highway environment (SARWQCB 2009; WADOE 2012; USEPA 2009):

- Average daily traffic volume - A traffic volume threshold of 25,000 or 30,000 average daily traffic (ADT) has been applied in stormwater permits and guidance documents as an indicator of conditions that could potentially threaten groundwater quality. Note that some researchers attributed potential water quality concerns in these areas as general urban sources vs. the specific traffic volumes (i.e. with ADTs of this level, monitoring sites were located in denser urban land use areas.)
- Industrial sites subject to an expected average daily traffic count (ADT) ≥100 vehicles/1,000 ft² gross building area (trip generation). Particularly those with heavy truck traffic.
- Other areas with potential high threat to water quality, such as industrial or light industrial activities; fleet maintenance, storage, and/or wash yards.
- Material storage areas, such as asphalt or salt storage areas.
- Agricultural land uses and nurseries.
- Other locally applicable guidance at the discretion of the project engineer.

The following list includes indicators of the pollutant attenuation capacity of soils (WADOE 2012):

- Cation exchange capacity (CEC) of the treatment soil should be at least 5 milliequivalents CEC/100 g dry soil (USEPA Method 9081). CEC values of greater than 5 meq/100g are expected in loamy sands, according to Rawls, et al. Lower CEC content may be considered if it is based on a soil loading capacity determination for the target pollutants that is accepted by the local jurisdiction.
- Organic content of the treatment soil (ASTM D 2974): Organic matter can increase the sorption capacity of the soil for some pollutants. A minimum of 1.0 percent organic content is recommended.
- Depth of organically active soils. An assessment of CEC and organic content should encompass all distinct layers below the base of the facility to a depth of at least 2.5 times the maximum design water depth, but not less than 6 feet.
- Other locally applicable guidance at the discretion of the project engineer.

4.4 Existing Soil and Groundwater Contamination

Section 3.2 describes the potential impacts that may result when stormwater is infiltrated in the vicinity of existing groundwater plumes, contaminated soils, septic systems, cemeteries, municipal solid waste disposal sites, and other potential sources of groundwater pollution. When conducting a site assessment to assess the feasibility of stormwater infiltration, the following sources may contain information that is useful in determining the potential risks associated with existing contamination:

- Records of previous uses of the site. This can indicate whether contamination may exist. This is a standard element of environmental site assessments that normally accompany land acquisition that was previously developed.
- Presence of historical fill materials and records of the source of these materials, if available. Historical fills in urban areas may have included industrial wastes that have residual

contamination. Additionally, beneficial re-use material (e.g., fly ash, foundry sand, cinders, other) may have been used in road construction zones and may pose a groundwater quality risk if water is infiltrated through these materials. Presence of historical fill materials indicates a higher risk that needs to be investigated unless records clearly demonstrate that they were from a clean source.

- Locations of current or historic septic systems, cemeteries, historic (informal) refuse dumps.
- Mapping of contaminated groundwater plumes and soils, which are typically available from local groundwater management agencies or state environmental quality agencies. For example, spatial databases and layers containing contaminated sites were identified in California, New Jersey, Connecticut, and Alaska (see References) as part of this effort; similar resources likely exist or are under development in other states.
- USEPA Envirofacts database (https://www3.epa.gov/enviro/), which contains locations and information regarding RCRA, CERCLA, brownfields, and clean-up sites (USEPA 2012a). Individual states may also have more detailed information available. Note that even closed sites may present a risk as they may have been approved to leave the contamination in place.

Table 5 summarizes risk factors that may indicate an elevated degree of risk and provides recommendations for potential mitigation measures related to infiltrating near groundwater plumes or contaminated soils.

Table 5. Risk Factors and Mitigation for Groundwater Contaminant Plumes and Soil Contamination

	Lower Risk Indicators	Moderate Risk Indicators	Elevated Risk Indicators
Risk Factors	• Contamination not suspected at site • Local data confirms no contamination • Historic land uses do not include industrial, agricultural or other uses suggesting potential for contamination • Not built on historical fill • Septic systems, cemeteries, municipal solid waste sites not present in project vicinity	• Historic site uses included industrial, agricultural, or other uses suggesting potential contamination, but contamination is unknown • Historic contamination is documented but has been fully remediated	• Known contamination at the site • Historical fill of unknown source or of documented deleterious quality. • Older urban areas built on fill materials. • Groundwater plumes (natural or unnatural) exist in site vicinity • Septic systems, cemeteries, former or current mining activities, municipal solid waste sites present in site vicinity and hydrogeologic connections with these sources are possible
Potential Additional Assessments and Risk Mitigation Measures for Sites with Elevated Risk	• Consult with regulatory agencies responsible for site cleanup and groundwater protection regarding potential benefits or consequences associated with stormwater infiltration at the site (see Section 5). • Conduct more detailed investigation of potential contamination to reduce uncertainties and better quantify potential risk. • Site infiltration BMPs to avoid infiltration of stormwater where there is significant unavoidable risk of mobilizing of pollutants or spreading of groundwater plumes. • Develop a stormwater management strategy involving less or no infiltration. • For large, centralized infiltration facilities, consider installing shallow groundwater monitoring wells to permit characterization of baseline groundwater quality and post project groundwater quality data.		

4.5 Wellhead and Spring Protection

The Safe Drinking Water Act or 1974 established the authority for the EPA Sole Source Aquifer (SSA) program, which requires EPA review of federally funded projects that lie within an SSA (https://www.epa.gov/dwssa). In 1986 the Safe Drinking Water Act (SDWA) was amended to require states to develop Wellhead Protection Programs. The SDWA was again amended in 1996 to require states to create a Source Water Assessment Program for all their public drinking water systems. This has led to the

development local wellhead protection and source water protection programs that may include statutes, policy, criteria and/or guidance related stormwater infiltration. This may include guidance and criteria that apply to entire wellhead protection zones (such as a portion of a watershed) or may be based on proximity to a production well (such as a 200-ft setback). See additional discussion in Section 5.

When assessing infiltration feasibility, state and local wellhead protection and source water protection programs should be reviewed to determine applicable criteria and guidance. Setbacks of 100 to 200 feet from springs and wellheads are typical in existing guidance (OCPW 2013, VCWPW 2011; WADOE 2012). In Washington State, a wellhead protection zones are also defined by the 1-year, 5-year, and 10-year travel times.

In absence of an applicable policy, it may be appropriate to develop site-specific setbacks. Table 6 summarizes the risk indicators associated with infiltration near wellheads and springs and recommends potential mitigation measures. However, where local programs and guidance exist, they should supersede Table 6.

Table 6. Risk Indicators for Wellhead and Stream Protection

	Lower Risk Indicators ↔	Elevated Risk Indicators
Risk Factors	• No springs or wellheads in close proximity downgradient of infiltration BMPs (greater than 100 to 200 feet; and greater than 1-year travel time, as applicable) • Low levels of contaminants expected in stormwater runoff after effective treatment • Roadways are not salted • Infiltration rates are low, and soils have substantial pollutant attenuation capacity • Groundwater is relatively deep (greater than 10 to 20 feet) • Higher flow-through rate of aquifer helps dilute salt plumes (if deicers used)	• Springs, wellheads, and/or gaining streams in close proximity downgradient of infiltration BMPs (less than 100 to 200 feet; or within 1-year travel time, as applicable) • High levels of contamination in stormwater runoff even after effective treatment • Roadways are salted • Infiltration rates are high, and soils have more limited pollutant attenuation capacity • Groundwater is relatively shallow (less than 10 to 20 feet) • Lower groundwater flow-through rate contributes to buildup of salt (if deicers used) • Karst topography (see Section 4.7)
Potential Risk Mitigation Measures for Sites with Elevated Risk	• Locate infiltration BMPs to maintain recommended setbacks. • Coordinate with local water provider or health department responsible for wellhead protection. • Follow mitigation measures for pollutants identified in Section 4.4. • Follow mitigation measures for existing soil and groundwater contamination in Section 4.3. • Assess potential acute effects of salt on nearby water wells (See Section 4.5.1 and the Groundwater Quality Assessment Tool in Section 7) • Install groundwater monitoring stations to evaluate impacts and inform operation. This could be coupled with an adaptive management approach. • Develop a stormwater management strategy involving less infiltration; infiltration of the full water quality volume may not be feasible or desirable if recommended setbacks cannot be preserved and/or risks to drinking water supplied or springs cannot be avoided.	

4.5.1 Acute Salt Impacts

If there are nearby wells that draw from unconfined aquifers, the potential for acute salt impacts on the well is a primarily a function of the salt loading rate relative to the dilution provided by lateral groundwater flow. This can be strongly influenced by local factors such as the thickness and gradient of the unconfined aquifer, the direction of flow relative to the roadway, the layering of soils, and other factors. The Groundwater Quality Assessment Tool was designed to help assess potential impacts and evaluate the sensitivity of factors contributing to acute salt impacts. If drinking water wells are located near infiltration BMPs that receive road salts, this Tool can be used as a preliminary, conservative assessment of the potential degree of impact (See Section 7). Note, the tool is based on modeling conducted for Madison, WI. The tool allows results to be scaled to other climates that receive similar patterns of precipitation (e.g., ratio of cold weather precipitation to warm weather precipitation) as Madison, WI. The tool can be reasonably extended to include CO, MT, WY, the Midwest, and the Northeast (including NY, NJ, and PA). It does not apply west of the Rocky Mountains or the Southeast, South, or Southwest.

The following publications can also serve as a reference for users:

Mullaney, J.R., Lorenz, D.L., Arntson, A.D. 2009, **Chloride in groundwater and surface water in areas underlain by the glacial aquifer system**, **northern United States**: USGS Scientific Investigations Report 2009–5086, 41 p. https://pubs.usgs.gov/sir/2009/5086/

Kunze, A.E. and Sroka, B. N. 2004. **Effects of highway deicing chemicals on shallow unconsolidated aquifers in Ohio--final report.** USGS Scientific Investigations Report 2004-5150. https://pubs.usgs.gov/sir/2004/5150/pdf/SIR2004_5150.pdf

Watson, L.R., Bayless, E.R., Buszka, P.M, Wilson, J.T. 2002. **Effects of Highway-Deicer Application on Ground-Water Quality in a Part of the Calumet Aquifer, Northwestern Indiana**. USGS Water-Resources Investigations Report 01–4260. Indianapolis, Indiana 2002. https://in.water.usgs.gov/newreports/watson-roadsalt.pdf

Corsi, S.R., Graczyk, D.J., Geis, S.W., Booth, N.L., and Richards, K.D. 2010. **A fresh look at road salt: Aquatic toxicity and water-quality impacts on local, regional, and national scales.** Environ. Sci. Technol., 2010, 44 (19), pp 7376–7382. https://pubs.acs.org/doi/abs/10.1021/es101333u

Bester ML, Frind EO, Molson JW, Rudolph DL. **Numerical Investigation of Road Salt Impact on an Urban Wellfield**. Ground Water Vol. 44, no.2: 165-175. https://www.ncbi.nlm.nih.gov/pubmed/16556199

4.6 Contaminant Spills

As discussed in Section 3.3, contaminant spills are a constant risk on roadways, with the potential to deposit high volumes of pollutants before responders can control the source of the spill. However, the most common spills are petroleum hydrocarbons, and the risk of these spills contaminating groundwater can generally be mitigated with appropriate measures. Where local groundwater protection requirements are in place, these requirements may include more rigorous spill containment measures to mitigated risks. Table 7 provides indicators of elevated risk and recommendations for potential mitigation measures to reduce these risks.

Table 7. Risk Factors and Mitigation Measures for Contaminant Spills

	Lower Risk Indicators	↔	Elevated Risk Indicators
Risk Factors	• Lower traffic roadways with lower heavy truck traffic • Groundwater is relatively deep (greater than 10 to 20 feet) • Tributary area does not contain fueling stations, warehouses, storage tanks, or similar potential sources of spills		• The aquifer is a sole source aquifer or otherwise is a very important local or regional water supply • Higher traffic roadways, particularly for truck traffic • History of spills in nearby area may be indicative of higher risk • Groundwater is relatively shallow (less than approximately 10 feet) • Tributary area contains fueling stations, warehouses, storage tanks, or similar potential sources of spills • Karst topography (see Section 4.7)
Potential Risk Mitigation Measures for Sites with Elevated Risk	• Include amended media treatment layer below the infiltration media, as needed when inert sandy or gravely soils are present, to improve sorption capacity to retain spills and improve bioremediation potential. • Consider treatment train options: oil-water separator, oil contamination boom, media filters, biofiltration systems, vegetated filter strip, upstream of infiltration system. • Develop spill response plan for project if a general spill response plan is not already administered by the project owner; include provisions for protection and remediation of stormwater BMPs in the event of a spill. • Include an isolation/diversion mechanism that can be activated by emergency responders in the event of a spill to prevent contamination from either entering the BMP if adequate storage is available and/or capturing the spill within the BMP prior to discharge to either groundwater or a surface receiving water; note it may not be practicable to isolate or divert flow from some BMP types, such as permeable pavement shoulders or filter strips which receive runoff as sheet flow.		

4.7 Special Considerations for Karst Topography

Karst topography refers to a specific geologic formation that has been shaped by the dissolution of soluble bedrock elements. Karst topography is most frequently associated with limestone or dolomite rock but may

be present in other types of rock as well. The karst landscape is characterized by containing sinkholes, underlying caves, and springs. Karst topography is present in various locales throughout the United States and is not characteristic of any one region.

Karst topography has extreme potential for groundwater contamination from stormwater infiltration. Surface soil layers are thin. Karst aquifers also provide the potential for direct hydraulic connections from the surface to groundwater via sinkholes, springs, and caves (Donaldson 2004; Weiss et al. 2008).

Unless site-specific analyses determine that infiltration can be safely achieved without impacts using robust treatment and spill containment methods, infiltration of roadway runoff should be avoided in Karst areas. Per the USEPA Underground Injection Control (UIC) program, an "Improved Sinkhole" is a Class V Injection Well requiring permitting, inventory, and reporting (https://www.epa.gov/uic).

5 Consultation with Local, State, and Federal Agencies

In the case of wellhead or source water protection programs, consultation with local, state groundwater management entities may be required. In the absence of required consultation, it can still be beneficial for DOTs to coordinate with agencies responsible for local groundwater management and underground utilities and resource agencies when infiltration is considered for a project. These agencies can clarify criteria that apply and often have extensive knowledge about these resources.

5.1 Local Groundwater Suppliers

Consulting with applicable groundwater supply agencies early in the project development process can help simplify the process of evaluating feasibility and desirability of infiltration. Through wellhead and source water protection programs, agencies may have locally applicable guidance, criteria, maps, or other resources that have already been developed. Groundwater supply agencies with groundwater management authority may include local governments, special water supply districts, or others.

A potential model for inter-agency coordination was developed in Orange County (CA) as part of development of the Orange County Technical Guidance Document (OCPW, 2013; http://prg.ocpublicworks.com/DocmgmtInternet/Download.aspx?id=1098; see Appendix VIII). The Technical Guidance Document was developed by Orange County Public Works (OCPW) and includes guidance of evaluating the feasibility of infiltration stormwater, with consideration of groundwater quality, among other factors. The Orange County Water District (OCWD) is a public agency responsible for providing water to more than 20 cities and more than 2 million residents of Orange County. OCWD is responsible for management of the water quality and basin yield of the groundwater basin that underlies the Santa Ana River in northern Orange County. OCWD was actively involved in the development of the Technical Guidance Document, as they have an interest in enhancing groundwater supplied through infiltration and have significant concerns about the potential for groundwater contamination due to stormwater infiltration. Through a collaborative approach, OCPW and OCWD developed criteria acceptable to both agencies, including the use of groundwater levels and plume locations provided from OCWD records to help develop screening tools. The agencies also established a process by which projects identified as having an elevated risk of groundwater impacts would be submitted for review by OCWD.

5.2 Water Resources Protection Agencies

Groundwater protection requirements are typically administered by state environmental quality agencies or regions of USEPA. These agencies are commonly the same agencies responsible for administering stormwater and surface water regulations; however different departments may be responsible for surface

water quality versus groundwater quality. Consulting with local resource agencies responsible for groundwater quality protection can also help streamline the process of evaluating feasibility and desirability of stormwater infiltration, for many of the same reasons introduced in Section 5.1. Water resources protection agencies are typically responsible for establishing groundwater quality objectives and developing plans to protect or improve groundwater quality, where needed. These agencies are also typically responsible for administering the cleanup of contaminated sites. Because of their multiple-resource purview, these agencies may be able to help provide input and strike a balance between the surface water quality benefits of stormwater infiltration versus potential impacts to water balance or groundwater quality. Consultation can also help identify if stormwater infiltration would have the potential to exacerbate existing problems that resource protection agencies are working to address.

5.3 EPA Underground Injection Control (UIC) Program

Depending on the location and design, infiltrating facilities may be considered "Class V Injection Wells" under the USEPA Underground Injection Control (UIC) program. Class V wells are defined as systems that are used to inject non-hazardous fluids underground, which could include drywells or deep infiltration basins. The minimum requirements for compliance are that fluid injected underground may not endanger underground drinking water sources and that the owners/operators must submit the required inventory information to their permitting authority. Some areas may have additional requirements and more information is available on the EPA website (https://www.epa.gov/uic). UIC programs are generally administered by EPA regional offices or state environmental quality agencies.

5.4 EPA Sole Source Aquifer Program

The EPA Sole Source Aquifer (SS) program (https://www.epa.gov/dwssa) allows EPA to design an aquifer as sole source, determine a review area for the SSA, and provides for EPA review of federally-funded projects within the SSA review area. More information is available at https://www.epa.gov/dwssa. Regional memorandums of understanding (MOUs) may provide more details about this review process.

5.5 Sanitation Districts and Other Underground Utilities

Infiltration of stormwater from roadway projects has the potential to elevate local groundwater tables, which can increase the amount of inflow and infiltration (I&I) to the sanitary sewers and/or cause impacts to other utilities. This risk is particularly high where groundwater levels are already relatively close to the elevation of sewer and/or utility elevations. Infiltrated stormwater can migrate into sewer lines, or flow within utility trenches.

The local operators of sewer collection and treatment systems should be consulted early in the planning process to evaluate whether stormwater infiltration may pose a concern related to increases in inflow and infiltration. An increase in inflow and infiltration may place an additional burden on these agencies, with respect to hydraulic conveyance capacity and waste water treatment plant treatment capacity, potentially resulting in increased incidence of sewer overflows in combined sewer areas. However, increased infiltration reduces the amount of water the discharges directly to sewers, so even in areas with significant I&I, the overall impact will typically be a reduction in total sewer flows. Local sewer agencies may have locally applicable criteria, maps, or other resources that have already been developed to assist in identifying areas where increased stormwater infiltration may be undesirable.

Similarly, agencies or companies that operate other underground utilities may have specific concerns regarding infiltration of stormwater and/or resources to assist in evaluating feasibility and desirability.

6 Summary

The potential risks of stormwater infiltration on water balance and groundwater quality are influenced by many site-specific factors, as introduced in this Guide. Careful attention should be paid to any site-specific actors that indicate elevated risks. These factors may indicate the need for mitigation measures that can be include in BMP selection, siting, and design. Measures for reducing risk include thorough site characterization, appropriate pretreatment, soil amendments, selection of appropriate infiltration sites, adherence to local wellhead protection criteria, and observance of minimum separation criteria between infiltration BMPs and the groundwater table. With these measures, the risks if stormwater infiltration are typically relatively low Additionally, watershed-scale plans and/or source water protection plans prepared by local jurisdictions may provide guidance for how cumulative risks can be mitigated to an acceptable level.

In some cases, site-specific factors can render infiltration wholly infeasible or undesirable. Failure to identify these conditions and make appropriate decisions about stormwater infiltration can result in impacts to water balance and/or groundwater quality which can create legal liability for a DOT. DOTs should have a comprehensive screening process to ensure that, where these factors are present, they are identified and have the appropriate “no-go” effect in infiltration decision making.

7 User’s Guide for the Groundwater Quality Assessment Tool

7.1 Introduction

The Roadside BMP Groundwater Water Quality Assessment Tool (the Tool) was developed to provide an interactive semi-quantitative framework to assess the magnitude and potential impacts associated with infiltration of stormwater runoff containing deicing salts in the highway environment. The Tool was developed based on results of pre-processed HYDRUS2D simulation models representing a range of groundwater table conditions including soil type, degree of soil layering, groundwater thickness and gradient. Climate and salt inputs in the tool were based on data for Madison, Wisconsin and the Wisconsin DOT, respectively, however, the Tool permits adjustment of average annual precipitation.

Within the tool, the user can select inputs describing the baseline site configuration and rapidly view the post-processed results of HYDRUS simulations corresponding to the defined scenario. The tool produces visualizations and summaries relating to groundwater response and salt application on highway during winter season.

Guidance for using the Tool is embedded within the Excel file. The following sections supplement the guidance provided within the tool to guide the user in selecting appropriate parameters. Technical documentation of tool calculations is also provided.

7.1.1 Limitations and Intended Uses

While certain estimates provided by the tool are quantitative, the interpretation of these visualizations is inherently semi-quantitative. This tool does not account for site-specific conditions and inherent environmental variability which may deviate from idealized modeling assumptions. This tool is primarily intended to be used for preliminary screening of risk factors and evaluation of sensitivity of site and BMP conditions. In cases with clearly low risk, the tool could be used as one line of evidence to justify a simple investigation of groundwater quality issues, such conducting investigations to verify that the tool assumptions are reasonably representative of the site. For more marginal conditions, the tool could be used

as a basis to reject the use of infiltration, collect more site data, or identify BMP locations or configurations that pose less risk.

The tool is based on modeling conducted for Madison, WI. Results are based on the precipitation patterns and deicing season typical of Wisconsin. The tool allows results to be scaled to other climates that receive similar patterns of precipitation (e.g., ratio of cold weather precipitation to warm weather precipitation) as Madison, WI. On this basis, the tool can be reasonably extended serve as a screening-level tool in CO, MT, WY, the Midwest, and the Northeast (including NY, NJ, and PA). Users should enter local precipitation depths and salting rates. The tool does not apply west of the Rocky Mountains or the Southeast, South, or Southwest.

The tool is based on two-dimensional water movement and salt transport. This does not allow attenuation in the direction of the roadway. Therefore, results effectively represent BMPs continuously applied along the length of the road. Therefore, results are conservative where BMPs are located at discrete intervals with spacing between them.

7.2 General Use of Tool

7.2.1 System Requirements

- The tool is intended to run in Microsoft Excel 2016; Most of the calculation routine is functional in older versions of Excel. However, the graphs and figures appearances may differ in older versions of Excel.
- The tool has been tested in a Windows 10 environment; user experience may differ in other operating system environments.
- The tool involves no traditional “installation”, therefore should generally not require administrator privileges to use. For users operating within strict security settings, administrator privileges may be required to enable macros within Excel.

7.2.2 Workflow of the Tool

To start a new project, follow these steps:

- Open the original tool spreadsheet by double-clicking the .xlsm file (this may need to be extracted from a zip folder depending on how the tool is obtained).
- Select the groundwater thickness, groundwater gradient, soil type and degree of soil layering from dropdown menus provided in the baseline configuration input section of the Tool.
- Select site-specific parameters using slide bars and dropdown menus provided in the site-specific input section of the Tool.
- The tabular results and visualizations be updated in real-time as users modify the input.
- Once the inputs are populated to best match the scenario, check the visualization and tabular results to support BMP feasibility screening.
- The worksheet can be printed using native Excel print functions. The user can use Excel menus to specify the paper size, printer preferences, and print ranges. Please consult Excel documentation and help files for guidance on printing from Excel.

These steps can be followed for each project/scenario being analyzed with the tool.

7.2.3 Organization and Navigation of the Tool

The inputs and output sections in the Tool are organized into one worksheet tab to facilitate viewing of the results as users adjust the input configurations as shown in Figure 2. For smaller screens or lower screen resolution, the user may need to scroll to different parts of the worksheet. On larger monitors, most of the tool inputs should fit legibly within a single view.

The Tool is divided into an input section, a tabular simulation result summary and a time series visualization section. While using the Tool, users can select a baseline configuration that best matches the groundwater table condition of the site of interest. Subsequently, users can adjust the salt loading related parameters and assess the chloride concentration from the tabular summary and time-series visualization.

The tool is password protected to inhibit accidental adjustment of data. The worksheet may be unprotected using the password "NCHRP". The user should not need to access the other tabs.

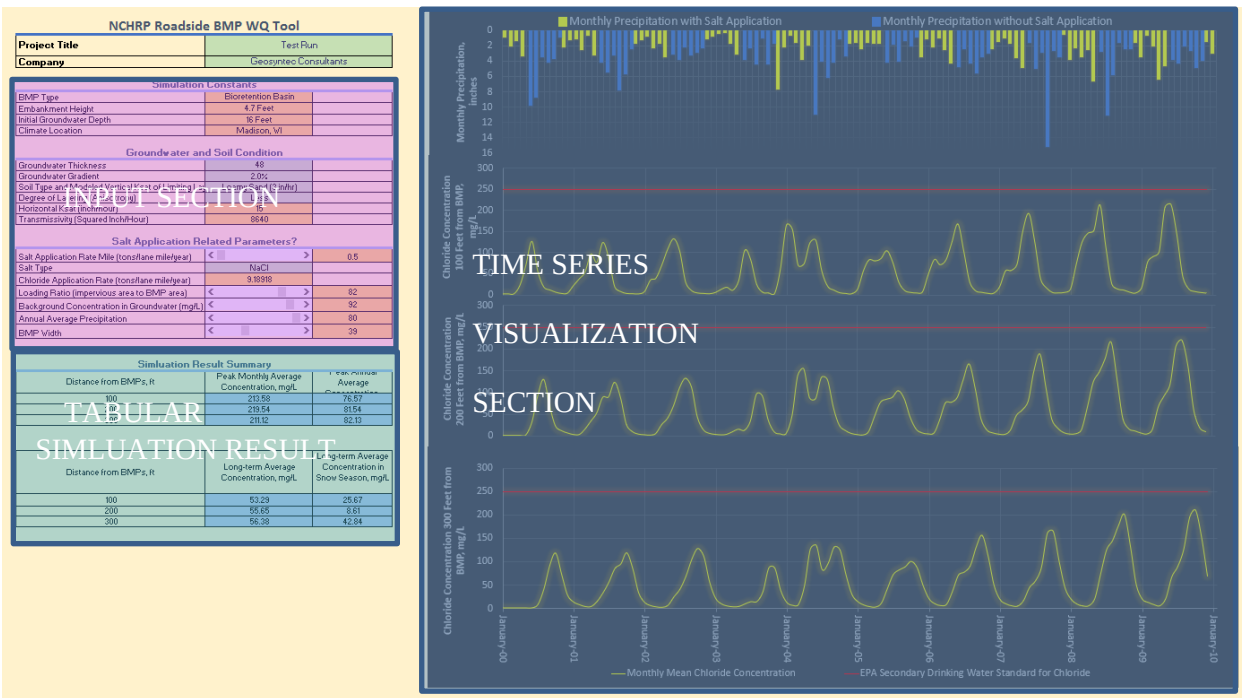

Figure 2. User Interface of NCHRP Roadside BMP Groundwater Quality Tool

For each input parameter, a dropdown selection menu or a slide bar is provided for the user. The values on the dropdown menus are discrete representative values in each input category. The slide bar also allows users to select values from representative range for each input parameter. As a result, the user needs to select the input parameter that best match the design scenario. If the actual conditions at a site are between the input increments, then the user could evaluate results that bracket the site conditions and interpolate between these values as a simple screening approach.

7.3 Tool Inputs

7.3.1 Simulation Constants

Each of the HYDRUS model runs that supports this tool is based on a constant set of simulation constants which include the cross-section geometry of the BMP (3-feet deep, 40-foot wide in the direction of groundwater flow), the loading ratio (20:1), and climate condition (Madison, WI). Madison, WI was used to represent evapotranspiration and precipitation because it is a location where salt is routinely applied on roadways during winter seasons. Precipitation patterns are similar to much of the upper Midwest and Northeastern United States.

A scaling approach is described in Section 7.5, which allows results to be estimated for different combinations of inputs.

BMP Geometry

The infiltration surface of the basin is located at the bottom of the embankment and is designed to collect runoff from the roadway. Water is infiltrated through an amended media layer. The infiltration surface of the basin is 16 feet above the initial groundwater depth. The modeled baseline basin is 3-foot deep with a 1.5-foot deep gravel layer at the bottom. Basins was modeled with a width of 40 feet perpendicular to the roadway, which is also perpendicular to the flow of groundwater. The user can modify the width of the BMP in the salt application parameter input as shown in Section 7.3.

Climate

Climate input determines the precipitation and the evapotranspiration (ET) patterns that were applied to the scenario in the HYDRUS model. A weather station in Madison, WI was chosen. The 10-year continuous precipitation data between January 2000 and December 2009. The average annual depth during this period was 36 inches. Users can adjust the precipitation depth to represent a specific location but are not able to modify the seasonal pattern of precipitation or salt loading. In the HYDRUS model, salt was applied from November to April every year. Figure 3 illustrates the monthly precipitation input applied in the models.

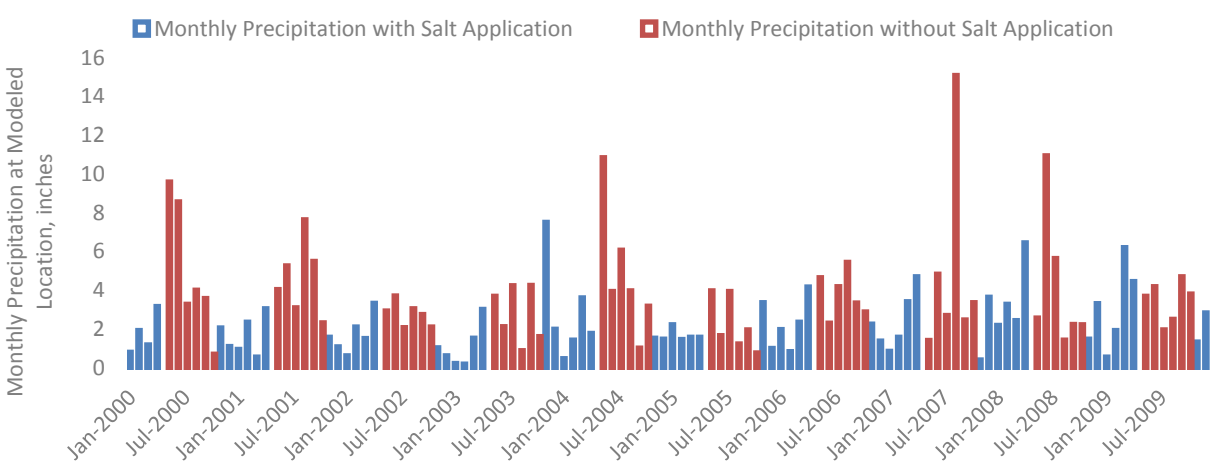

Figure 3. Continuous Precipitation Input in HYDRUS Models at Madison, WI

The monthly evapotranspiration data was obtained from NCHRP Report 802 (Strecker et al., 2015) and is shown in Figure 4. The monthly potential ET values were applied in the HYDRUS models throughout the 10-year simulation period.

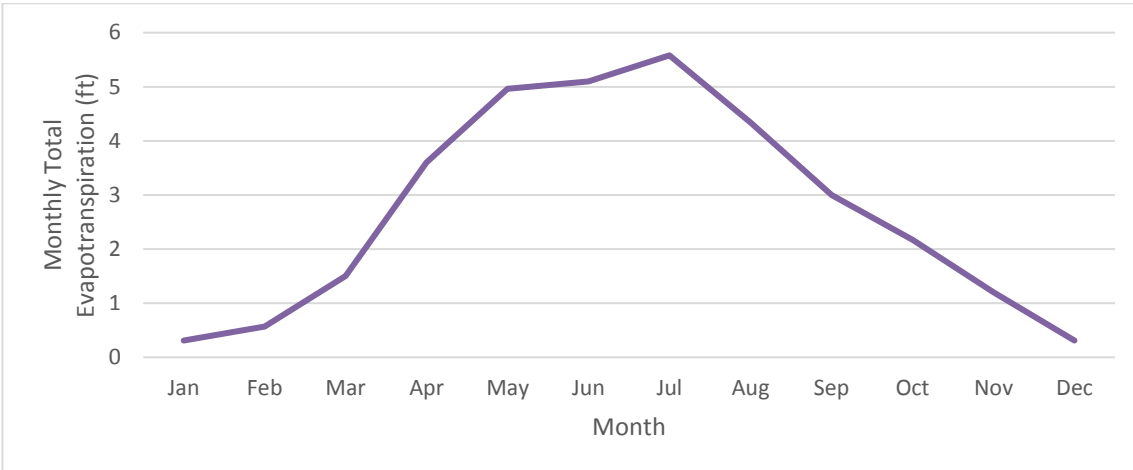

Figure 4. Modeled Monthly Potential Evapotranspiration at the Madison, WI Climate Station

7.3.2 Groundwater and Soil Condition

Each HYDRUS model is based on a unique combination of groundwater and soil condition. By selecting a combination of groundwater thickness, gradient, soil type and degree of layering that best assembles the site condition, the Tool allows users to display the simulation results from a baseline model run that is closest to the design scenario. Each of the four groundwater/soil input parameters will be explained in detail.

Groundwater Thickness

The transmissivity of the unconfined aquifer, which is defined as the volume of water flowing through the aquifer is computed using the following equation:

$$T = Kb$$

Where T is transmissivity, K is the horizonal hydraulic conductivity and b is the thickness of the aquifer. As such, the thickness of aquifer is directly proportional to the transmissivity, which determines the amount of water flux going through the aquifer underneath the BMP infiltration surface. Users can select from three s of aquifer thickness available in the Tool: 12, 24 and 48 feet.

Groundwater Gradient

The water flux going through the aquifer in the HYDRUS models is calculated using the following equation:

$$v = -Ki$$

Where *v* is the aquifer water flux, K is the hydraulic conductivity and *i* is the gradient of the aquifer. As such, the aquifer water flux is directly proportional to the gradient of the aquifer. Users can select from four levels of aquifer gradient available in the Tool: 0%, 0.1%, 0.5%, 2%. This should be the regional

groundwater gradient in the vicinity of the highway and BMP. It should not account for local increases in groundwater gradient caused by the BMP. Such localized increases are accounted for in the simulation.

Soil Type

Soil type determines the modeled saturated hydraulic conductivity used in the HYDRUS models as well as other soil properties. Simulations were run for the following soil texture classes and the associated vertical hydraulic conductivity:

Sandy Loam (1 in/hr)

Loamy Sand (3 in/hr)

Sand (15 in/hr)

Other soil parameters, such as porosity and suction properties, were associated with the soil texture class based on default HYDRUS guidance.

Soil Layering

Two levels of anisotropy are included in the HYDRUS model runs, representing a more layered and a less layered soil structure. Anisotropy is the ratio of the horizontal hydraulic conductivity to the vertical hydraulic conductivity. The Tool displays the horizonal hydraulic conductivity based on users' selected soil type and degree of layering. In runs with higher layering (higher anisotropy), the horizontal hydraulic conductivity was greater. This effectively represents a case with layering of higher and lower permeability soils such that water can move laterally within more permeable soils, but vertical infiltration is limited to a lower hydraulic conductivity in the vertical direction based on the less permeable soil layers.

7.3.3 Salt Application Related Parameters

After specifying the groundwater and soil condition, users of the Tool can adjust salt application related parameters to that best represent the design scenario. These parameters either affect the total water flux or the chloride flux during the simulation. Based on the user's selections of salt application parameters, a multiplier is computed and applied onto the simulation result of the baseline simulation model results. The detail of the multiplier calculation is shown in Section 7.5.

Salt Application Rate

The salt application rate is an important input parameter as it determines the concentration and total flux of the salt discharging into the BMP. A default value of 15.3 tons per lane mile per year as sodium chloride (NaCl) was applied to the baseline model, based on records from Wisconsin DOT. This represents 9.3 tons per lane mile per year of chloride. The user can use the slider to choose between 0.5 to 20 tons/lane mile per year.

Salt Type

Users can choose one out of three common types of salt being applied on the highway: sodium chloride (NaCl), magnesium chloride ($MgCl_2$) and calcium chloride ($CaCl_2$). Each type of salt has a different chloride mass fraction as summarized in Table 8. The chloride mass fraction and the salt application rate are used to compute the chloride application rate.

Table 8 Chloride Mass Fraction of Three Salt Types Available in the Tool

Salt Type	Molecular Weight (g/mol)	Chloride Mass (g/mol)	Chloride Mass Fraction
NaCl	58.44	35.45	60.7%
$MgCl_2$	95.21	70.9	74.5%
$CaCl_2$	110.98	70.9	63.9%

Loading Ratio

Loading ratio of a BMP is defined as the area ratio between the impervious roadway that generates stormwater runoff and the BMP infiltrating footprint. The loading ratio determines the total inflow into the BMPs associated with a given volume of precipitation. The default loading ratio in the baseline model is 20:1. Users can select any value between 5:1 and 100:1 using the built-in slider and can specify values outside of this range using the manual entry box.

Background Concentration in Groundwater

The background chloride concentration in groundwater determines the flux of chloride associated with groundwater flow upgradient of the BMP. The default background chloride concentration in groundwater is 10 mg/L. Users can choose any value between 5 and 100 mg/L using the built-in slider.

Annual Average Precipitation

While the same precipitation pattern is used in all HYDRUS model runs (based on patterns at Madison, WI), users can apply a scalar multiplier to the precipitation time series to simulate the precipitation at a different location. Higher annual average precipitation leads to lower concentration of chloride in the runoff discharged into the modeled basin due to the increase in volumetric loading without increasing the chloride flux. The annual average precipitation amount at the modeled weather station is 36 inches per year. Users can choose any value between 10 and 80 inches per year using the built-in slider. Note that precipitation is expressed as water equivalent. Snowfall and snowmelt are not explicitly simulated.

Because the Tool does not permit adjustment to annual precipitation patterns, the Tool is most accurate for areas with similar precipitation patterns to Madison. Specifically, the Tool will be most accurate for areas with a similar annual distribution of runoff that is impacted by salting compared to runoff that is not impacted by salting (i.e., the ratio of salted to unsalted precipitation). Accordingly, the Tool would be most accurate for locations with similar climates such as the Upper Midwest, Great Lakes region, and Northeast. However, by adjusting the total precipitation the Tool may also be used in drier areas that have similar relative seasonal patterns to Madison, Wisconsin (e.g. Denver and the Great Plains). Generally, the Tool would be least accurate for areas with more winter precipitation than summer precipitation (e.g. mountainous regions closer to the Pacific Ocean).

BMP Width

The width of the BMP is defined as the dimension of the infiltration BMP in the direction of groundwater flow. With the same loading ratio, a wider basin increases groundwater concentrations as there is not as

much dilution via water flowing in the aquifer. The width of the baseline model is 40 feet. Users can choose any value between 10 and 100 feet using the built-in slider.

7.4 Simulation Results

7.4.1 Tabular Statistical Summary

Chloride concentration at nodes located 100, 200 and 300 feet away from the BMP along the groundwater movement direction were used to provide a summary of the simulation results. The highest monthly average concentration and the highest average annual concentration are reported for each monitored location. The long-term average concentration throughout the simulation period is also reported. Example summary results are shown in Figure 5.

Reference values are included for the average background concentration, average stormwater concentrations, and the stormwater inflow as a percent of the total water flowing through the model domain. These statistical summaries are based on simulation result from the baseline model and prorated by a multiplier computed based on salt application input parameters. The methodology to calculate the multiplier is explained in Section 7.5.

Simulation Result Summary

Distance Downgradient of BMP, ft	Peak Monthly Average Concentration, mg/L	Peak Annual Average Concentration, mg/L	Long-term Average Concentration, mg/L
100	1,451	529	369
200	1,499	553	383
300	1,346	502	345

Reference Values

Background Chloride Concentration in GW Upgradient of BMP (mg/L)	15
Average Annual Chloride Concentration of Infiltrating Water in BMP (mg/L)	2,166
Long Term Infiltrated Water Volume as Percent of Total Groundwater Flow	15%

Figure 5. Example of Tabular Simulation Result Summary in the Tool

7.4.2 Time Series Visualization

In addition to the statistical summary, a time series visualization is also provided in the Tool as shown in Figure 6. The top quarter of the diagram illustrates the monthly precipitation color-coded by the presence of salt application. The bottom three quarters of the diagram illustrate the monthly average chloride concentration throughout the simulation period at 100, 200 and 300 feet downstream from the BMP infiltration surface.

EPA's secondary drinking water standard for chloride (250 mg/L) is included in the times series for reference. Local criteria may be more stringent. These time series values are based on simulation result from the baseline model and prorated by a multiplier based on salt application input parameters. The detailed methodology to calculate the multiplier is explained in Section 7.5.

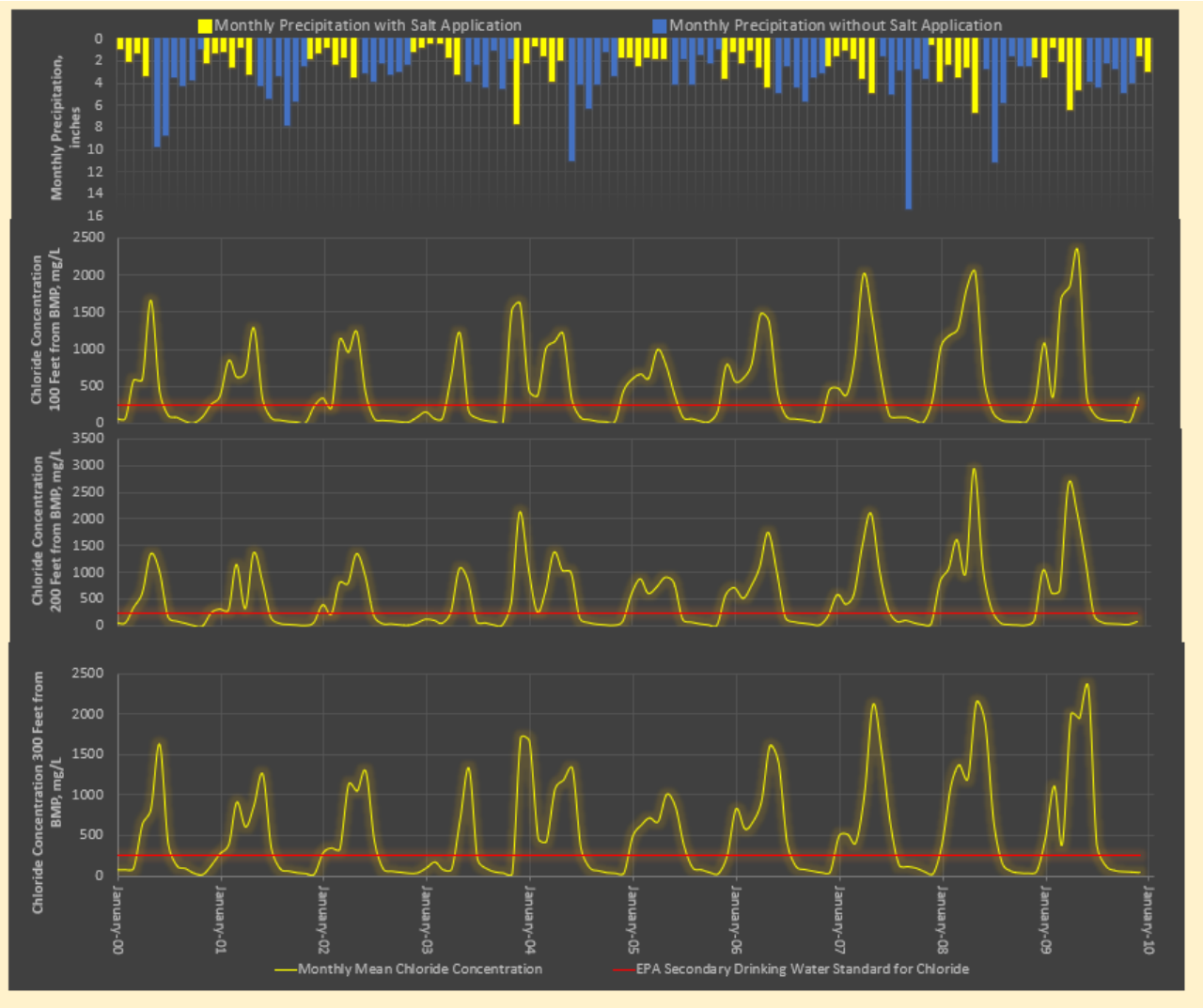

Figure 6. Example Time Series Visualization of the Chloride Concentration in the Tool

7.5 Technical Approach

7.5.1 Results Extraction

Model results were extracted from HYDRUS model domains at observation nodes located various distances from the BMP at various depths within the aquifer. Results were expressed as chloride concentration. Results were extracted from the baseline modeling scenarios described in Section 7.3. Because chloride is effectively a conservative tracer pollutant, the results can be scaled to other combinations of inputs as discussed below.

7.5.2 Multiplier Calculation

Water and chloride enter the model domain via one of two ways: BMP loading or aquifer flow. The relative magnitude of these two sources affects the groundwater concentrations. The tool uses a multiplier approach to account for model parameters that deviate from the scenario that was modeled. Water and chloride flux from stormwater and groundwater sources are estimated based on user inputs. From these inputs, a multiplier is calculated based on mass balance principles, which is then applied to the baseline chloride concentration from the model output and displayed in the tabular summary and time series visualization in the tool. Steps in this calculation are summarized below.

A. Water Flux from BMP Loading

The water flux from BMP loading can be calculated using the following equation based on rational method to calculate stormwater runoff:

$$Q_{BMP} = Loading\ Ratio \times BMP\ Width \times Precipitation \times k$$

Where Q_{BMP} is the water flux discharging into the BMP and k is a unit conversion constant.

The BMP width, annual precipitation, and loading ratio can be adjusted directly by users using the built-in sliders. Each of these as a linear relationship with the amount of stormwater infiltrating per linear foot of highway.

B. Chloride Flux from BMP Loading

The flux of chloride discharging into the BMP can be calculated by multiplying the concentration of chloride by the water flux discharging into the BMP. Adjustments to the salt application rate and average annual precipitation have a direct response on the concentration of chloride entering the BMP. The concentration multiplied by the water flux, with unit conversion, equals the chloride flux.

C. Water Flux from Aquifer

The water flux through the aquifer is calculated using Darcy's Law:

$$Q_{Aquifer} = Ti = Kbi$$

Where $Q_{aquifer}$ is the water flux from aquifer, T is the transmissivity of the aquifer, K is the hydraulic conductivity, b is thickness of the aquifer and i is the gradient of the aquifer. Water flux through the aquifer generally has the effect of diluting salts loading from stormwater runoff.

D. Chloride Flux from Aquifer

The chloride flux from aquifer is directly proportional to the background chloride concentration specified by the user:

- $Cl_{Aquifer} = [Cl]_{Background} \times Q_{Aquifer} \times k$

E. Chloride Concentration Multiplier

The combined average chloride concentration can be calculated by dividing the total chloride flux computed from the Step B and D by the total water flux computed from Step A and C. This calculation is done for both the baseline model and the modified scenario using the following equation:

$$[Cl]_{Total} = \frac{Cl_{BMP} + Cl_{Aquifer}}{Q_{BMP} + Q_{Aquifer}}$$

Subsequently, the ratio of combined chloride concentration between the modified scenario and the baseline model is used as a scalar multiplier used to scale the concentration of chloride at each location in the baseline model. The prorated results are displayed in the tool as the user adjusts parameters.

7.6 Results Interpretation and Known Limitations

Several assumptions should be considered in interpreting results:

- Modeling analyses were performed in two dimensions - vertical and in the direction of groundwater flow the roadway. This inherently does not account for lateral dispersion perpendicular to the direction of groundwater flow. Therefore, results may be conservative, particularly for centralized facilities and for points further away from the BMP. In these cases, it would be likely for a three-dimensional dispersion field to have important effects. In contrast, if a BMP system is linear or BMPs have relatively uniform spacing along a section of roadway, the two-dimensional simplification has less influence.
- Model inputs assumed that all applied salt washes off the roadway and is immediately soluble. In real systems, there is likely to be incomplete recovery of applied salt and there may be a lag for some portion of the mass of salt to solubilize in stormwater. Therefore, the model may predict higher peak concentrations than would be expected in real systems.
- Modeling was performed for a certain chloride application rate (9.3 tons Cl /lane mi/year), BMP loading ratio (20:1), and climate (Madison, Wisconsin) for various combinations of soil type, layering, groundwater gradient and thickness. Due to the conservative nature of chloride, these results can be scaled for other salt application rates, background concentrations, BMP loading rates, and annual precipitation depths. However, some factors, such as the pattern of precipitation and the pattern of plume migration cannot be scaled, so the Tool is most accurate for areas with similar relative precipitation patterns between winter (i.e. salting season) and the remainder of the year. Given this, the tool can be reasonably extended to include CO, MT, WY, the Midwest, and the Northeast (including NY, NJ, and PA) if the user enters local data for annual precipitation depth and salt application ratios. t does not apply west of the Rocky Mountains or the Southeast, South, or Southwest.
- Concentrations are based on the average of saturated observation nodes at the specified distance from the BMP. For cases with steeper groundwater gradients, fewer nodes may saturated at downgradient locations than upgradient locations, therefore a different number of nodes would

be included in the average. This can result in the appearance of minor increase in concentration with distance from BMP, however this is a modeling artifact.

- In the base simulations, nearly all water was infiltrated. This may not be true of all BMPs, particularly those with relatively high loading ratios and/or finer grained soils. Therefore, this is somewhat conservative for assessing groundwater quality effects.
- It is reasonable to interpolate between modeling scenarios.
- Results are only presented for a shallow, unconfined aquifer, assuming simple hydrogeology. Results are not relevant for confined aquifers or for sites with complex soil layering.
- Results are only presented for up to 300 feet from the roadway. If there are no impacts identified at this distance, then there should be no impacts at further distances. If there are impacts at this distance, an analysis should be done that includes site-specific consideration of lateral dispersion processes.

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