Appendix C

Roadside BMP Groundwater Mounding Assessment Guide

and

User's Manual for Groundwater Mounding Assessment Tool

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

Appendix C

Roadside BMP Groundwater Mounding Assessment Guide and User's Manual for Groundwater Mounding Assessment Tool

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1 Introduction

1.1 Purpose and Orientation

Groundwater mounding refers to the development of localized high groundwater below BMPs on a temporary basis in response to stormwater infiltration. The development of a groundwater mound is an inherent hydrogeologic phenomenon in response to point loading of stormwater infiltration at levels greater than background conditions. In effect, the local hydraulic gradient formed by the mound is the mechanism by which water is transferred laterally away from the point loading. However, the height and duration of the mound can vary greatly depending on a range of factors.

Groundwater mounding can lead to several types of problems as introduced in this Guide. As such, an assessment of potential groundwater mounding serves critical roles as part of screening the feasibility of infiltration BMPs and supporting design decisions. This Guide is intended to help the user (1) understand the risks posed by mounding, (2) understand the factors that affect mounding, (3) evaluate how these factors influence mounding risk, and (4) apply tools to support this evaluation based on the combinations of conditions that exist at a given site. This Guide is accompanied by an Excel-based Groundwater Mounding Assessment Tool.

1.2 Risks Associated with Groundwater Mounding and Soil Moisture Increase

Potential impacts associated with groundwater mounding and near-roadway soil moisture increase include:

- Increase in moisture content of soils with associated impacts to soil weight and strength;
- Flooding or damage to structures and utilities;
- Flow of water through existing utility trenches potentially leading to formation of sinkholes;
- Increase in inflow and infiltration into municipal sanitary sewer systems;
- Mobilization of contaminants in the vadose zone;
- Reduction in the separation between BMPs and the groundwater table, which can compromise the pollutant attenuation processes in the vadose zone; and
- Reduction in BMP performance and/or extended periods of inundation; this is caused by an effective reduction in infiltration rate caused by the formation of the mound.

Groundwater mounding is not an inherent limitation. The degree of mound development and the potential for mounding to pose actual risks depends on site-specific factors, as explained further in this Guide.

1.3 Approach for Development of Guidance and Tools

Various existing tools are available to assess potential groundwater mounding. These range from steady state numerical solutions (e.g. Hantush, 1967; Carlton, 2010) to sophisticated modeling platforms such as HYDRUS (PC Progress), SEEP/W (Geo-Slope), and VS2D (USGS). The latter group of models solve saturated and unsaturated flow equations at discrete timesteps based on a computational mesh or grid. These are designed to account for transient soil moisture and flow processes in both the unsaturated and saturated zone.

Limitations exist at each end of this range. A simple steady-state model requires the user to presume what rate and duration of loading is applied. This inherently requires the user to make judgments about the size and type of storm event that would generate a critical mound. It also does not allow quantification of how groundwater mounding influences actual infiltration rates (i.e., does formation of a mound restrict flow into the soil?). Finally, these methods do not provide information on zones of elevated soil moisture (near saturation) that can occur outside of the extents of the saturated mound. On the other end of the spectrum, setting up a site-specific numerical model can be time consuming, expensive, and require expertise in the modeling platform and underlying algorithms.

This Guide and the accompanying Excel-based tool developed as part of this project are intended to provide an efficient method that balances these tradeoffs. These resources were developed using a four-part process.

Step 1. Monitoring Site Analysis. The research team identified BMP sites that were previously monitored for BMP inflows, BMP water level, and groundwater level. Based on the field monitoring data from these sites, the research team investigated and interpreted the monitored groundwater response below the monitored BMPs. The authors developed time series of precipitation, inflow, ponding levels, and groundwater response. We used this to assess the timescales and magnitudes of response. The research team also compiled available soil and groundwater data from these sites.

Step 2. Develop HYDRUS Models of Monitoring Sites. The research team developed HYDRUS models of the sites that were analyzed in Step 1. HYDRUS is a finite-element model that is widely used to analyze both unsaturated and saturated water flow in granular soils. The site models were developed using information that would have typically been available to designers at the time of BMP design. We complemented this information with literature values. We applied the respective timeseries of climatic data and hydrologic loading to these sites. The research team then compared the results of HYDRUS models to available monitoring data. The modeled BMP ponding levels, overflow volumes, and groundwater levels provided a reasonable match to observed data. Because data for groundwater model calibration are not typically available at the time of BMP design process, no calibration of parameters was conducted before making the comparison to monitored data. This step provided validation that the use of default literature parameters in the HYDRUS model along with commonly-available site information produced results that predicted the measured groundwater response with reasonable accuracy (typically within 1 to 2 feet).

Step 3. Analyze Idealized Scenarios. Based on the BMP representations and parameters used in the second step, the research team developed idealized scenarios for six climate zones, three highway profiles, 5 soil types, 6 BMP types, 4 groundwater depths, various loading ratios, and a variety of other permutations, resulting in approximately 13,000 models. We then ran each model for a 6-month period of record including storms with approximate 10-year return intervals at various durations. Unlike steady-state model results, this modeling framework accounts for the transient effect of groundwater processes in response to real storm events. The maximum initial separation to groundwater modeled in these scenarios was 16 feet. The results can be used for cases with greater initial separation. ***However, the results cannot be used in cases where the height of the calculated groundwater mound exceeds 16 feet (i.e., the maximum separation to the BMP bottom).*** If the tool is run with an initial separation of 16 feet and the resultant mound is 16 feet or greater, then these results may not be reliable. These cases would indicate relatively severe limits on infiltration. A site-specific modeling study may be needed.

Step 4. Results Interpretation and Tool Development. The research team extracted the results of the idealized scenarios and interpreted these results to develop screening level guidance. The research team also developed an Excel-based tool for evaluating model results for several thousand combinations of conditions.

The accompanying Project Summary Report provides extensive documentation of the methods and limitations of this analysis.

Figure 1 shows an example HYDRUS model domain. This case shows a bioretention/infiltration basin located at the toe of a low embankment roadway with a 16-foot depth to groundwater. Results represent the peak mound for loamy sand soil in Olympia, WA, with a loading ratio of 20 to 1 (ratio of impervious surface to BMP surface).

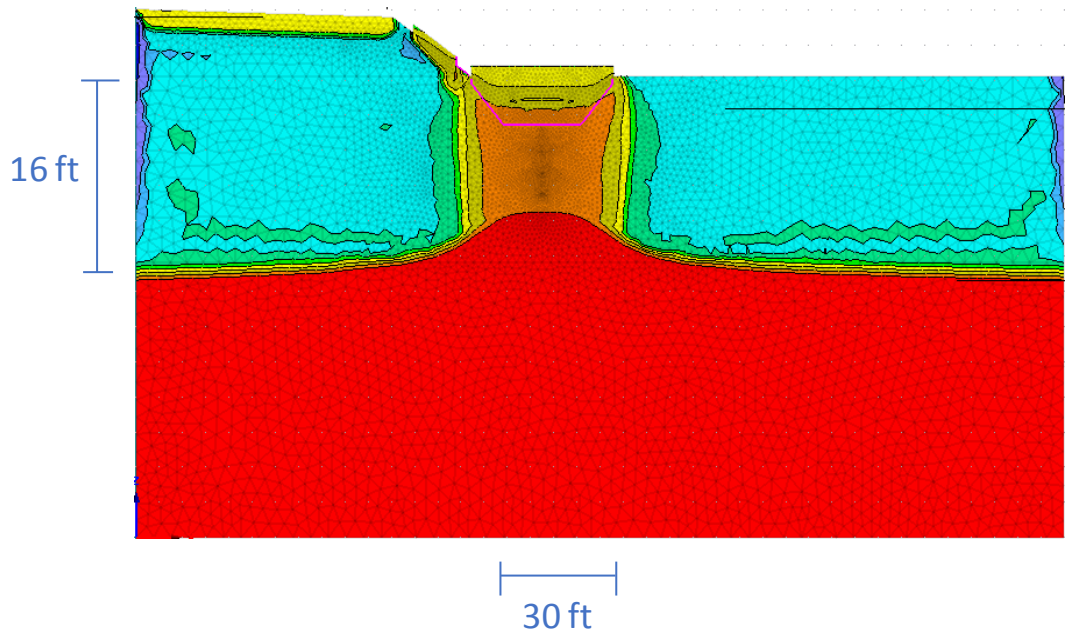


Figure 1. Example Domain of a HYDRUS2D Model Developed as Part of this Project (red indicates saturation)

2 Guidelines for Assessing Potential Groundwater Mounding Effects

2.1 Recommended Assessment Approach

The potential for risks to arise from groundwater mounding depends on (1) the degree of mound development or soil moisture increase, and (2) how the development of a mound or elevated soil moisture zone interfaces with the roadway or adjacent infrastructure, and (3) how the development of a mound would diminish the BMP performance and/or the pollutant attenuation capacity of vadose zone properties.

The authors recommend a three-step approach for assessing groundwater mounding:

1) Conduct a preliminary assessment of the relative magnitude of mounding for a given project. For some conditions and BMP types, mounding may not be an issue that warrants further consideration. The screening-level guidance provided in this section supports this step. The Groundwater Mounding Assessment Tool can also be applied rapidly to support this step.

2) If it appears that mounding may pose risks, conduct a more detailed evaluation of potential groundwater mounding and soil moisture impacts based on additional project-specific information. The Groundwater Mounding Assessment Tool is specifically designed to support this step. This tool can also be used to evaluate how design alternatives (BMP type, loading ratio, presence of underdrains, etc.) differ in terms of groundwater mounding risk.

3) When evaluating infiltration feasibility, use the mounding characterization from Step 2 to assess geotechnical and/or groundwater quality risks. Appendices D and E provide guidance on groundwater quality and geotechnical evaluations, respectively. The degree of expected mounding and/or soil moisture increase can be used as inputs to these assessments, as applicable. In conditions that are marginal (i.e., mounding appears to pose risk), the

Section 2.2 introduces the metrics used within this Guide to characterize potential mounding impacts. Section 2.3 introduces the key factors that influence mounding. Section 2.4 presents preliminary screening tools to support Step 1 above. Section 3 describes the Groundwater Mounding Assessment Tool and how it can be used to conduct site-specific evaluations.

2.2 Groundwater Mounding Metrics

This Guide defines four key metrics to assess the degree of groundwater mounding and associated effects:

- **Height and extent of saturated groundwater mound:** What height of mound develops below the BMP? How broad is the mound? Project teams can use this metric to evaluate whether the mound would pose risks to the roadway, infrastructure, embankments, utilities, etc. or inundate areas of contaminated soils. Project teams can also use this metric to assess whether the mound would reduce the separation to groundwater and therefore reduce the pollutant attenuation effects of the unsaturated soil zone.

- **Transient soil saturation:** Do saturated zones form near the BMP in addition to what is associated with a mound? The formation of a saturated bulb or column near a BMP is a common phenomenon and does is not necessarily a risk. However, if these saturated zones form in the embankment, or near infrastructure or utilities, this could pose risks.

- **Pavement subgrade soil moisture increase**: Does infiltration near the pavement subgrade cause elevated moisture content that could reduce the strength of these soils to support the pavement structure? This can have implications for pavement longevity.
- **Reduction of effective infiltration rate:** Does the formation of a mound reduce the effective infiltration rate of soils? This could result in degradation of BMP performance beyond what would be estimated based on the nominal estimates of infiltration rate from soil explorations. It could also result in extended ponding durations. Project teams can use this metric to determine appropriate adjustments to measured infiltration rates for use in BMP design (as discussed in Appendix B).

As introduced above, the research team conducted HYDRUS analyses to develop guidance and tools to assess the potential magnitude of these effects based on combinations of site-specific conditions.

2.3 Factors Influencing the Degree of Groundwater Mounding and Associated Effects

Several factors influence the potential magnitude and duration of groundwater mounding as summarized in the following paragraphs. This summary is informed by the case study site evaluations and HYDRUS modeling scenarios introduced above.

- **Soil type.** Soil texture class and permeability strongly influence the degree of mound development. Finer grained soils exhibit greater potential for mounding.
- **BMP geometry and dimensions**. BMPs with broader width and deeper depths tend to result in greater mound development. Linear BMPs with narrower width and/or shallower depth tend to result in less mound development.
- **Loading ratio**. Loading ratio refers to the impervious area tributary to the BMP divided by footprint area of the BMP. Greater loading ratios result in greater mound development as more water is effectively loaded into the same footprint.
- **Climate.** Climate can influence mounding because of differences in intensity of precipitation and/or differences in seasonal accumulated precipitation depths. In HYDRUS modeling of 6 stations (Birmingham, AL, Philadelphia, PA, Madison, WI, Denver, CO, Los Angeles, CA, and Olympia, WA), the climate station had a moderate effect on mound development; however, differences were not as great as would be expected based on comparison of average long-term precipitation totals. This is because the most intense periods of rainfall leading to critical mounding were not as different between the six stations as the long-term averages.
- **Layering/anisotropy.** Vertical K_{sat} is typically used in BMP design. In most soils, the horizontal K_{sat} is higher than vertical K_{sat}. Anisotropy is defined as the ratio of horizontal to vertical K_{sat}. Anisotropic behavior of soils is partly explained by soil particle arrangement. It is also influenced by the degree of soil layering. For groundwater mounding assessment, degree of layering of soils is the most dominant source of anisotropic behavior. For a given soil structure, the vertical flow of water is limited by the least permeable layer while the horizontal flow of water can occur preferentially in more permeable layers. For a given vertical K_{sat}, less mound development tends to occur in soils with higher anisotropy. This is because for a given vertical K_{sat}, water dissipates laterally at a greater rate in cases with higher anisotropy. Soil layering, vertical fracturing, and vegetation root growth can all influence the overall ratio of vertical to horizontal K_{sat}. For these reasons, it can be very difficult to estimate or measure anisotropy.

Therefore, the research team treated anisotropy as a sensitivity parameter in the Groundwater Mounding Assessment Tool.

- **Initial groundwater depth.** The "initial depth to groundwater" is a very sensitive parameter to determine if mounding would cause issues. For cases with shallower depth to groundwater, it was much more likely for the mounded groundwater table to intersect with the base of the BMP, saturate the roadway subgrade, and/or reduce the effective infiltration rate of the BMP.

  The HYDRUS model domain is focused on localized mounding, which is additive to seasonal fluctuations or regional rise of the groundwater table. Therefore, the initial groundwater depth used in a mounding analysis should be the seasonal high groundwater table for the location, accounting for seasonal fluctuations. It should also account for any regional-scale rise in the water table that could result from widespread stormwater infiltration, sea level rise, or other factors. Field measurements of groundwater depth may be a snapshot of conditions that are less than seasonal highs. Therefore, longer term monitoring may be needed to develop this parameter. In the case of anticipated regional rise in the groundwater table, this may need to be estimated based on regional modeling.

  The maximum depth to groundwater modeled in HYDRUS was 16 feet. Results can be interpreted for cases with greater than 16 feet. ***However, the results cannot be used if the modeled mounding height exceeds 16 feet.***

- **Roadway embankment height.** The embankment height could theoretically reduce mounding because of greater unsaturated soil above the groundwater table. In HYDRUS simulations, embankment height had little effect on maximum mound development but did influence some geotechnical risk factors such as likelihood of pavement saturation, re-emergence of flow along the slope, and saturation of points within the slope.

- **Underdrain.** Some BMPs can be installed with an underdrain that conveys treated discharge away from the BMP. HYDRUS analyses were run to compare bioretention/infiltration basins and infiltration swales/linear bioretention with and without underdrains. Underdrains resulted in lower infiltration and reduction in mounding. When placed below the level of the adjacent pavement subgrade, the presences of underdrains greatly reduced or eliminated saturation of the subgrade soil.

- **Thickness of aquifer.** The thickness of the unconfined (i.e., near-surface) aquifer effects the processes by which a mound can dissipate. This refers to the thickness of the first groundwater formation encountered below the surface, measured to the first confining layer. It does not refer to deeper, confined aquifers. In HYDRUS simulations, thickness of groundwater had minor influence on peak mound height mound within the range analyzed (6 to 48 feet). With greater thickness, mounds tended to dissipate more quickly and have a lower zone of influence. With less thickness, the mound tended to dissipate more slowly and cover a broader area.

- **Groundwater gradient.** The regional groundwater gradient was found to have a negligible effect on localized mound development for the range of slope analyzed (0.001 to 0.02 ft/ft gradient).

- **Limiting soil layer.** Case study scenarios were run in which the upper soil zone was one material and the lower soil zone was a much less permeable material. Based on these analyses, the mound was generally most influenced by the lower permeability soil. However, the tool is not designed to account for cases where soils with very different properties are present in the soil structure.

While these factors are discussed separately above, the interaction between these factors is also important. The Groundwater Mounding Assessment Tool provides estimates based on the combined effects of most of the factors above.

2.4 Screening Charts for Assessing Potential Groundwater Mounding Risk

This section presents a series of screening charts and tables derived from HYDRUS model results that are intended to support an initial assessment of potential groundwater mounding response. These charts are primarily intended to help a user understand if a site poses limited or no potential groundwater mounding. If there is potential for groundwater mounding, the user should apply the Groundwater Mounding Assessment Tool (Section 3) to obtain a more detailed characterization of groundwater mounding. This tool can also be used for preliminary screening in lieu of the charts in this section.

2.4.1 Groundwater Mound Height

Figure 2 through Figure 7 can be used as simple tools to evaluate how the maximum groundwater mound height is influenced by weather station, BMP type, and loading ratio. Charts are based on an average degree of soil layering (anisotropy) and do not describe the uncertainty interval on the estimated mound height. For cases where the mounding height may be of concern, users should apply the tool to obtain a better understanding of uncertainty and the effect of soil layering.

To use these charts:

1) Find the climate station and BMP type that best matches the site.
2) Select the soil type that best matches the site or the soil types that bracket the site. The following vertical K_{sat} values were assumed for the development of these charts: Clay = 0.1 in/hr, Silt = 0.3 in/hr, Sandy Loam = 1 in/hr, Loamy Sand = 3 in/hr, and Sand = 15 in/hr. Because saturated water flow is the primary process in mounding, selecting the soil that best matches (or brackets) the permeability of site soils is recommended, even if the texture class does not match the site soils.
3) Estimate the loading ratio to the BMP. This is the ratio of the impervious roadway area tributary to the BMP divided by the plan-view footprint area of the wetted area of the BMP.
4) Read the estimated mound height from the charts. If the estimated mounding height from the charts exceeds the actual depth to groundwater for a site, then the mound would intersect with the BMP. If mounding height exceeds 16 feet (i.e., the maximum separation simulated in HYDRUS scenarios), then site-specific analysis is warranted. Actual mound height may exceed 16 feet.

In general, the BMP type (and the width and loading ratios associated with BMP type) has a strong influence on the development of a mound. Soil type also has a strong influence. The combination of narrower BMP types (i.e., BMPs other than bioretention basins/infiltration basins), sandier soils, and lower loading rates tends to produce little mound. Silt and clay soils, higher loading rates, and/or larger BMPs (i.e., bioretention/infiltration basins) tend to increase the development of a mound.

Note: These results are not reliable to predict mound height if the resulting mound height from the charts is greater than 16 feet. Site-specific analysis is needed in these cases.

Figure 2 through Figure 7 are based on scenarios without underdrains, which is more conservative than cases with underdrains. The tool provides the ability to assess alternatives with underdrains.

Birmingham, Alabama

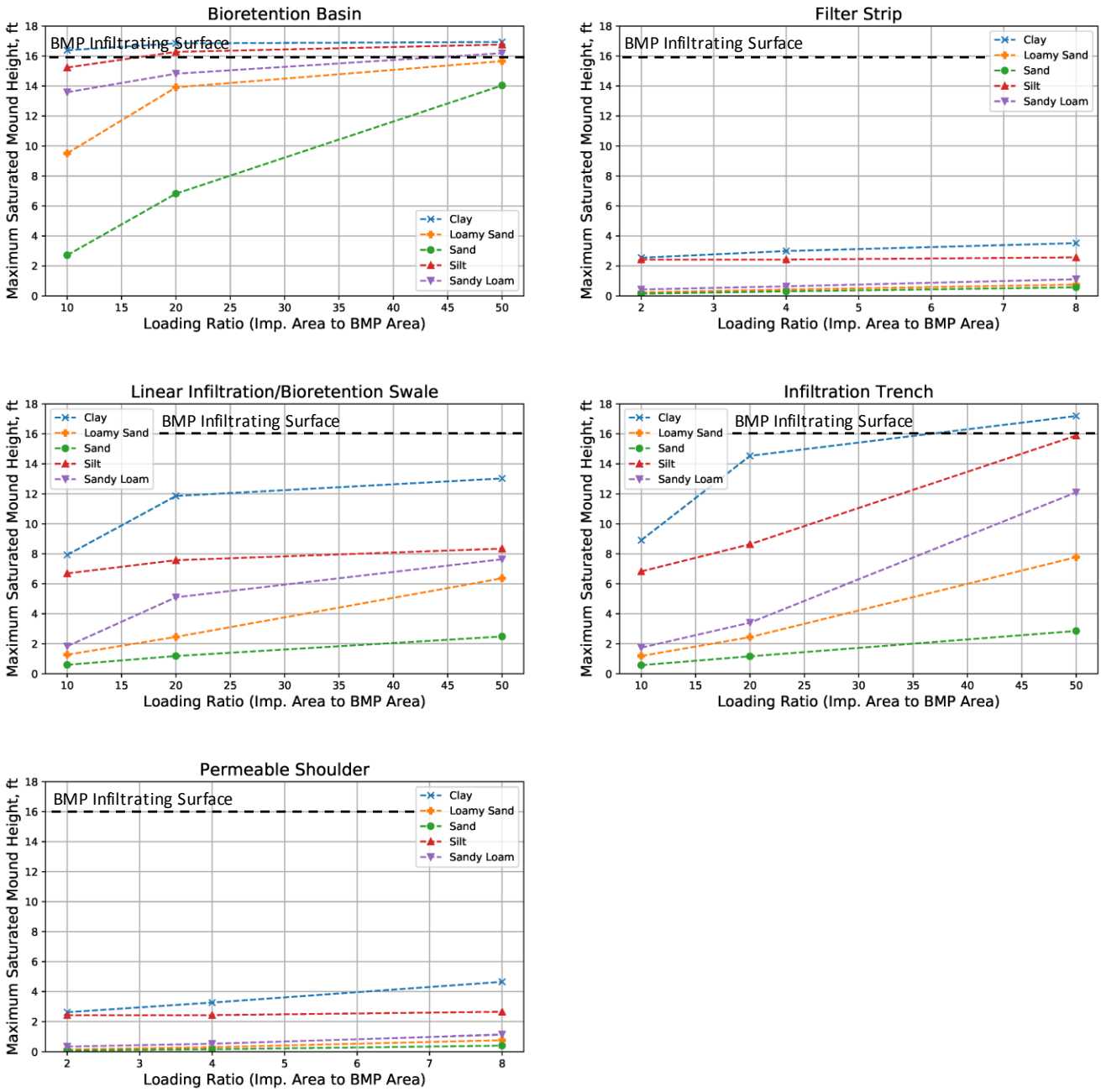


Figure 2. Groundwater Mound Nomographs for Birmingham, AL

Denver, Colorado

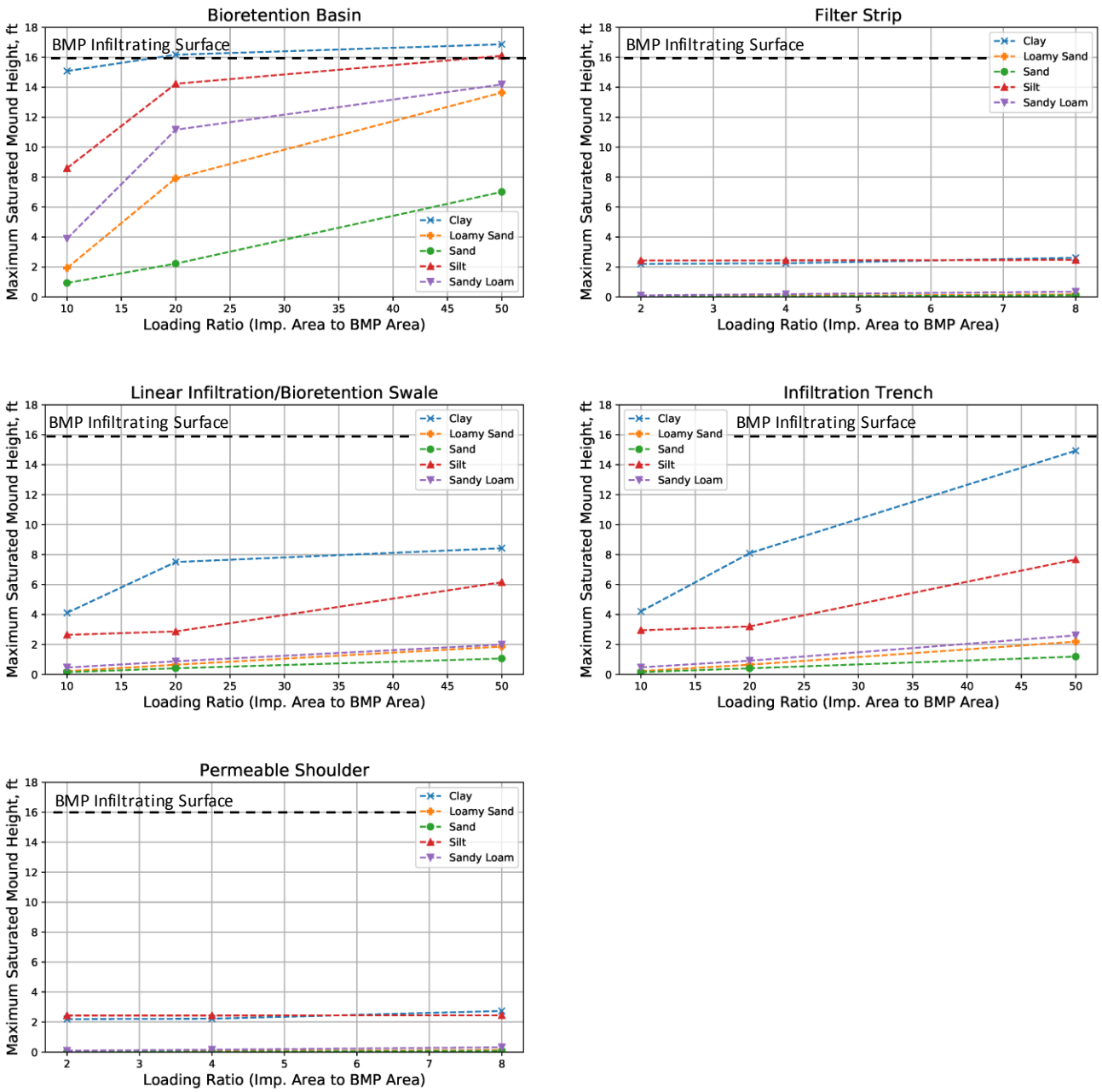


Figure 3. Groundwater Mound Nomographs for Denver, CO

Los Angeles, California

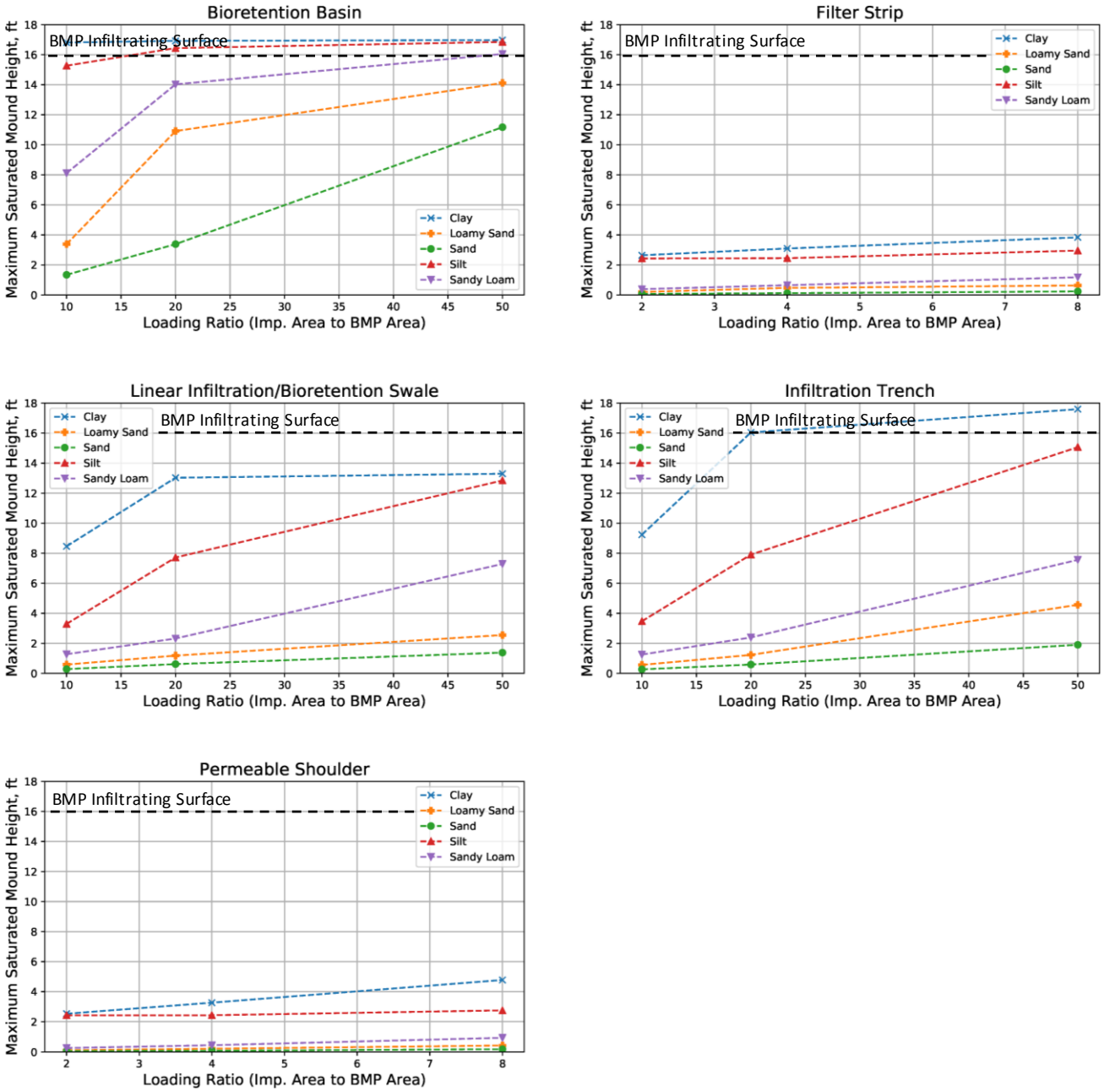


Figure 4. Groundwater Mound Nomographs for Los Angeles, CA

Madison, Wisconsin

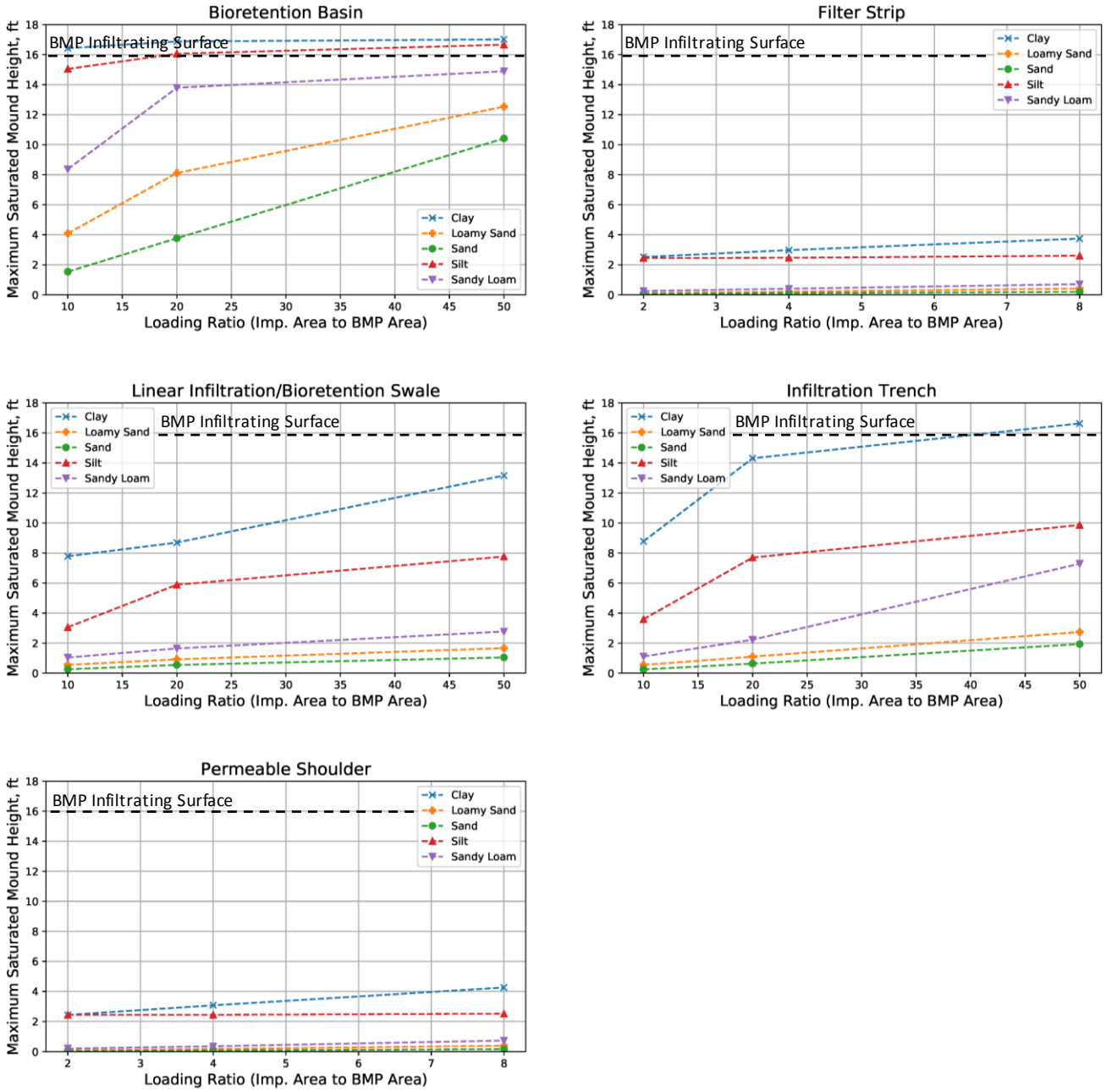


Figure 5. Groundwater Mound Nomographs for Madison, WI

Philadelphia, Pennsylvania

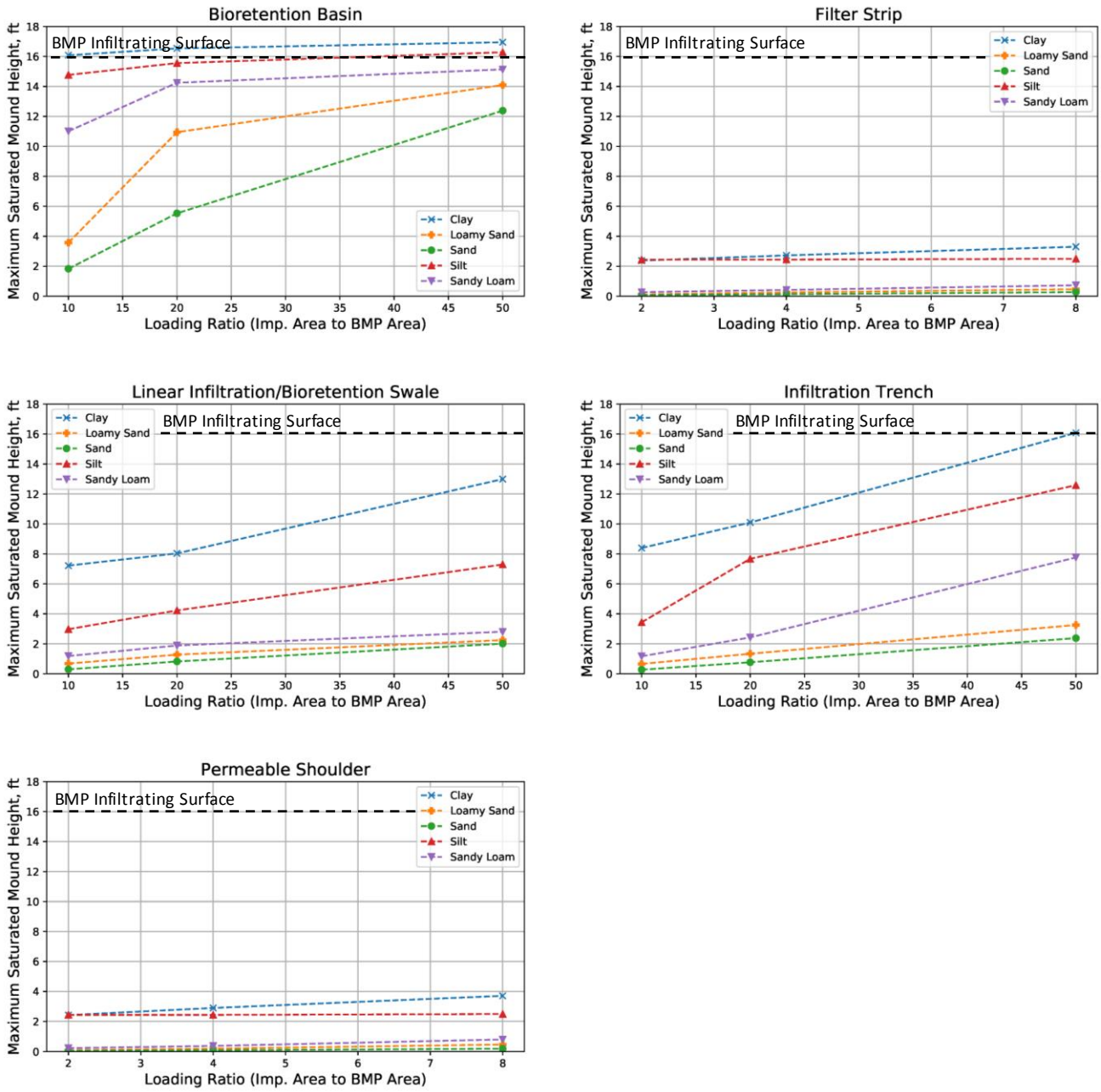


Figure 6. Groundwater Mound Nomographs for Philadelphia, PA

Olympia, Washington

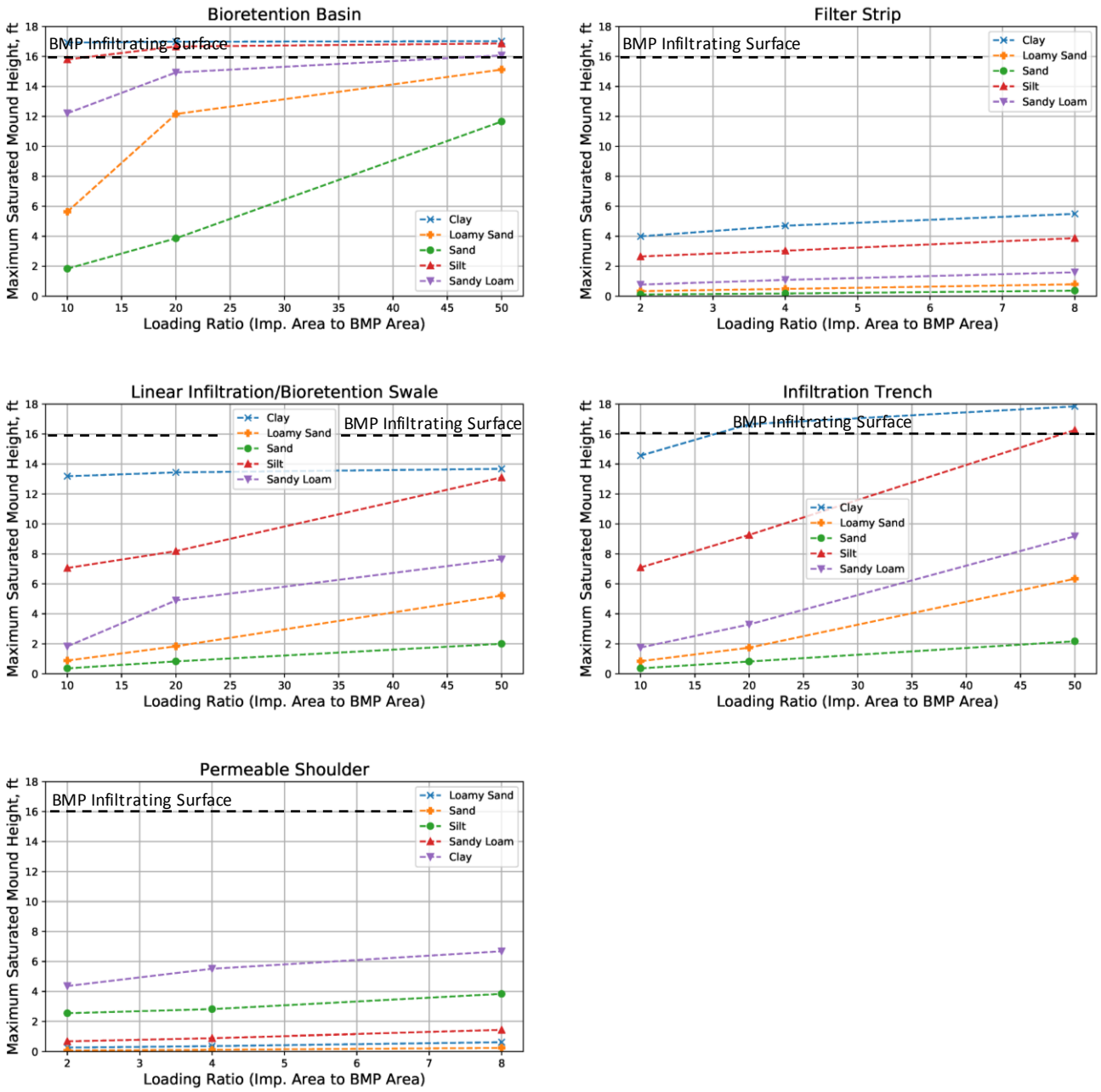


Figure 7. Groundwater Mound Nomographs for Olympia, WA

2.4.2 Transient Saturation of Embankment and Near-BMP Areas

For BMPs located at the toe of slope (bioretention/infiltration basins, infiltration swales/linear bioretention, and infiltration trenches), the formation of saturated zones generally only occurred within 10 feet on either side of the BMP and directly below the BMP. Simple set-backs between BMPs and infrastructure and utilities are adequate to avoid impacts associated with these saturated zones.

For BMPs located on the embankment (permeable shoulders and filter strips), saturated zones were more likely to occur within the embankment and near the roadway. No simple design charts are available to assess this metric. The Groundwater Mounding Assessment Tool can be used to inspect saturation at points in the embankment and in the roadway subgrade. The spatial extents of these zones were generally greater in silty and clayey soils than sandy soils.

2.4.3 Saturation of Road Base

Saturation of road base was at a point located at the subbase/subgrade interface below the edge of pavement and at a point located 1.5 feet below this interface. These are considered the most susceptible points as they are closest to where infiltration BMPs would be placed.

Saturation of the road base at these points did not occur in any cases where BMPs were at the toe of slope and the roadway was on the embankment. For these types of BMPs (bioretention/infiltration basins, infiltration swales/linear bioretention, and infiltration trenches), road base saturation only occurred in the no embankment roadway geometry. For permeable shoulders, road base saturation occurred in both the on-grade and embankment geometries. Filter strips did not result in saturation or near-saturation of the road base in any case.

For combinations of BMP and roadway geometry where some level of saturation was observed in model runs, Table 1 summarizes the percent of time the road base was greater than 90 percent saturation. This table reports the modeled conditions at a point located 1.5 feet below the subbase/subgrade interface below the edge of pavement. This presents the average of all groundwater depths, stations, and anisotropy values. Therefore, this table is intended for trend analysis only. However, where the result is zero to very small, issues would not be expected to occur. Users can analyze more specific combinations of conditions using the Groundwater Mounding Assessment Tool.

On average, elevated soil moisture near the roadway was very uncommon in sand and loamy sand soils, and uncommon in most cases in sandy loam soils. BMPs in silty and clayey soils with higher loading rates were most likely to result in saturation or near saturation of the road base. This is consistent with findings that mounding was also most severe in these conditions. Use of the Groundwater Mounding Assessment Tool is essential for evaluation of project-specific combinations of parameters, particularly in soils with K_{sat} approximately 1 in/hr and lower.

Table 1. Percent of Time Greater Than 90% Saturation Below the Edge of Pavement (1.5 feet below the subbase/subgrade interface)

BMP	Loading	Soil Type				
		Sand (15 in/hr)	Loamy Sand (3 in/hr)	Sandy Loam (1 in/hr)	Silt (0.3 in/hr)	Clay (0.1 in/hr)
Bioretention Basin/ Infiltration Basin (no embankment)	10	0%	0%	3%	24%	50%
	20	0%	1%	9%	37%	64%
	50	1%	5%	17%	51%	76%
Infiltration Swale/Linear Bioretention (no embankment)	10	0%	0%	1%	19%	32%
	20	0%	0%	3%	24%	37%
	50	0%	1%	8%	30%	43%
Infiltration Trench (no embankment)	10	0%	0%	0%	0%	4%
	20	0%	0%	0%	1%	14%
	50	0%	0%	0%	7%	31%
Permeable Shoulder (no embankment)	2	0%	0%	0%	15%	40%
	4	0%	0%	1%	20%	49%
	8	0%	0%	3%	28%	60%
Permeable Shoulder (on embankment)	2	0%	0%	0%	1%	15%
	4	0%	0%	0%	4%	25%
	8	0%	0%	1%	8%	39%

2.4.4 Groundwater Mounding Influence on BMP Drawdown Rate

The HYDRUS results were analyzed to estimate the average actual drawdown rate of the BMP when ponded water was present. This accounts for the hydraulic head on the BMP, the formation of a groundwater mound, and infiltration out of both the bottom and the side-walls of the BMP.

The actual drawdown rate is expected to be higher than vertical K_{sat} (due to hydraulic gradient and flow out of the side walls) if groundwater mounding does not limit but may decline in some conditions if groundwater mounding becomes the limiting factor.

Table 2 shows how the ratio of actual drawdown rate to vertical K_{sat} is influenced by BMP type, initial groundwater depth, and degree of soil layering (anisotropy). This table is an average of climate stations, loading ratios, and soil types. Therefore, it is intended for trend analysis only. Users can analyze more specific combinations of conditions using the Groundwater Mounding Assessment Tool.

All BMPs were somewhat sensitive to depth to groundwater and degree of soil layering. Bioretention/infiltration basins are most susceptible to declines in drawdown rate, particularly in shallower groundwater conditions. This is due to the broader, flatter nature of these BMPs and the greater potential to form a mound. Infiltration trenches tended to have the highest ratios (due to large side-wall area). Use of the Groundwater Mounding Assessment Tool is essential for evaluation of project-specific combinations.

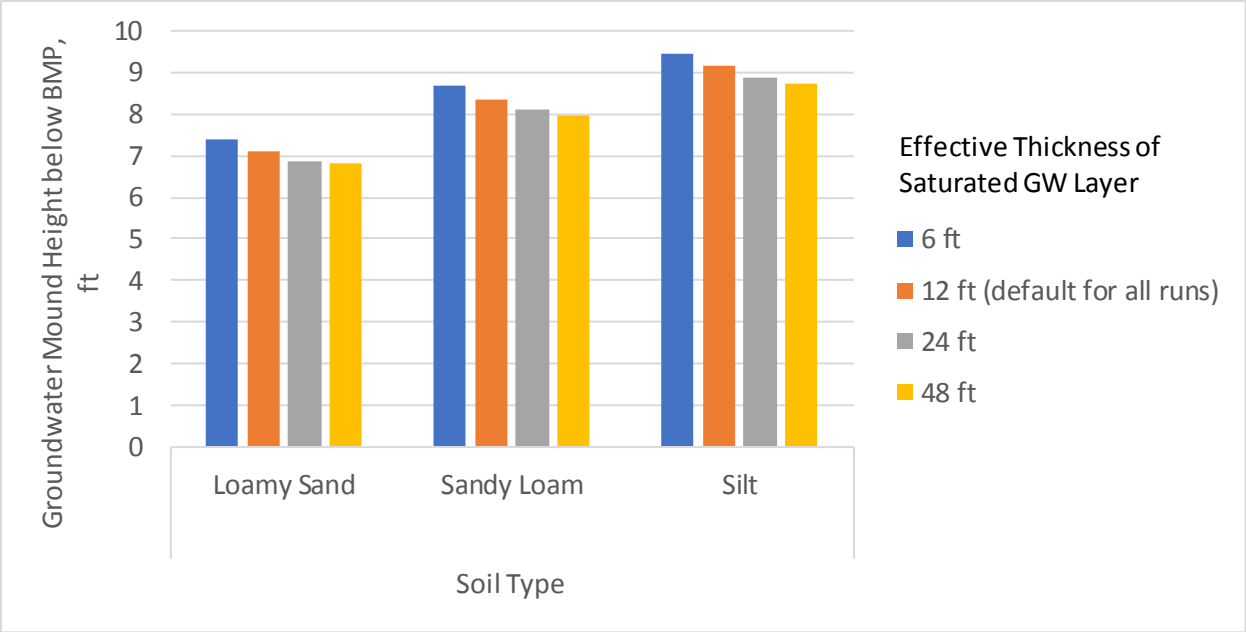
Table 2. Ratio of Actual BMP Drawdown Rate to Modeled Vertical K_{sat}

BMP Type	Initial Depth to Groundwater (below Infiltrating Surface)	Ratio of Actual Drawdown Rate to Modeled Vertical K_{sat}	
		Lower Layering	Higher Layering
Bioretention Basin/ Infiltration Basin	2	0.19	0.56
	4	0.34	0.95
	8	0.68	1.46
	16	1.08	1.86
Infiltration Swale/Linear Bioretention	2	0.65	1.83
	4	1.24	3.17
	8	2.03	4.10
	16	2.52	4.22
Infiltration Trench	2	1.27	2.76
	4	2.04	4.35
	8	3.13	5.50
	16	3.96	5.95
Permeable Shoulder (no embankment only)	2	0.55	1.31
	4	1.17	2.36
	8	1.95	2.81
	16	2.31	2.89

2.5 Effect of Groundwater Thickness

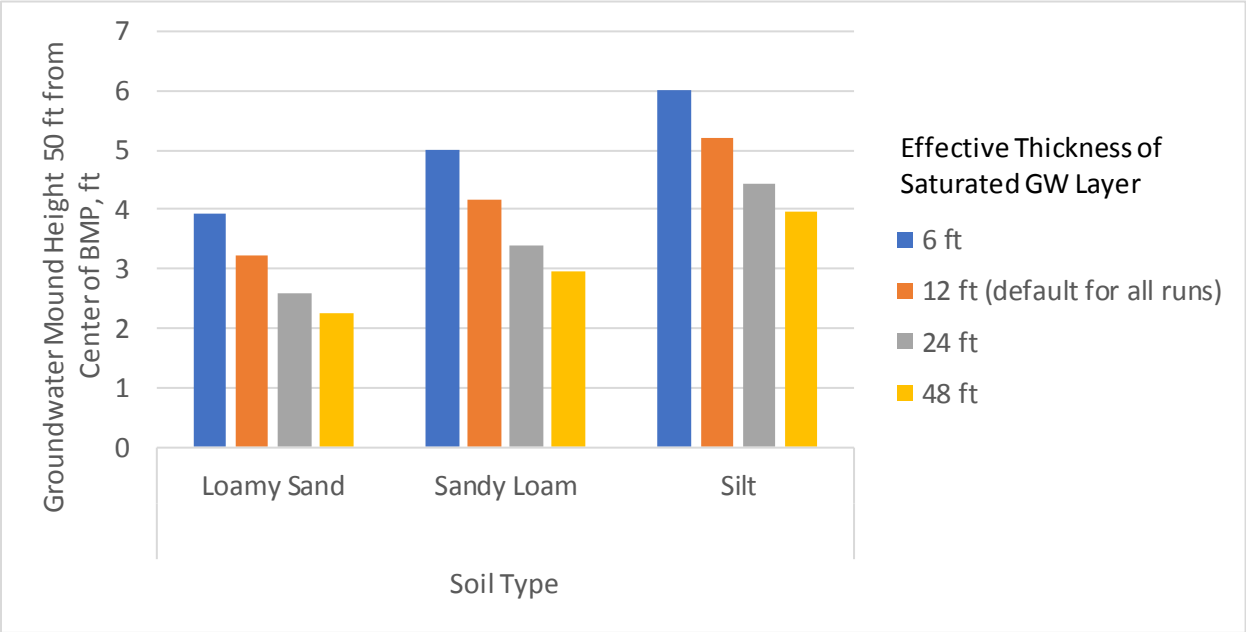
Groundwater thickness is the vertical dimension measured from the groundwater table to the first confining layer. The lower limit of the groundwater layer could be defined by a bedrock layer or a layer of less permeable soil (i.e., an “aquitard”). As introduced above, a thicker layer results in greater capacity for mound dissipation and results in smaller mounds.

Figure 8 shows the average maximum mound height below the BMP for various groundwater thicknesses. Figure 9 average maximum mound height at distance 50 feet away from the BMP for various groundwater thicknesses. Both charts are based averages for 20:1 loading ratios for bioretention basins with 16 feet initial groundwater depth. These charts represent average of high and low anisotropy. These charts show that that the groundwater thickness had less than 1 ft average effect on mounding below the BMP but had greater effect on the width of the groundwater mound.



Base of BMP = 16 ft

Figure 8. Effect of Groundwater Thickness on Mound Height Below BMP



Base of BMP = 16 ft

Figure 9. Effect of Groundwater Thickness on Mound Height at a Distance of 50 feet from the BMP

2.6 Effect of Underdrains on Mounding and Water Balance

The design of bioretention/infiltration basins and linear infiltration/bioretention swales allows the opportunity to include an underdrain. The effect of the underdrain on mounding, pavement saturation, and water balance was evaluated for example combinations of conditions. In scenarios with underdrains, the underdrain discharge elevation was located 1.5 feet below the BMP surface and a 1.5-foot thick layer of

gravel was simulated below the underdrain discharge elevation. The underdrain is at the top of the gravel layer and the bottom of the media layer Figure 20 shows how the BMP profile changes with the addition of an underdrain. This profile applies to both bioretention basins and infiltration swales.

Figure 10 shows a comparison of maximum mound height without underdrains and with underdrains. Results are averaged across all climate stations. Results may vary for individual locations. Users can analyze individual climate stations using the tool. These figures show that underdrains reduced mounding by approximately 2 feet on average and limited the maximum mound to a level below the infiltrating surface.

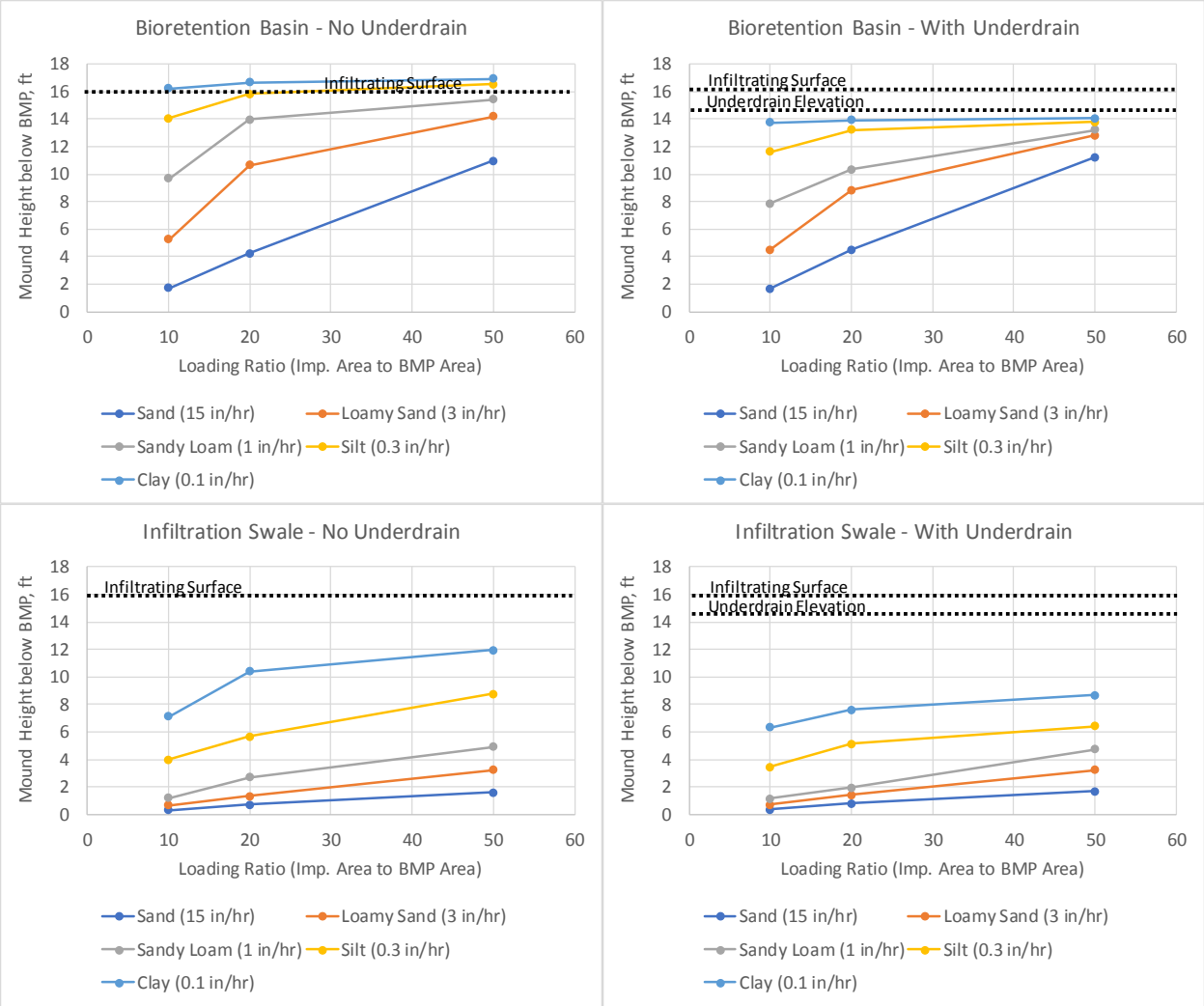


Figure 10. Effect of Underdrains on Maximum Mound Height (average of all climate stations)

Figure 11 shows a comparison of water balance (percent of water infiltrated) for same scenarios. Including an underdrain resulted in some reduction in total volume infiltrated but did not greatly change the water balance. For example, at a loading ratio of 20:1 in sandy loam, a bioretention basin resulted in 95 percent infiltration without underdrains and 77 percent infiltration with underdrains. The water balance of swales tended to be less sensitive to underdrains. At 20:1 loading in sandy loam soils, infiltration swale without underdrain resulted in 91 percent infiltration and reduce to 86 percent infiltration with the addition

of underdrains. The lesser effect of underdrains on performance of infiltration swales is associated with shallower ponding depth of infiltration swales (1 foot vs. 3 feet) and therefore a greater volume of sump storage below the underdrain discharge elevation as fraction of total storage.

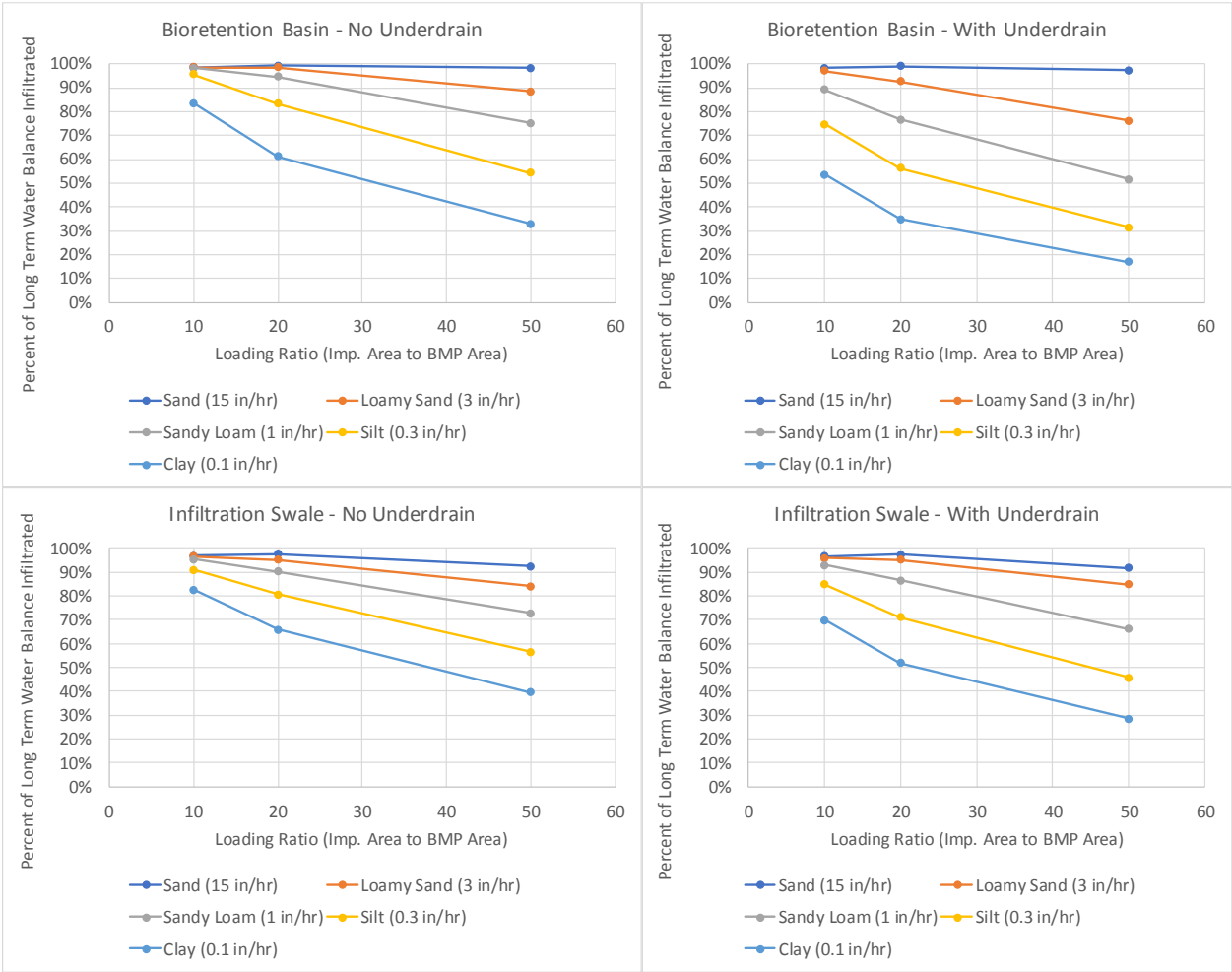


Figure 11. Effect of Underdrains on Water Balance (average of all climate stations)

Figure 12 shows how the presence of underdrains changed the percentage of time that soil moisture exceeded 90 percent at an elevation 1.5 feet below the subbase/subgrade interface below the edge of pavement. These statistics were based on the average of all scenario with initial groundwater depth of 2 feet or 4 feet. For the scenarios evaluated, the addition of an underdrain in the bioretention basin effectively eliminated near saturated conditions at this point. The infiltration swale was somewhat sensitive to the inclusion of an underdrain. This is because the underdrain in in the swale was at a higher elevation than the bioretention basin relative to the pavement elevation. This suggests that site-specific design decisions about the elevation of the underdrains can have large influence on whether saturation of the roadway subgrade would occur.

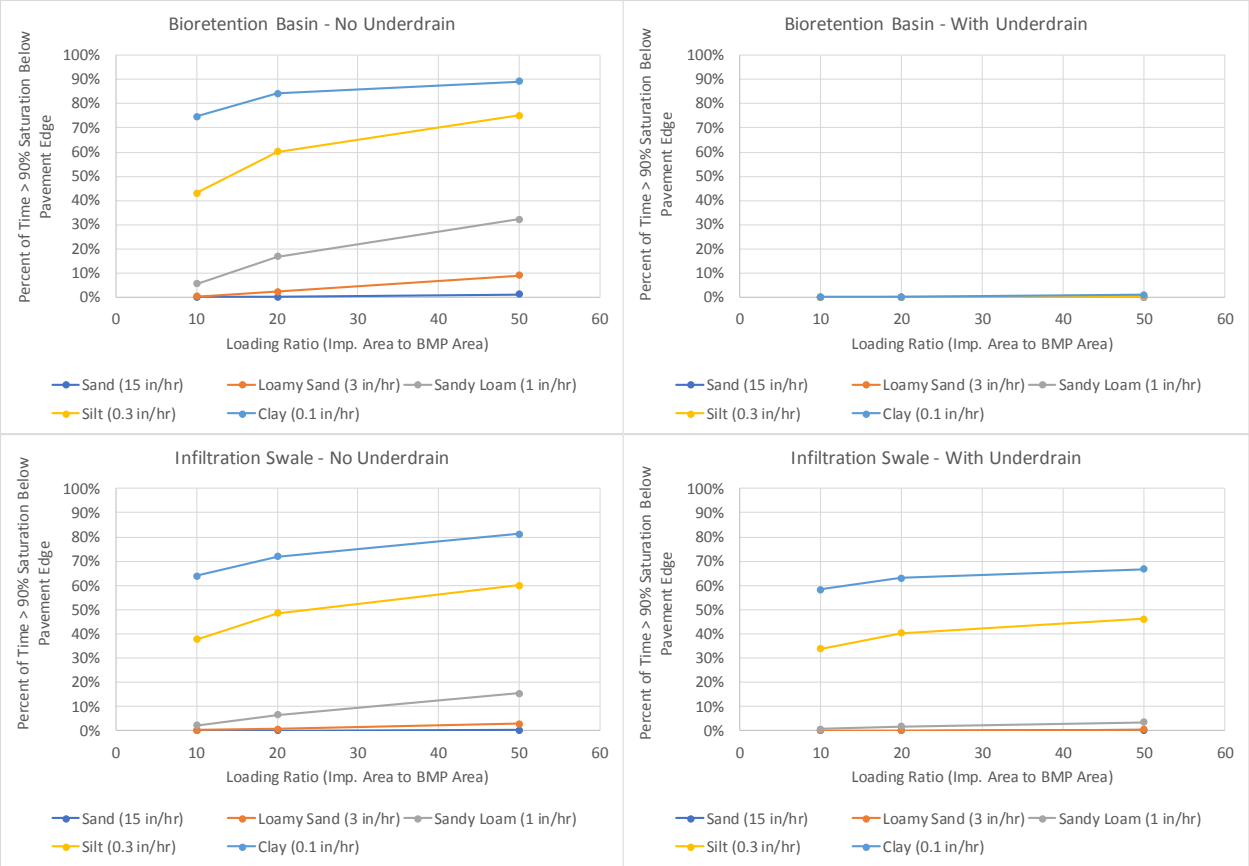


Figure 12. Effect of Underdrains on Subgrade Soil Saturation (average of all climate stations)

2.7 Summary

Based on inspection of the charts and tables presented in Section 2.4, groundwater mounding can be ruled out as controlling factor in some combinations of conditions. In general, if no infrastructure or utilities are in the BMP vicinity, the remaining separation to groundwater is adequately protective of groundwater quality after accounting for mound formation, and saturation or near saturation of the roadway subbase is not expected, then further investigation of groundwater mounding may not be needed. However, if groundwater mounding risks cannot be clearly ruled out, then more focused assessment using the Groundwater Mounding Assessment Tool is recommended as explained in Section 3.

3 Roadside BMP Groundwater Mounding Assessment Tool

3.1 Introduction

The Groundwater Mounding Risk Assessment Tool (the tool) was developed to provide an interactive semi-quantitative framework to assess the magnitude and potential impacts associated with groundwater mounding below infiltration BMPs in the highway environment.

Within the tool, the user can select inputs describing the climate, BMP type, embankment geometry, initial groundwater depth, loading ratio and site soil type and rapidly view the post-processed results of HYDRUS simulations (introduced in Section 2) corresponding to the defined scenario. The tool produces visualizations and summaries of key metrics relating to groundwater response and potential geotechnical risk.

The tool contains guidance embedded within its interface. The following sections supplement the tool's guidance to help the user in selecting appropriate parameters.

3.1.1 Intended Uses

While certain estimates provided by the tool are quantitative, the interpretation of these visualizations is inherently semi-quantitative due to the uncertainty and variability in environmental processes associated with groundwater mounding. This tool does not account for site-specific conditions 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 exploration of mounding issues. For example, review of available data could confirm that the tool assumptions (above) are reasonably representative of the site, and the tool could serve as the basis for finding that mounding is not of concern. For more marginal conditions, the tool could be used as a basis to reject the use of infiltration, collect more site data, or select BMPs that pose less risk. If infiltration is proposed in marginal conditions, it should always be accompanied by a site-specific evaluation of conditions and mounding processes. In this case, the project geotechnical or hydrogeologic professional should select a model and develop inputs based on site-specific conditions, agency standards, and professional experience/judgement.

3.1.2 Assumptions

Key assumptions used in generating the tool include:

- **Reasonably uniform soil properties.** The tool assumes uniform soil properties. Typical layering of soils (interbedding of different properties) is accounted for in the tool via the application of anisotropy as a model parameter. In moderately layered soils, selecting a soil type that represents the least permeable layer will tend to produce reasonable results. A ratio of permeability of 20:1 (most permeable to least permeable layer) would be a reasonable upper limit to be considered for moderate layering. More extreme layering, such interbedding of relatively permeable layers with relatively impermeable layers is not explicitly modeled.
- **Horizontal soil layers.** Modeling assumes horizontal soil layering. Soil formations that have sloping layers were not modeled. This condition could result in groundwater flow pathways that are different from what is represented in the tool.
- **No nearby lateral obstructions.** Modeling assumes that no lateral obstructions (such as retaining walls, rock outcrops) exist within approximately 200 feet of the infiltration BMP. Obstructions could reduce the rate of mound dissipation compared to what is modeled.
- **No steep slopes down gradient of roadway.** Modeling assumes that adjacent land does not include steep slopes. While groundwater gradient was not found to be a key factor in localized mounding, adjacent slopes (>10 percent) within 100 feet of the roadway could introduce effects not accounted for in the tool.
- **Results are valid within the parameter ranges modeled.** Extrapolation outside of these ranges is not supported. Interpolation may be reasonable, but it should be noted that trends may not be linear between increments.
- **No other BMPs in the lateral direction from the roadway.** The tool is based on groundwater movement in two dimensions – vertical and lateral to the highway. It effectively accounts for a cases where BMPs are continuous along the highway. Therefore, this type of interaction between BMPs is implicitly. This is the most common case. However, if multiple BMPs are present at the same roadway station, at different distances from the roadway, or on opposite sides of the roadway, then the tool may under-estimate mounding. The user can inspect the mounding profile, including the lateral spread of the mound to determine if interactions between BMPs would be expected. Where the spread of the mound overlaps, this may indicate that an interaction is present. This is unlikely to be an issue if BMPs are spaced more than 100 feet in the lateral direction from the roadway. For more distributed BMPs (swales, filter strips, permeable shoulders), mounds are unlikely to interact if BMPs are offset by 50 feet.

If site conditions deviate from these assumptions, then use of the tool may not be reliable.

3.2 General Use of Tool

3.2.1 System Requirements

The following computer system environment is recommended:

- The tool is intended to run in Microsoft Excel 2016; macros must be enabled for the tool to run properly. 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", and 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.

3.2.2 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).
- When the tool opens, it is necessary to enable macros. The process of enabling macros varies depending on local security settings in place. If macros are not enabled, the user should consult Excel support for guidance in enabling macros.
- Select the climate, BMP type, embankment height, initial groundwater depth, loading ratio and soil type from dropdown menus provided in the input section of the tool.
- The visualization and geotechnical risk summary will be updated in real-time as users modify the input. A warning message will appear to alert users for invalid input configurations. If invalid input configurations are entered, the tool will not present results until a valid input configuration is entered.
- Once the inputs are populated to best match the design scenario, check the visualization and tabular results to support various elements of 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.

3.2.3 Organization and Navigation of the tool

The input and output sections in the Tool are organized into one worksheet tab to facilitate viewing of the results as users adjust the input configurations. For smaller screens or lower screen resolution, the user may need to scroll to different parts of the worksheet. On larger monitors (24-inch and larger), most of the tool inputs should fit legibly within a single view.

The tool is divided into one input form, three data visualization components and several tabular summaries. The user can define each input parameter by selecting one item from the dropdown menu. By working from the top of the input list to the bottom, the available dropdowns will display. Changing input parameters out of sequence can result in warning messages, particularly when changing from one BMP type to another, as some options that apply to one BMP type do not apply to others. To resolve warnings, start at the top of the input list and select each input in the order presented.

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.

3.3 Input Parameters

The input form in the Tool, as shown in Figure 13, consists of seven items: 1) Climate Type, 2) BMP Type, 3) Embankment Height, 4) Initial Groundwater Depth, 5) Loading Ratio, 6) Soil Type, and 7)

Underdrain Presence (only applicable to bioretention basins or infiltration swales with low embankment as a "what if" scenario). A dropdown selection menu is provided for each input parameter. Dropdown menu values are discrete representative values for each input category. The user will need to select the input parameter that best matches the design scenario. If actual conditions fall between the tool input increments, a simple screening approach would be to evaluate results that bracket the site-specific value and then interpolate between these values.

NCHRP Roadside BMP Groundwater Mounding Assessment Tool

Project Title	Test Run
Project Location	Portland, OR
Company	Geosyntec Consultants

Climate, Site, and BMP Configuration Selection

Climate Type	Denver, CO	Select most similar location
BMP Type	Bioretention Basin	Select BMP type
Roadway Embankment Height	Low	Select embankment height
Initial Groundwater Depth (ft)	8	Select representative groundwater depth
Loading Ratio (imp. area to BMP area)	10:1	Select representative loading ratio
Soil Type and Modeled Vertical Ksat of Limiting Layer	Sandy Loam (1 in/hr)	ect representative soil type
Underdrain Presence (available for BB and IS BMPs with no embankment)	N/A	Select whether an underdrain is present (if supported)

Simulation Summary and Climate Inputs

Six month simulations were run in HYDRUS to estimate groundwater mounding from infiltration, BMP water balance, geotechnical risks, and the effect of mounding on infiltration rates. Summaries of these results are presented in this Tool.

Climate Location	Denver, CO
Total Simulation Precipitation (in) (6 months)	14.1
Maximum 24-hour Precipitation (in)	3.2
Maximum 7-day Precipitation (in)	4.2
Maximum 30-day Precipitation (in)	6.3
Total BMP loading depth (in)	134

Explanation Precipitation inputs inlude approx. 10-year return interval precipitation depths for the 6-month, 1-month, 7-day, and 1-day duration. A base 6-month period was used from precipitation records. Real events from other periods were nested within the base 6-month period, if needed, to yield the constructed record.

Figure 13. Project Information Section of Tool

3.3.1 Climate Type

Climate type input determines the precipitation and the evapotranspiration (ET) patterns that were applied to the scenario in the HYDRUS model. Six locations were selected to represent six typical climate patterns in the U.S. as shown in Table 3. Users should choose the station that most resembles the project

location's climate pattern. Results from multiple climate stations can be viewed to evaluate the sensitivity of climate to mounding response. The tool does not explicitly account for the effective of temperature variations on water viscosity and associated soil hydraulics. It also does not explicitly account for snowmelt processes (all loading is in water equivalent).

Model results are based on continuous simulations with a duration of six months. An artificial 6-month precipitation record was constructed for each climate station by nesting real events with a 10-year average return interval at four different durations, including 1-day, 7-day, 1-month, and 6-month durations. The details of the hyetograph synthesis methodology are presented in the Project Summary Report. Simulation results therefore represent conditions with approximately a 1 in 10-year average return interval.

Table 3. Statistical Summary of Precipitation Records and Synthesized Precipitation for Six Climate Types Applied in HYDRUS Model

	Precipitation Totals				
Location	10-Year, 1-Day Event (in)	10-Year, 1-Week Event (in)	10-Year, 1-Month event (in)	10-Year, 6-Month Event (in)	Total Precipitation of Synthesized Hyetograph[1] (in)
Birmingham, AL	5.9	8.2	14.5	39.4	39.7
Denver, CO	3.2	4.2	6.3	14.5	14.1
Los Angeles, CA	3.5	7.3	11.6	20.9	22.1
Madison, WI	4.0	6.8	10.9	31.1	31.5
Philadelphia, PA	5.0	6.8	10.9	32.2	33.3
Seattle, WA	4.4	8.5	16.6	51.1	50.6

1- Due to nesting/substitution of events within the 6-month period, the actual simulated rainfall was slightly different than the calculated 10-year, 6-month precipitation.

The monthly evapotranspiration data were obtained from NCHRP Report 802 (Strecker, 2015).

3.3.2 BMP Type

BMP type input determines the basic cross-section geometry and location of infiltration surface in the HYDRUS models. Users can select from one of the five BMP types. These BMPs are summarized below. Schematics of BMP geometry and dimensions are provided in Section 3.6.

- **Bioretention/Infiltration Basins (BB)** are located at the bottom of the embankment and are designed to collect runoff from the roadway. Water is infiltrated through an amended media layer. In some scenarios, the effect of underdrains was modeled. The modeled basin is 3 feet deep, underlain by 1.5 feet of loamy sand amended soil. If underdrains are present, there is a 1.5-foot deep gravel layer at the bottom below the underdrain discharge elevation. Basins were modeled with a top width of 40 feet perpendicular to the roadway.
- **Linear Infiltration/Bioretention Swales (IS**) are located at the bottom of the embankment. They are similar to bioretention basins but are narrower in the direction perpendicular to the roadway (8-foot width) and are shallower (1-foot depth). In some scenarios, the effect of underdrains was modeled, with a similar subsurface profile as bioretention/infiltration basins.

- **Infiltration Trenches** have the same footprint as infiltration swale (8-foot width) but are deeper (6 feet) and filled with gravel. This provides more surface area for water to migrate out of the side walls of the system.
- **Filter Strips (FS)** are located along the roadway on the top segment of the embankment with a width of 15 feet. Infiltration can occur over the entire strip. Surplus runoff will flow down the embankment (where infiltration can also occur) to a ditch at the bottom of the embankment.
- **Permeable Shoulder**s are located at the top of the embankment adjacent to the travel lanes. The permeable shoulder includes a gravel filled reservoir, with a sump depth of 1-foot set below interface between the subbase and subgrade of the roadway. The permeable shoulder is 10 feet wide. When the gravel reservoir is filled, surplus runoff will flow down the embankment (where infiltration can occur) to a ditch at the bottom of the embankment.

3.3.3 Embankment Geometry

Three embankment geometry configurations were modeled and are available in the Tool: High, Low and None (at-grade). The height of embankment of each configuration is summarized in Table 4.

Table 4. Embankment Height for each Geometry Category

Embankment Geometry	Embankment Height (ft)
High	13
Low	5
At Grade	0

3.3.4 Initial Groundwater Depth

For BMPs that are placed at the toe of the embankment (bioretention basins, infiltration trenches and infiltration swales), the initial groundwater depth was defined as the vertical distance from elevation of the infiltrating surface. For BMPs located on the embankment (filter strips and permeable shoulders), the initial groundwater depth was defined as the vertical distance from the toe of the embankment.

Four initial groundwater levels were modeled and are available in the tool, including 2 ft, 4 ft, 8 ft, and 16 feet. For sites with initial depth between these increments, the user can bracket results using the nearest increments. Conditions with depth to groundwater greater than 16 feet can use the 16 feet scenario. But if estimated mounding intersects with the BMP, then this indicates that actual mounding could be greater than 16 feet. Conditions with extreme mounding (such as exceeding 16 feet) likely warrant site-specific investigation beyond the scope of this tool.

The initial groundwater depth inputted in the tool should be the seasonal high groundwater table. This should account for seasonal fluctuations in water table. This should also account for any anticipated regional rise in the groundwater table associated with widespread use of stormwater infiltration, sea level rise, or other factors. Long term monitoring (1 to 3 years) may be needed to develop this parameter. In the case of anticipated regional rise in the groundwater table, this may need to be estimated based on regional modeling.

3.3.5 Loading Ratio

Loading ratio of a BMP is defined as the area ratio between the impervious roadway that generates stormwater runoff and the BMP footprint. For linear BMPs (length of BMP is the same as the length of the roadway), the loading ratio is equal to the ratio between the width of the road and the width of the BMP. For more centralized BMPs, the loading ratio is simply the area of impervious roadway divided by the footprint area of the BMP. The loading ratio determines the total inflow into the BMPs associated with a given volume of precipitation. Table 5 summarizes the loading ratio options for each BMP type in the tool.

Table 5. Modeled Loading Ratio for Each BMP Type

BMP Type	Loading Ratio Options
Linear (Permeable Shoulders, Filters Strips)	2:1 4:1 8:1
Centralized (Bioretention Basins, Infiltration Trenches, Infiltration Swales)	10:1 20:1 50:1

3.3.6 Soil Type and (Layering) Anisotropy

Soil type is a critical input in the Tool because it determines the modeled K_{sat} 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:

- Clay (0.1 in/hr)
- Silt (0.3 in/hr)
- 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.

Model results were bracketed by a higher and lower range of soil anisotropy, which was used to represent more layered and less layered soil structures. Anisotropy is the ratio of the horizontal hydraulic conductivity to the vertical hydraulic conductivity. Therefore, in runs with higher layering (higher anisotropy), the horizontal K_{sat} was greater (holding soil type and vertical K_{sat} fixed). This effectively represents a case with moderate 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. Assumptions for lower and higher bounds of anisotropy are summarized in Table 6.

Table 6. Modeled Loading Ratio for Each BMP Type

	Anisotropy	
Scenario	**Low**	**High**
Embankment Soil	2	10
Underlying Soil	10	50

3.3.7 Underdrains

BMP designs with underdrain are included in the tool for bioretention basins and infiltration swales without embankment. This input design parameter allows the user to estimate the mounding reduction with the presence of an underdrain outlet. This configuration is not supported for all conditions and BMP types. If underdrains are selected, the tool returns results for a modified BMP cross section including: 1.5 feet of gravel added below the media, and an underdrain located at the interface between the gravel layer and the amended soil layer (1.5 feet below the BMP surface). Figure 20 provides a diagram of this configuration. The underdrain was modeled with enough capacity to convey any excess water that does not infiltrate.

3.4 Data Visualization

3.4.1 Maximum Mounding Visualization

The "Peak Groundwater Mounding Cross Section" pane of the tool (Figure 14) is designed to depict the geometry of the cross-section of the selected embankment and BMP configuration and the maximum mounding elevation for soil. The results are bracketed by results for high and low anisotropy (higher and lower layering). The cross-section geometry of the BMPs are identical to the HYDRUS cross-section input. The mound is inferred from the pressure head results for a range of "observation nodes" which are the location where the HYDRUS results were outputted.

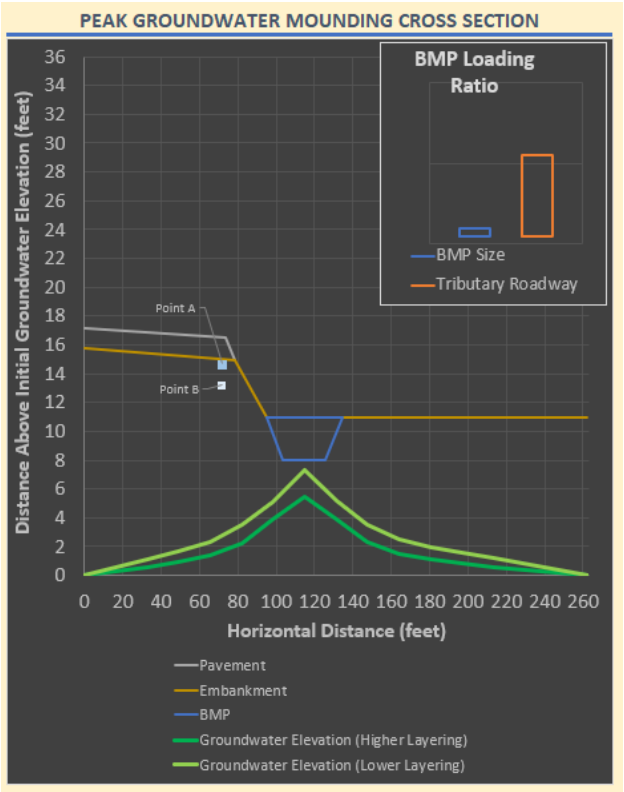


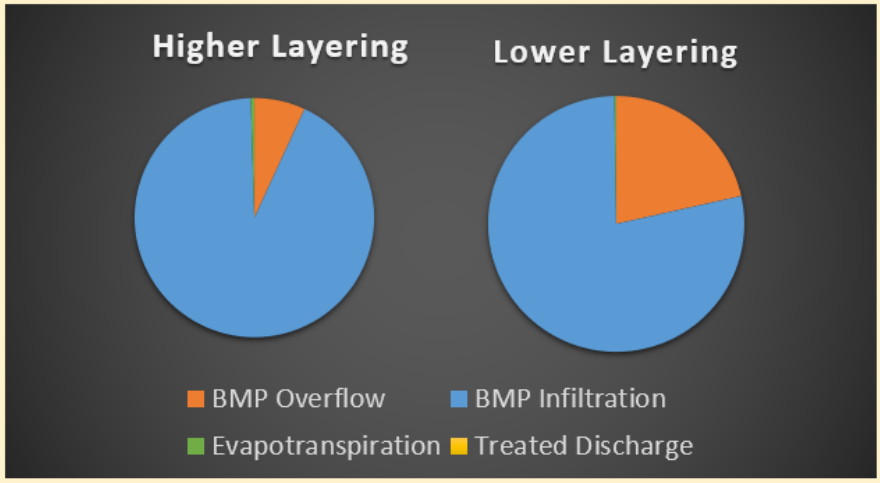
Figure 14 Maximum Mound Cross-Section Visualization Example in the Tool

3.4.2 BMP Water Balance

The BMP water balance pie charts in the tool summarize the cumulative fate of the water that enters the BMP over the period of simulation. It is divided into four categories:

- **Surface Discharge/Overflow**: the amount water bypassing the BMP treatment.
- **Infiltration**: the amount of water leaving the BMP via infiltration into the soil, below where evapotranspiration is active.
- **Evapotranspiration**: the amount of water leaving the BMP via evaporation from soil and transpiration from plants.
- **Treated Discharge**: the amount of treated water discharged via an underdrain pipe from selected BMPs (underdrains are present in selected scenarios only).

Two pie charts represent the higher and lower soil layering scenario (higher and lower anisotropy) as shown in Figure 15.



Water Balance Component	Higher Layering	Lower Layering
BMP Overflow	7%	21%
BMP Infiltration	93%	78%
Evapotranspiration	0%	0%
Treated Discharge	0%	0%

Figure 15 Example of Simulated Water Balance in the Tool

Note that for filter strips and permeable shoulders, the water balance is calculated for the entire BMP system including the storage component of the BMP and the embankment. As a result, the runoff component for these two BMPs represents the runoff volume discharged to the ditch located at the bottom of the embankment. The infiltration and evapotranspiration components are calculated based on the infiltration and evapotranspiration that occurred over the entire embankment.

3.4.3 Simulation Time Series

A time series plot is created for each input configuration to visualize the temporal variation in the average daily loading and how the BMP reacts to the inflow throughout the model simulation period. As shown in

Figure 16, the daily average loading is shown on the top half of the figure. On the bottom half of the figure, two bands are plotted representing the daily mean mounding height at the point directly underneath the infiltration BMP and the daily mean ponding depth within the BMP (if present). The bands are bounded by the HYDRUS model output values for higher and lower soil layering (anisotropy) scenarios. The elevations of the BMP bypass and the infiltration surface for the selected model configuration are also plotted to provide reference elevations for the ponding depths and critical head values. Ponding is not relevant for filter strips.

The time series plot is useful in assessing how often within the 6-month period mounding exceeded levels of interest. For example, did the critical mound occur briefly and was not regularly observed? Or did mounding occur regularly? The time series plot can also be helpful in assessing the duration of ponding in the BMP. For example, in the example presented in Figure 16, the combination of low infiltration rates and extended mounding resulted in periods of inundation of the BMP that extended more than 3 months. This is clearly a problematic condition for infiltration.

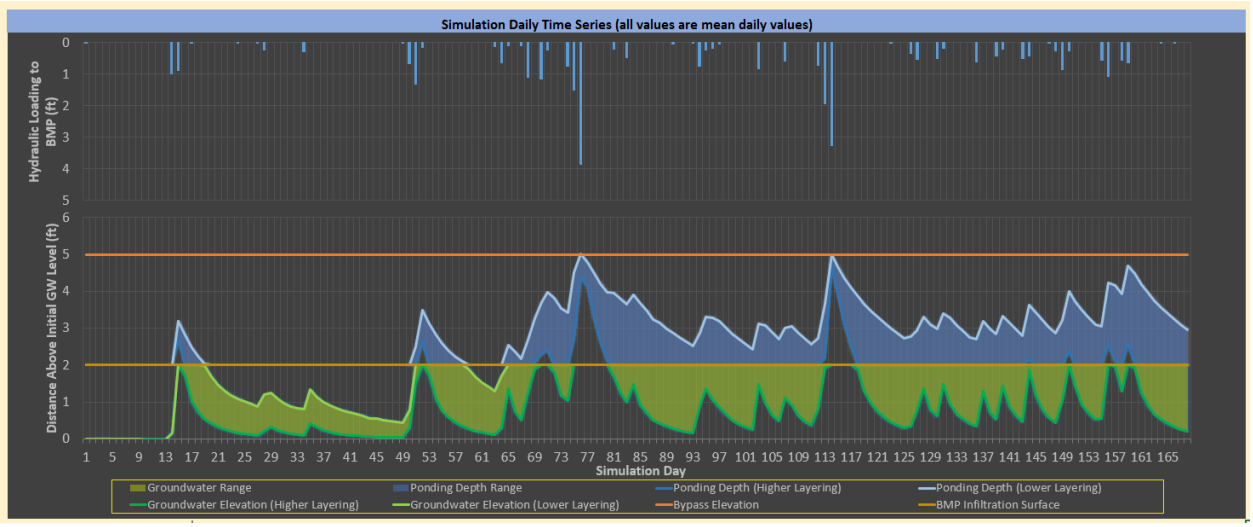


Figure 16 Example Simulation Time Series Plot in the Tool

3.4.4 Embankment Saturation

For scenarios with BMPs on embankments (filter strips, permeable shoulders), a visualization is provided that illustrates the zones where saturation occurred during the simulation.

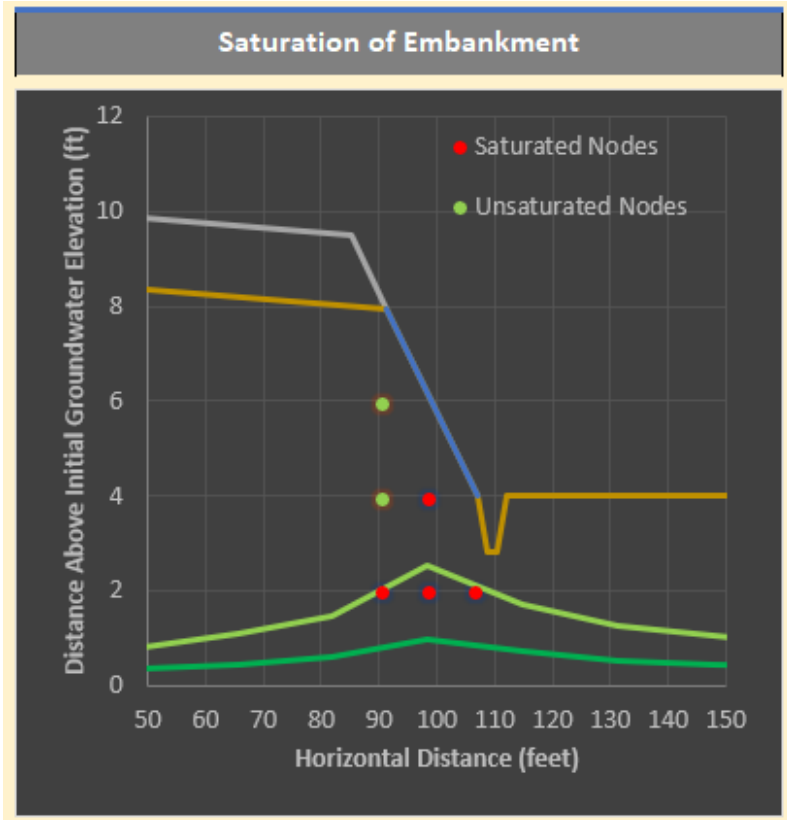


Figure 17 Example Embankment Saturation Plot in the Tool

3.5 Tabular Summaries

The tool provides summary statistics that also can be used to support screening of the geotechnical risk. The details of these summary tables and their implication on the associated geotechnical risks are explained in this section.

3.5.1 Actual Drawdown Rate vs. Modeled Vertical Ksat

The actual drawdown rate of a BMP (i.e., the rate at which the water level drops after an event) is not inherently equal to the K_{sat}. Under favorable conditions, the actual drawdown rate can exceed the vertical K_{sat} of a soil because of (1) hydraulic gradient on the soil, (2) suction effects of the soil and (3) the contribution of lateral flow out of the sidewalls of the BMP in addition to the floor footprint. However, if a mound forms, the effective hydraulic gradient and the effective drawdown rate of the BMP can be reduced. The tool reports the average of the actual drawdown rate (based on the average of all times when ponding occurred) in comparison to the modeled vertical K_{sat}. This is reported for the low soil layering (low anisotropy) scenario only which is somewhat more conservative. The two infiltration rates are presented for the selected configuration as shown in Figure 18.

Actual Drawdown Rate vs. Nominal Vertical Ksat	
Modeled Vertical K_{sat} Value of Limiting Layer (in/hr)	1.00
Mean Actual Drawdown Rate from BMP (in/hr)	0.49

Notes

For BMPs in sand with amended media the vertical Ksat is 5 in/hr because the media is the limiting layer. Otherwise, Ksat is assigned by soil type.

Average drawdown rate is reported in cases where ponding occurs. Actual drawdown rate greater than Ksat is common due to hydraulic gradient, soil suction and sidewall/lateral effects.

Figure 18 Tabular Summary of Actual Drawdown Rate vs. Nominal Vertical K_{sat}

A decline in actual drawdown rate is not necessarily a flaw but is in an indicator that groundwater mounding should be considered in estimating the actual drawdown rate.

3.5.2 Roadway Saturation

Data were extracted from two points within the HYDRUS models to summarize saturation of the roadbed. These points are located below the edge of pavement at a point where the subbase meets the subgrade and a point located 1.5 feet below this interface. The locations of these monitoring points are illustrated in the cross-section visualization shown in Figure 14. An example of the tabular summary is shown in Figure 19.

Saturation below Pavement Edge		
Distance Below Subgrade Interface	Saturation occurs?	Time 90% Sat
0 Foot (Point A)	No	0.0%
1.5 Feet (Point B)	No	0.0%

Figure 19 Tabular Summary of Roadway Saturation

As shown in Figure 19, the tool informs users about whether the soil at these monitoring locations was fully saturated during the simulation period. The percent time during which the two monitoring locations stay above 90 percent saturated is also presented in the roadway saturation summary.

3.5.3 Discharge from Toe of Slope

Where the groundwater mound intersects with the toe of the slope, this is an indication that some water infiltrated on the embankment may emerge back to the surface drainage system. Additionally, this could be an indicator of a risk of slope instability. The pane shown in Figure 17 can be inspected to determine if this condition is expected.

3.6 Assumed BMP Geometry for Tool

Figure 20 through Figure 24 show the modeled geometry of each BMP type, including how the elevations of the BMP related to the adjacent pavement. Review of these schematics is recommended as part of using the tool confirm that the modeled BMPs are reasonably representative of proposed BMPs.

Note that in the no embankment (on-grade) scenarios, the elevation of the BMP ponded water surface relative to the roadway subbase would be expected to have important influence on the potential risk associated with the subbase and subgrade saturation. For modeling scenarios in the at-grade roadway geometry, the maximum ponding depth of the BMP was assumed to be equal to the elevation of the interface between the subbase and subgrade (1.5 ft below the elevation of the travel lanes). If BMPs will pond to a level higher than this elevation, then saturation of the pavement subbase and subgrade would be expected regularly. A cutoff wall or membrane could be considered in these cases but were not explicitly modeled.

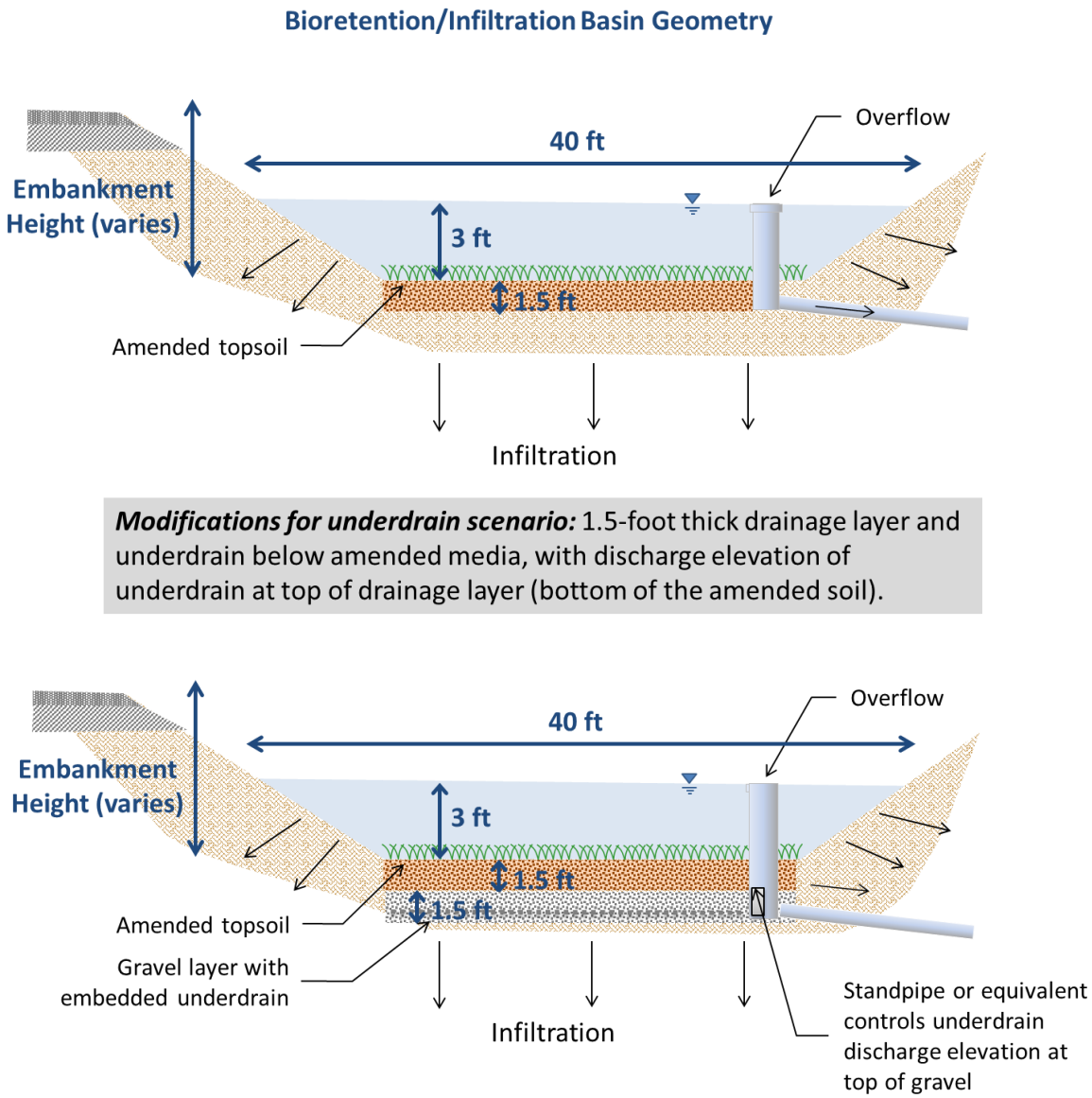
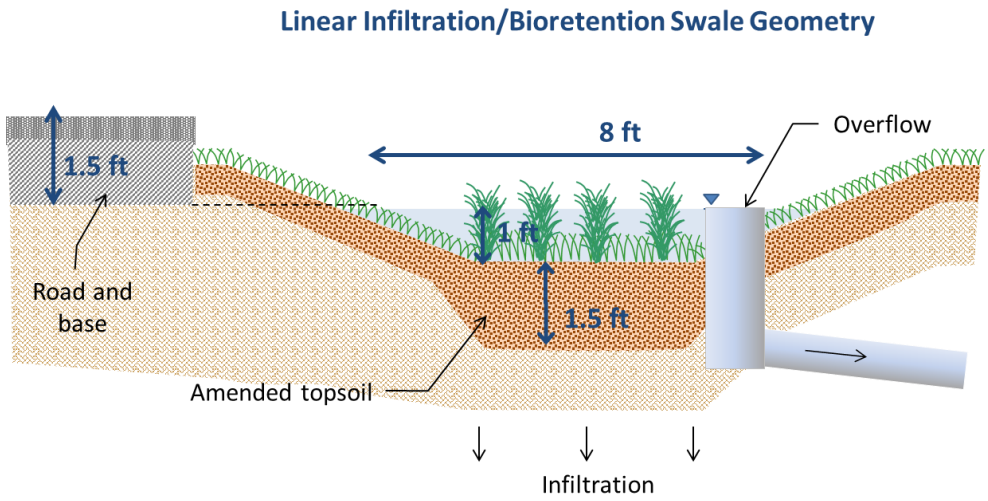


Figure 20. Modeled Dimensions of Bioretention/Infiltration Basin BMPs



Note: Pavement edge scenario shown. In embankment scenarios, the bottom of the swale is modeled at the toe of slope.

Modifications for underdrain scenario: 1.5-foot thick drainage layer and underdrain below amended media, with discharge elevation of underdrain at top of drainage layer (bottom of the amended soil).

Figure 21. Modeled Dimensions of Linear Infiltration/Bioretention Swale BMPs

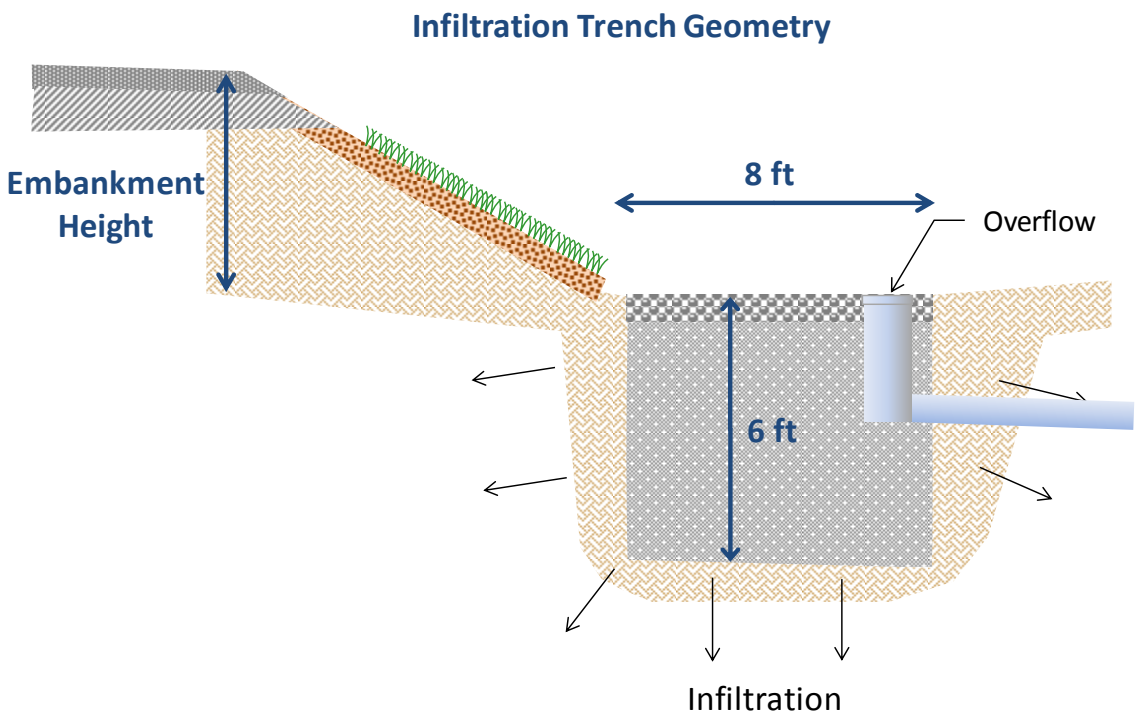


Figure 22. Modeled Dimensions of Infiltration Trench BMPs

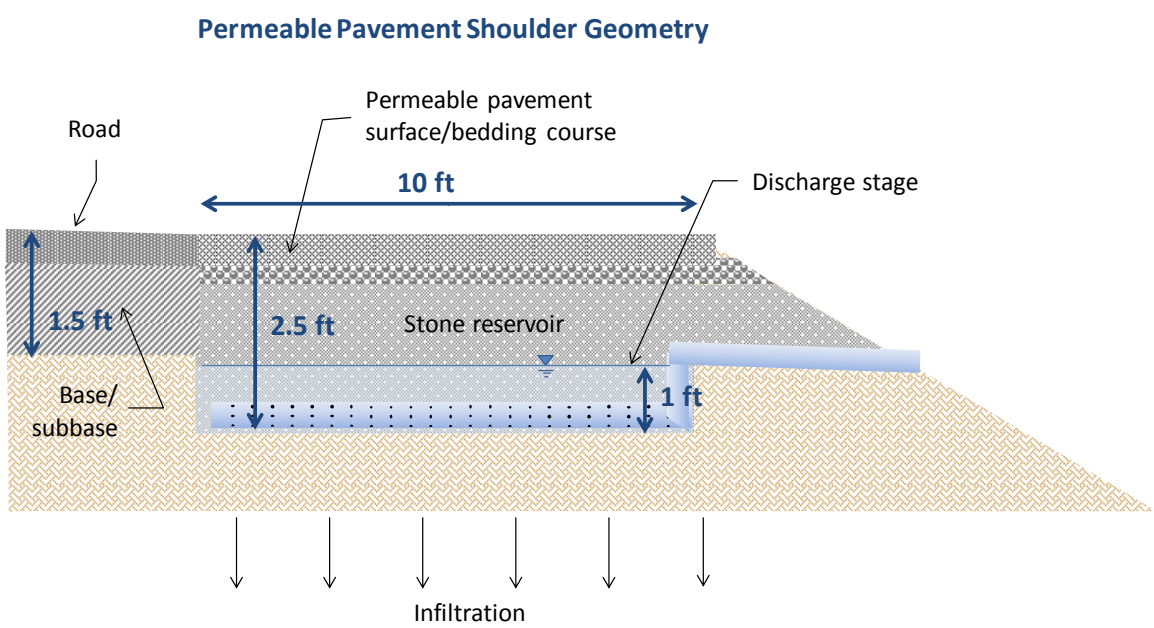


Figure 23. Modeled Dimensions of Permeable Shoulder BMPs

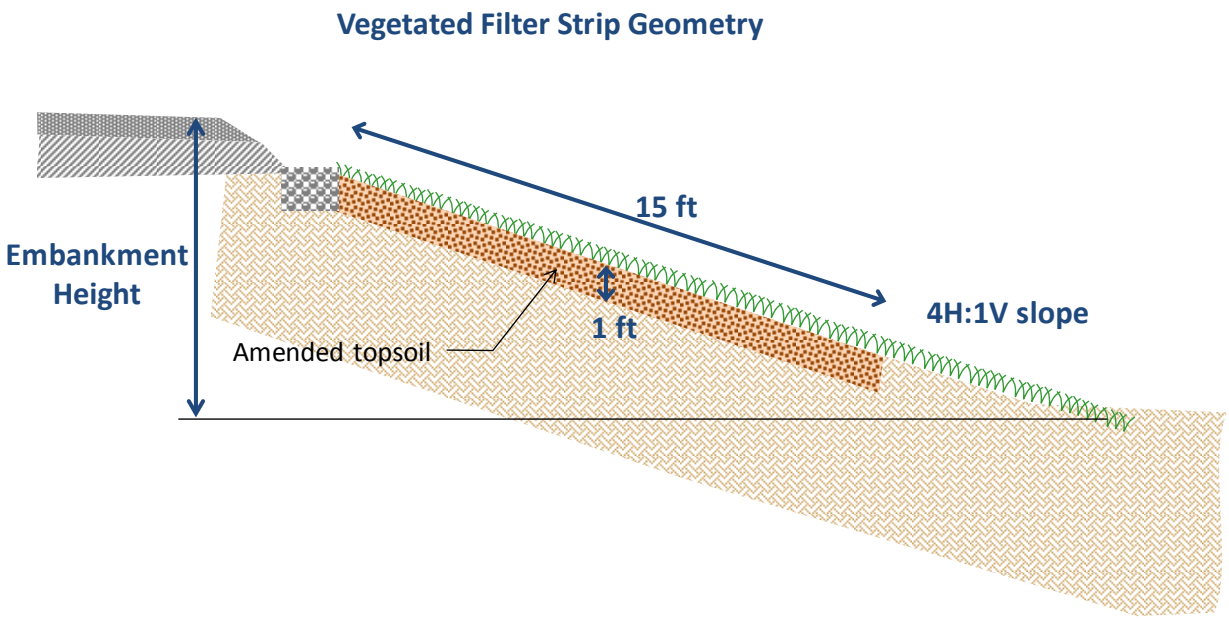


Figure 24. Modeled Dimensions of Filter Strip BMPs (only applicable in low or high embankment geometry)

4 References

Carleton, G.B., 2010, Simulation of groundwater mounding beneath hypothetical stormwater infiltration basins: U.S. Geological Survey Scientific Investigations Report 2010-5102, 64 p.

Hantush, M.S., 1967, Growth and decay of groundwater mounds in response to uniform percolation: Water Resources Research, v. 3, p. 227–234

See the accompanying Project Summary Report for additional references consulted by the research team in development of the Groundwater Mounding Assessment Tool.