Appendix G

Whole Lifecycle Cost and Performance Example

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Whole Lifecycle Cost and Performance Example

1 Introduction

The Guidance Manual (Sections 4.4 and 4.5) identifies several potential design variations that can be considered to improve the adaptability and resiliency of infiltration BMPs, such as providing the ability to adapt operations (i.e., a backup plan) or reducing the susceptibility of the BMP to unknown conditions (i.e., sensitivity to infiltration rate, susceptibility to sediment loading). Design alternatives involve addition of features such as:

- Including an underdrain that remains normally capped unless it is needed.
- Adding an internal infiltration sump within the design and providing a supplemental pathway for discharge (i.e., an elevated underdrain).
- Including a sacrificial sand layer in the bottom of an infiltration BMP that can be replaced periodically.
- Providing more robust pre-treatment than would ordinarily be provided.

While these options have the potential to make the system less sensitive to unknown conditions and reduce the potential for failure, they may add capital costs. The tools developed as part of this Guidance Manual along with tools developed as part of previous NCHRP projects can be used to help evaluate these design features with respect to whole lifecycle cost, performance and reliability.

This appendix presents a case study example of how built-in features intended to reduce sensitivity to infiltration rate can affect the whole lifecycle cost, performance and resiliency of the design. The case study focuses on the question of whether to install underdrains in bioretention basin to reduce the sensitivity of the design to the actual infiltration capacity below the facility. This case study evaluates the following three questions:

- **Upfront cost impact.** What is the estimated effect of the additional design elements on capital costs?
- **Resiliency to uncertain conditions.** How do those the design alternative affect the capture efficiency and pollutant load reduction performance of the BMP under a reasonable range of conditions that could occur due to uncertainty in design assumptions and/or changes in condition over the life of the facility?
- **Lifecycle impact.** How does the alternate design affect potential lifespan/length of maintenance cycles, and how does this impact whole lifecycle cost effectiveness?

This case study also demonstrates the use of the Groundwater Mounding Assessment Tool (Appendix C) to evaluate the effect of underdrains on groundwater mounding-related risks.

2 Methods

The case study involved defining a baseline design and an alternative design. Boundary conditions were then varied within reasonable ranges, representing the uncertainty range on soil infiltration rate. Results were evaluated relative to how the BMPs compared under expected conditions as well as how they compared under adverse conditions (i.e., lower infiltration rates).

The Whole Lifecycle Cost and Performance Tool associated with NCHRP Report 792 was used to conduct the cost and performance evaluation as part of this case study. Additionally, the Clogging Risk

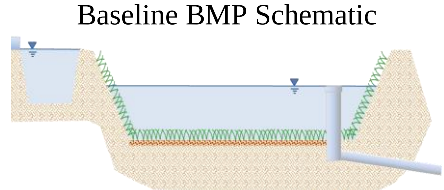
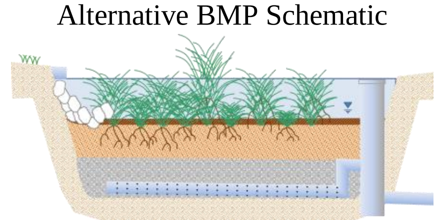
Assessment Tool (Appendix F) was used to support evaluation of lifecycle impacts related to clogging. Input from the clogging risk assessment tool was used to adjust maintenance and life cycle assumptions in the Whole Lifecycle Cost and Performance Tool. The Groundwater Mounding Assessment Tool (Appendix C) was used to evaluate groundwater mounding-related risks.

3 Case Study Inputs and Results

3.1 Case Study Conditions and Design Alternatives

Table 1 summarizes key case study conditions and describes the two design alternatives under consideration.

Table 1. Summary of Key Case Study Parameters

Tributary Areas	• Located in Philadelphia, PA; Denver, CO; and Olympia, WA • 12 acres total • 9.5 acres of roadway • 2.5 acres of adjacent slopes • 20,000 AADT roadway	
BMP Site Conditions	• Soils are loamy sand with moderate layering • Best estimate of raw vertical infiltration rate = 4 in/hr • Design infiltration rate = 1.0 in/hr (Factor of Safety = 4.0) (Note: this is a typical factor of safety based on the method introduced in Appendix B.) • Decline of infiltration rate to 0.5 in/hr would trigger maintenance • Slopes are well vegetated and do not produce sediment under anticipated conditions • Groundwater is 8 feet below the bottom of the basin.	
Baseline BMP Design	• Infiltration basins without underdrains • Ponding depth of 3 feet • No bioretention soil media used • Simple forebay pre-treatment • Sized at an impervious area to BMP ratio of 50 to 1 (approximately a 2% sizing factor).	Baseline BMP Schematic  (conceptual, not to scale)
Alternative Design Option	• Bioretention with underdrains elevated above an internal stone infiltration reservoir • Ponding depth of 3 feet • 1.5 feet of bioretention soil media • 1.25 feet of stone below the underdrain discharge elevation • A hydrodynamic separation BMP is used for pre-treatment • Bioretention soil is engineered to have a permeability of 20 in/hr and is restricted to 5 in/hr • Same sizing as baseline	Alternative BMP Schematic  (conceptual, not to scale; pre-treatment not shown)

3.2 Clogging Risk Evaluation

3.2.1 Expected Conditions

To estimate the maintenance frequency and lifespan of the design alternatives, the Clogging Risk Assessment Tool (Appendix F) was set up for each scenario. Philadelphia climate inputs were used for this analysis. For the baseline design (infiltration basin), the Tool was set with an initial infiltration rate of 4.0 in/hr (assuming measurements were accurate) and the minimum allowable infiltration rate of 0.5 in/hr, corresponding with a 72-hour drawdown time. The Tool was used to calculate the estimated time to rehabilitative maintenance based on the starting and ending infiltration rated. Screen captures from the Tool are included below (Figure 1).

BMP Design Inputs

Step 1: Provi

Parameter	Value
Practice Type	Infiltration
Underlying Soil Type	Sand (HSG A)
Default Initial Soil Infiltration Rate (in/hr)	4.49
User-Provided Soil Infiltration Rate (in/hr)	4
Will a sacrificial media or sand layer be used over the underlying soil?	No
Minimum Allowable Infiltration Rate To Trigger Maintenance (in/hr)	0.5

Step 2: Provi

Parameter	Value
85th Percentile Event Runoff Volume (ft^3)	27312
Practice Storage Volume (ft^3)	32500
BMP Infiltrating Footprint Area (ft^2)	8276.4
Select Flow Configuration	Off-Line
Average Annual BMP Sediment Capture Rate (%)	80%
Is pretreatment present?	Yes
Type of Pretreatment	Sediment Forebay Only
Sediment Removal Efficiency of Pretreatment (%)	25%
Is the BMP exposed to the surface or below grade?	Surface
Is the BMP vegetated?	Vegetated

Figure 1. Inputs to Clogging Risk Assessment Tool for Baseline Infiltration Basin Scenario

The baseline scenario resulted in an estimate of 6 years to rehabilitative maintenance (Figure 2).

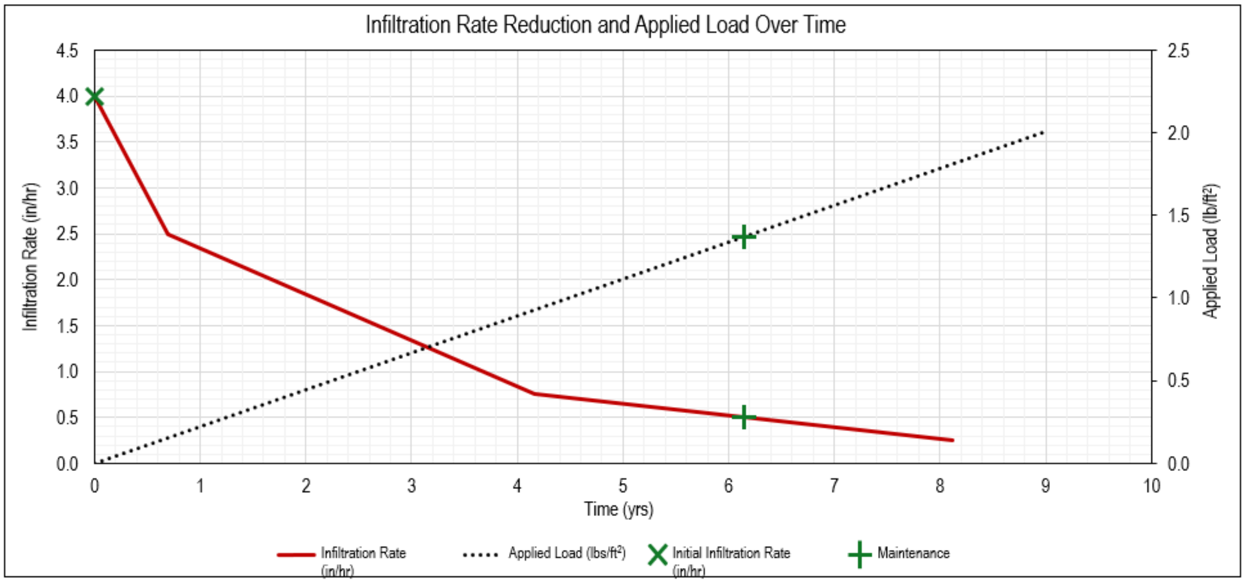


Figure 2. Results of Clogging Risk Assessment Tool for Baseline Infiltration Basin Scenario

For the alternative bioretention scenario, Tool was set to include a media layer which has higher initial infiltration rate. This is the limiting surface for clogging. It is reasonable for a typical bioretention soil to have a media filtration rate of 20 in/hr when placed. Outlet control (orifice affixed to the underdrain) was used to reduce the rate of flow through the media to improve detention and pollutant removal. Screen captures from the Tool are included below (Figure 3).

Parameter	Value
Practice Type	Infiltration
Underlying Soil Type	Sand (HSG A)
Default Initial Soil Infiltration Rate (in/hr)	4.49
User-Provided Soil Infiltration Rate (in/hr)	4
Will a sacrificial media or sand layer be used over the underlying soil?	Yes
Initial Media Layer Infiltration Rate (in/hr)	20.0
Minimum Allowable Infiltration Rate To Trigger Maintenance (in/hr)	0.5
Parameter	**Value**
85th Percentile Event Runoff Volume (ft^3)	27312
Practice Storage Volume (ft^3)	32500
BMP Infiltrating Footprint Area (ft^2)	8276.4
Select Flow Configuration	Off-Line
Average Annual BMP Sediment Capture Rate (%)	80%
Is pretreatment present?	Yes
Type of Pretreatment	TAPE Pretreatment GULD
Sediment Removal Efficiency of Pretreatment (%)	50%
Is the BMP exposed to the surface or below grade?	Surface
Is the BMP vegetated?	Vegetated

Figure 3. Inputs to Clogging Risk Assessment Tool for Alternative Bioretention Scenario

The alternative design configuration resulted in an estimated time to rehabilitative maintenance of 20 years (Figure 4). This was partly due to the higher initial infiltration rate of the media and partly due to the superior pre-treatment BMP used. The cost of both additional features are later considered in the whole lifecycle cost analysis.

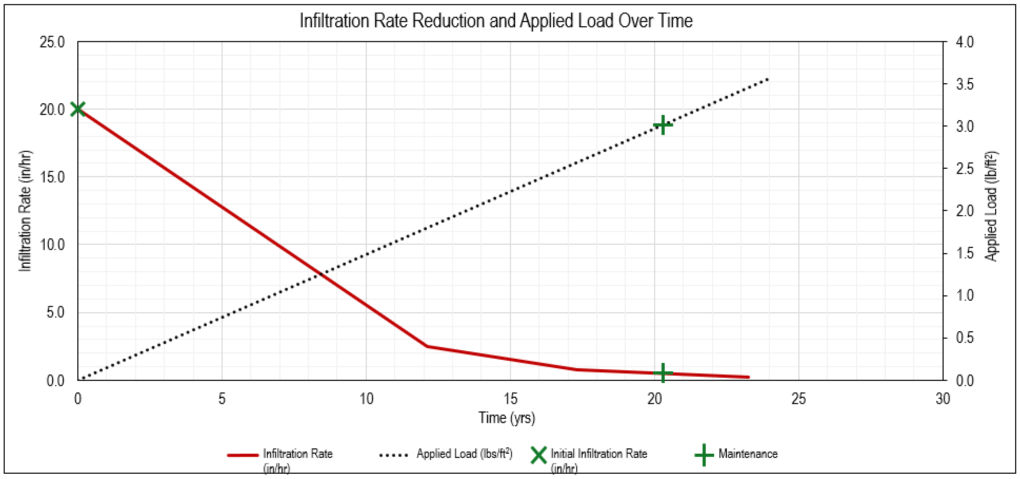


Figure 4. Results of Clogging Risk Assessment Tool for Alternative Bioretention Scenario

3.2.2 Adverse Conditions

Another infiltration basin scenario was considered in which the actual underlying infiltration rate was one-third of the estimated rate and the system was therefore allowed to decline from 1.3 to 0.5 in/hr between maintenance cycles. This reduced the maintenance interval to 4.5 years.

The error in estimating underlying infiltration rate had no effect on the lifespan of the bioretention basin with underdrains because the controlling surface for clogging was the surface of the media.

3.3 Whole Lifecycle Cost and Performance Inputs and Assumptions

The Whole Lifecycle Cost and Performance Tools associated with NCHRP Report 792 were used for this analysis. These tools provide estimates of long-term capture efficiency, volume reduction, pollutant load reduction, capital cost, and whole lifecycle cost based on user-defined BMP scenarios. This set of tools includes seven separate Excel workbooks, each for a different type of BMP, including:

- Bioretention
- Dry Extended Detention
- Vegetated Filter Strip
- Permeable Friction Course
- Sand Filter
- Vegetated Swale
- Wet Pond

The Bioretention Tool from Report 792 was used as for this analysis. Based on the scenarios defined above and the results of the Clogging Risk Assessment Tool, 12 versions of the Bioretention Tool were configured:

- Three climate stations (Philadelphia, Denver, and Olympia). Note, lifespan was held fixed across climate stations, however some differences in lifespan could arise from climate differences.
- Two BMP types (infiltration and bioretention with underdrains).

- Two soil conditions (original and reduced by two-thirds).

Figure 5 shows an example screen capture from the Bioretention Evaluation Tool.

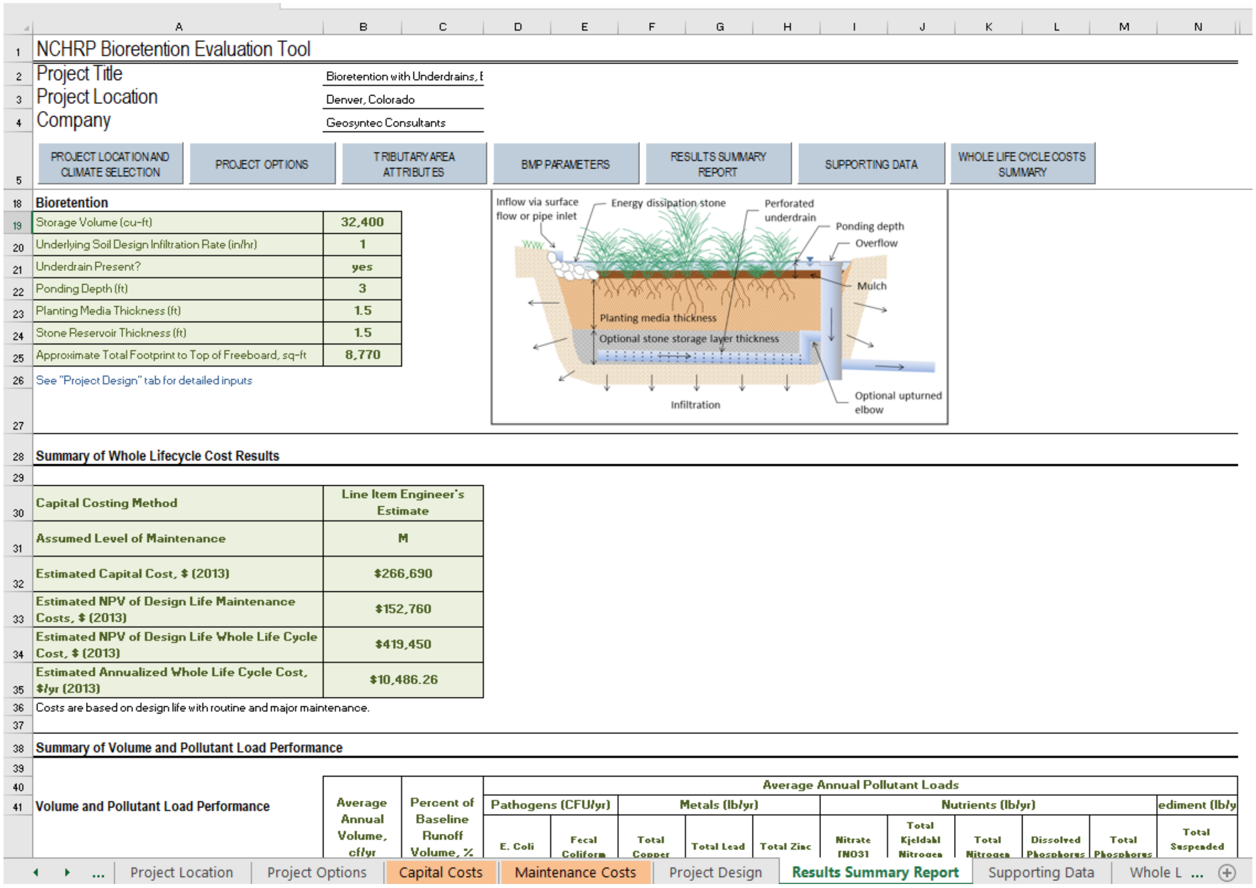


Figure 5. Example Screen Capture from Bioretention Whole Lifecycle Performance and Cost Evaluation Tool

Starting from the default costing assumptions in this tool, various adjustments were made to represent the scenarios. Key differences in capital cost line items are summarized in Table 2.

Table 2. Summary of Differences in Capital Cost Line Items

Capital Cost Item	Baseline Infiltration	Bioretention with Underdrains
Bioretention Soil	6-inch layer at $43/CY (default) to support plants	18-inch layer at $60/CY to provide filtration
Plants	$1/sq-ft for simple plants	$2/sq-ft for more complex plants (default)
Underdrain gravel and piping	Not included	Included at default cost
Hydrodynamic separator	Not included	Included at default cost
Forebay	20% extra footprint for forebay	Not included

Key differences in maintenance cost assumptions are summarized in Table 3.

Table 3. Summary of Differences in Maintenance Cost Line Items

Maintenance Cost Component	Baseline Infiltration	Bioretention with Underdrains
Regular vegetation and debris maintenance	Less expensive due to simpler plant pallet (30% less than default)	More expensive due to more complex plants (default)
Cleanout of Hydrodynamic Separator	Not included	Yearly
Major Rehabilitation for Clogging	6-year frequency, accounting for plant replacement at $1/sf.	20-year frequency, accounting for plant replacement at $2/sf.
Reconstruction of Facility	1/3 of initial construction cost every 20 years (after 3 clogging cycles)	40 years lifespan (two clogging cycles)

Other than these differences, assumptions were based on tool defaults and were held consistent between the scenarios. For the analysis of adverse conditions (lower infiltration rate, shorter design life), maintenance activities were increase by a ratio of 1.33 which is proportional to the estimated difference in design life (6 years/4.5 years). A 40-year lifecycle cost estimating period was assumed across scenarios.

3.4 Whole Lifecycle Cost Results

Based on the scenarios and assumptions described above, the whole lifecycle cost comparison is presented in Table 4. While the bioretention alternative was estimated to have a capital cost more than 80 percent higher than the simpler infiltration basin, the whole lifecycle cost was estimated to be similar because of considerably more frequent maintenance in the baseline scenario to alleviate clogging. This does not explicitly account for the effect of plant roots, which could potentially increase the lifespan of both systems.

Table 4. Summary of Whole Lifecycle Cost Estimates

Cost and Lifecycle Estimates	Baseline: Infiltration Basin	Infiltration Basin with Reduce Infiltration Rate (shorter design life)	Alternative: Bioretention With Elevated Underdrains
Capital Cost, $/imp acre	$16,000	$16,000	$28,100
Estimated Period to Rehabilitative Maintenance (clogging), years	6	4.5	20
Estimated Lifespan to Major Reconstruction, years	20	15	40
Time Period for Whole Lifecyle Cost Analysis, years	40	40	40
Inflation Rate, %	5%	5%	5%
Discount Rate,	5%	5%	5%
Lifecycle Cost, $/yr/imp acre	$41,700	$50,200	$44,100

3.5 Performance and Cost Effectiveness Results

3.5.1 Expected Conditions

Table 5 presents the results of the two alternatives under as-expected conditions for the three climate zones. Capture efficiency refers to the fraction of the long-term stormwater runoff volume that is managed by the BMP (treatment plus surface volume runoff reduction). Volume reduction refers to the portion of the long-term runoff volume that is lost and does not discharge to surface waters via direct surface discharge (this water may still discharge via groundwater). All results are presented as long-term averages.

Table 5. Performance and Cost Effectiveness Under As-Expected Conditions

Long Term Cost Effectiveness Estimates	Philadelphia		Denver		Olympia	
	Baseline: Infiltration Basin	Alternative: Bioretention With Elevated Underdrains	Baseline: Infiltration Basin	Alternative: Bioretention With Elevated Underdrains	Baseline: Infiltration Basin	Alternative: Bioretention With Elevated Underdrains
Long Term Capture Efficiency	81%	96%	92%	98%	84%	99%
Long Term Volume Reduction	81%	41%	92%	59%	84%	57%
Surface Drawdown Time, hours	36	7	36	7	36	7
Percent of TSS Load Removed	83%	81%	92%	88%	84%	88%
Cost Effectiveness for TSS ($/lb removed)	$4.60	$5.30	$12.09	$13.30	$3.98	$4.03
Percent of Total Copper Load Removed	83%	75%	83%	83%	84%	83%
Cost Effectiveness for TCu ($/lb removed)	$4,700	$6,000	$12,400	$14,400	$4,100	$4,400

This comparison offers several insights:

- Based solely on up-front capital cost, the simpler infiltration basin design costs approximately 40 percent less than the bioretention basin with underdrains and enhanced pre-treatment.
- However, because of the expectation of more frequent maintenance to remediate clogging, the 40-year lifecycle costs are similar between the two scenarios. While there is considerable uncertainty in maintenance planning and lifecycle cost estimation, this suggests that the additional upfront cost for a more resilient design can be offset by reduced frequency of major maintenance.
- Due to the presence of underdrains, the bioretention alternative achieves about half of the volume reduction of the infiltration basin. This is partly offset by the higher filtration rates of the

amended bioretention media than the infiltration rates of the underlying soils which results in higher capture efficiency by the bioretention alternative.

- Both the absolute pollutant removal and the cost effectiveness of pollutant removal are similar between these cases.
- When the size of a facility is held fixed, the cost effectiveness tends to be higher in wetter climates where the system is utilized more often. In practice, systems would tend to be smaller in climates that experience less intense rainfall, such as Denver, and the cost-effectiveness would improve.

Under as-expected conditions these scenarios are reasonably equivalent. Provided that the engineer has reasonable confidence that the expected infiltration rates can be reliably maintained, either option could be justified. The deciding factor may be whether project budget is available support higher capital costs to reduce ongoing costs.

3.5.2 Adverse Conditions

Table 6 presents the results of the same two alternatives under adverse conditions where the actual infiltration rate is two-thirds lower than initially estimated (1.3 in/hr raw; 0.3 in/hr design infiltration rate). This analysis investigated how the performance and operations would be affected by a lower infiltration rate than expected. It also accounted for the higher lifecycle costs associated with more frequent maintenance cycles.

Table 6. Performance and Cost Effectiveness Under Adverse Conditions

Long Term Cost Effectiveness Estimates	**Philadelphia**		**Denver**		**Olympia**	
	Infiltration Basin	**Alternative: Bioretention With Elevated Underdrains**	**Infiltration Basin**	**Alternative: Bioretention With Elevated Underdrains**	**Baseline: Infiltration Basin**	**Alternative: Bioretention With Elevated Underdrains**
Long Term Capture Efficiency	71%	95%	84%	98%	58%	98%
Long Term Volume Reduction	71%	28%	84%	46%	58%	34%
Surface Drawdown Time, hours	120	7	120	7	120	7
Percent of TSS Load Removed	71%	77%	84%	84%	58%	81%
Cost Effectiveness for TSS ($/lb removed)	$6.57	$6.09	$16.04	$13.88	$7.07	$4.34
Percent of Total Copper Load Removed	81%	70%	83%	78%	58%	74%
Cost Effectiveness for TCu ($/lb removed)	$6,776.00	$6,900	$16,577.00	$15,328	$7,260.00	$4,900

Based on this comparison, several observations can be made:

- Most notably, the estimated drawdown time of the infiltration basin increased three-fold to 120 hours. In some cases, this could be considered failure and could prompt remedial action or conversion of the system to a different BMP type. Costs of immediate BMP reconstruction or conversion were not considered; however, costs of more frequent maintenance were considered.
- In contrast, the drawdown rate of the bioretention BMP continued to be controlled by the media filtration layer and was unaffected by the lower infiltration rate.
- Both alternatives experienced a reduction in infiltration losses. This affected the capture efficiency of the infiltration basin but did not have an appreciable effect on the capture efficiency of the bioretention alternative as an increase treated volume compensated for a reduction in infiltration losses.
- As a result, the pollutant load reduction and cost-effectiveness of the bioretention alternative was similar to the results for bioretention in the as-expected condition. Pollutant load reduction and cost effectiveness deteriorated for the infiltration basin.
- Deterioration of infiltration basin performance was most acute in Olympia, which is characterized by long storm events and extended periods of wet weather. The extension of the infiltration drawdown period resulted in a major reduction in capture efficiency and associated reduction in pollutant removal.

This shows that under reduced infiltration conditions, the bioretention alternative tends to provide similar or better pollutant load reduction at a lower lifecycle cost. When accounting for the potential maintenance issues for the infiltration basin option associated with extended ponded water duration (e.g., vector control, biofouling, maintenance access issues), it is possible that an infiltration basin could be rendered non-viable under the reduced infiltration conditions. While good exploration and careful construction-phase controls can help reduce the likelihood of encountering adverse conditions, the assumed reduction for this "what-if" scenario (4 in/hr estimated to 0.3 in/hr actual) is not unreasonable given the variability of site conditions, the uncertainty in converting infiltration tests to full scale facilities, and the sensitivity of infiltration rate to compaction and other factors.

3.6 Groundwater Mounding Evaluation

The Groundwater Mounding Assessment Tool was also applied to evaluate the baseline and alternative design options. This comparison was based on a vertical K_{sat} of 1 in/hr (sandy loam soil) and the scenario inputs described above. Figure 6, Figure 7, and Figure 8 show groundwater mounding, water balance, and time series results for the baseline scenario, respectively.

In the baseline scenario, groundwater mounding intersected with the BMP surface routinely during the simulation period. This may be permissible in some cases, but could introduce geotechnical issues, prolonged drawdown time, and/or groundwater quality issues. Bypass made up approximately 30 to 40 percent of the long-term water balance. Note this is not comparable to the capture efficiency reported in Table 5 because the Groundwater Mounding Tool was developed based on a 6-month period with relatively extreme rainfall and used different methods than the NCHRP Report 792 tools.

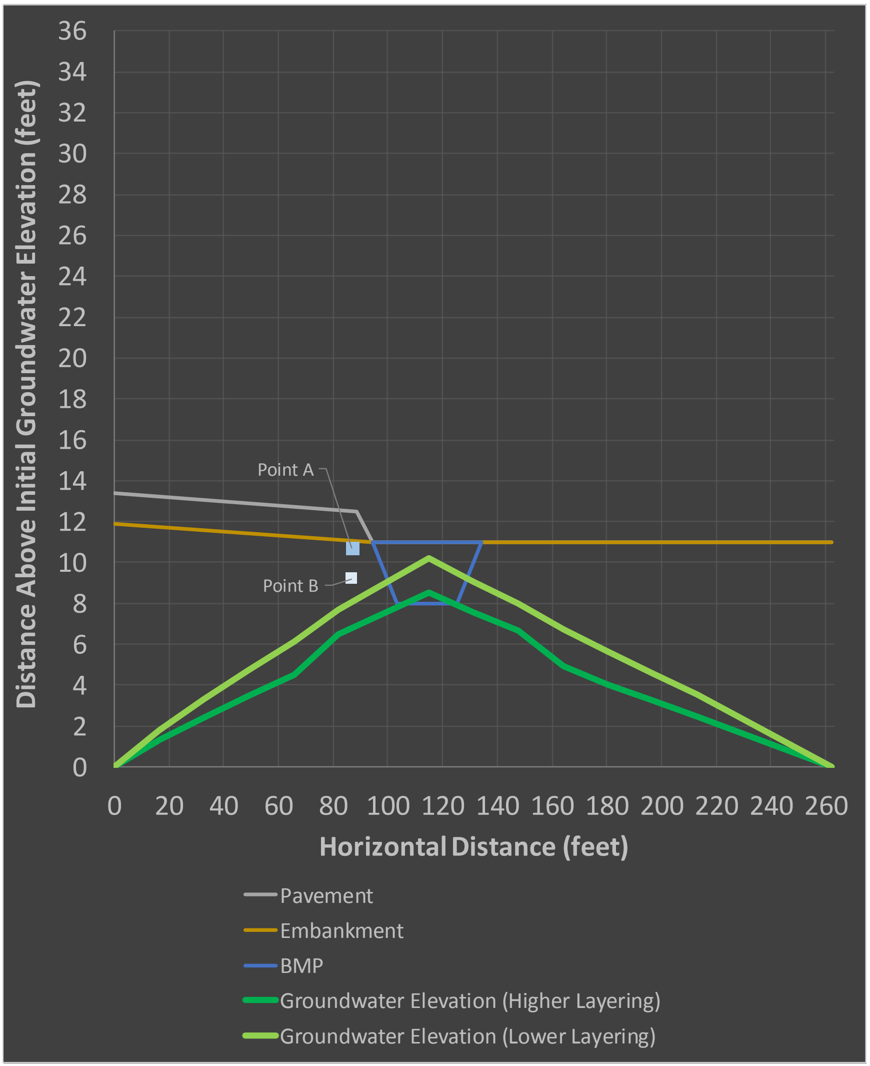


Figure 6. Groundwater Mounding Estimate for Baseline Scenario

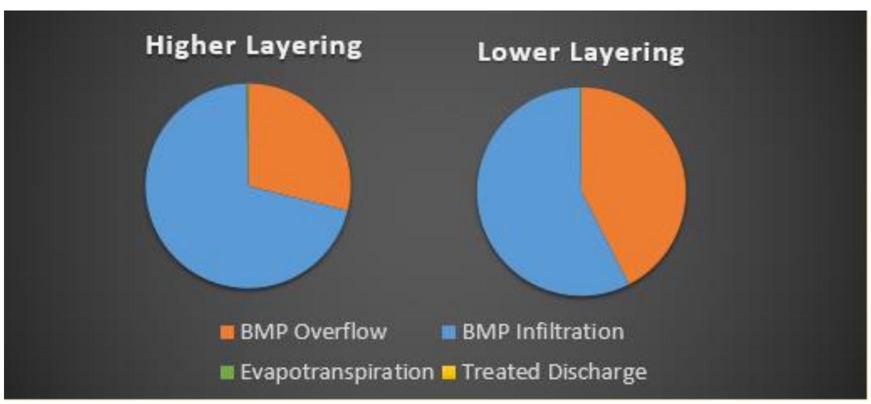


Figure 7. Water Balance Results for Baseline Scenario

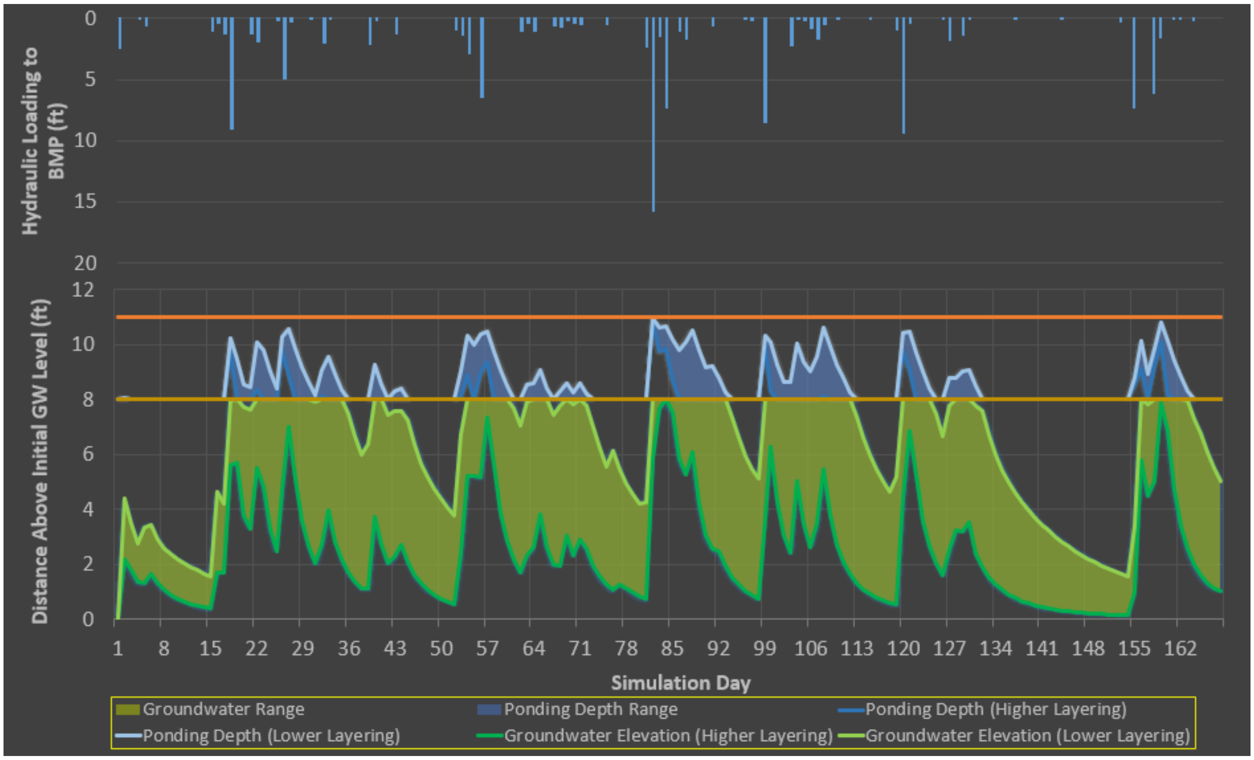


Figure 8. Time Series of Mounding and Ponding for Baseline Scenario

Figure 9, Figure 10 and Figure 11 show groundwater mounding, water balance, and time series results for the alternative scenario. As anticipated, the addition of the underdrain to the alternative scenario reduced the maximum level of mounding and greatly reduced periods of standing water. It also increased the capture efficiency to nearly 90 percent but reduced the infiltrated volume. Note that the time series of ponding are reported as daily average water levels. Actual simulations were hourly. Intra-day peaks resulted in bypass events that are not shown in these plots.

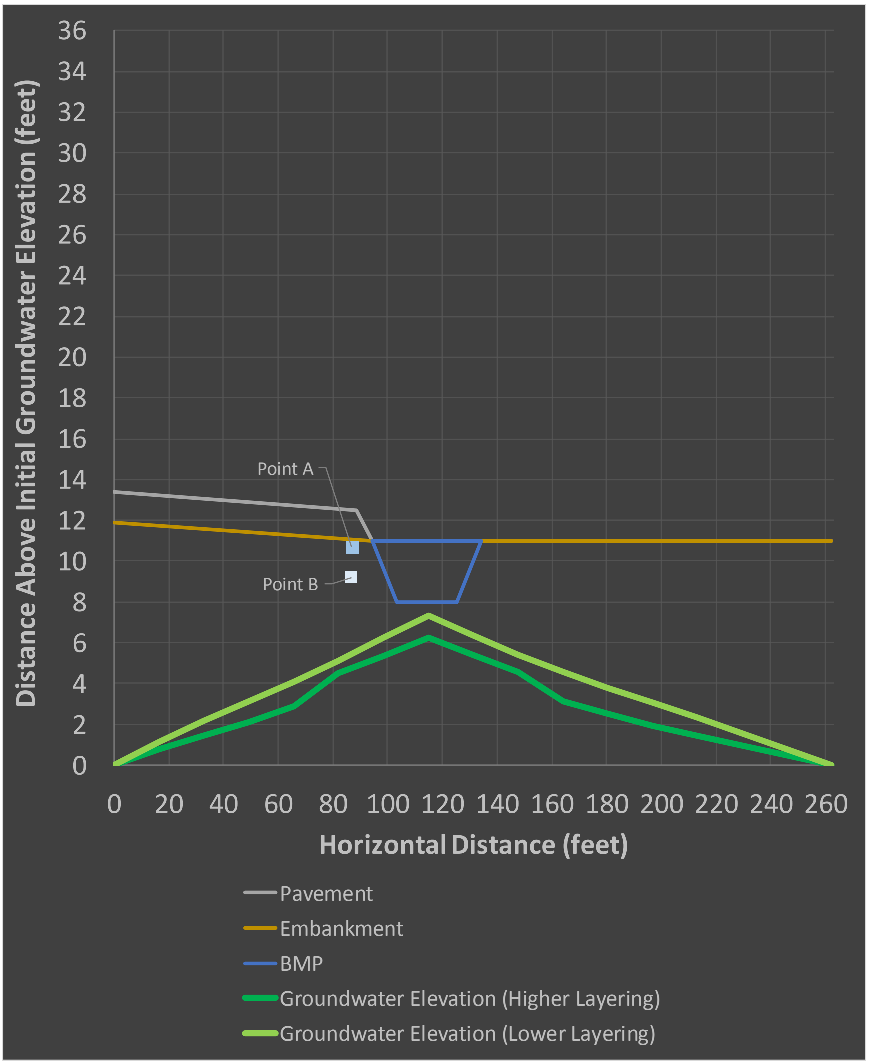


Figure 9. Groundwater Mounding Estimate for Alternative Scenario (with underdrains)

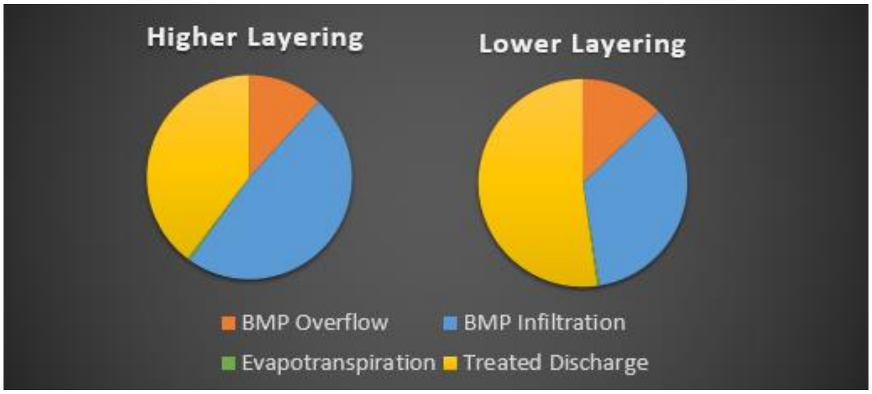


Figure 10. Water Balance Results for Alternative Scenario (with underdrains)

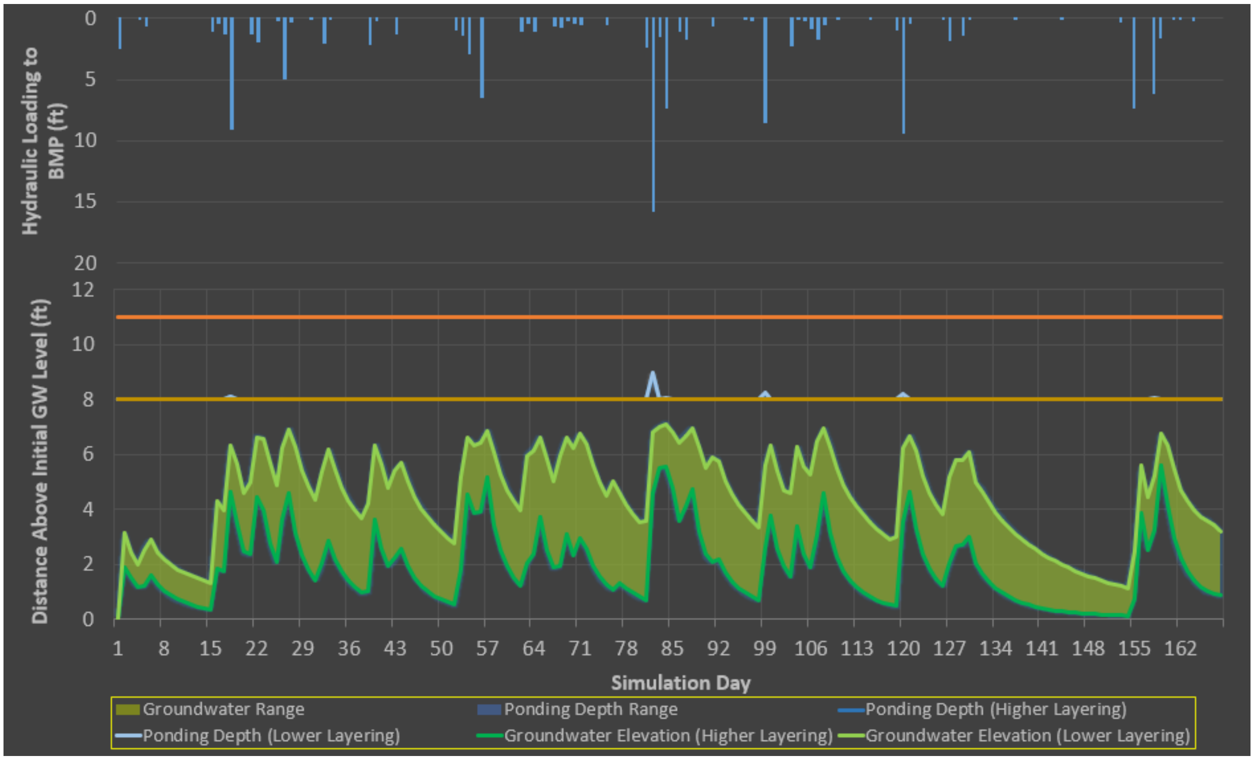


Figure 11. Time Series of Mounding and Ponding for Alternative Scenario (with underdrains)

4 Summary

This case study demonstrated the use of available tools to help support BMP selection and design decisions. Using these tools, this case study compared two design alternatives based on whole lifecycle costs, performance, cost effectiveness, and the response of the alternatives to a “what if” scenario regarding uncertainty in estimated infiltration rate.

The results of this analysis are supported by reasonable, but hypothetical assumptions and are not intended to support categorical conclusions. However, this case study shows that additional capital costs to improve the adaptability of BMPs can be offset by lower long-term maintenance costs, longer design life, and/or improved resiliency to uncertainty in infiltration rates and/or groundwater conditions. This case study can be used as a template for conducting similar comparisons using these tools based on site-specific conditions.