EPA United States Environmental Protection Agency

2012 GREEN INFRASTRUCTURE TECHNICAL ASSISTANCE PROGRAM
City of La Crosse
La Crosse, WI

Using Green Infrastructure to Mitigate Flooding in La Crosse, WI

Assessment of Climate Change Impacts and System-Wide Benefits

Photo credit: Jennifer Olson, Tetra Tech

December 2014
EPA 832-R-15-002

About Green Infrastructure and the 2012 Community Partner Program

Stormwater runoff is a major cause of water pollution in urban areas. When rain falls in undeveloped areas, the water is absorbed and filtered by soil and plants. When rain falls on our roofs, streets, and parking lots, however, the water cannot soak into the ground. In most urban areas, stormwater is drained through engineered collection systems and discharged into nearby waterbodies. The stormwater carries trash, bacteria, heavy metals, and other pollutants from the urban landscape, degrading the quality of the receiving waters. Higher flows can also cause erosion and flooding in urban streams, damaging habitat, property, and infrastructure.

Green infrastructure uses vegetation, soils, and natural processes to manage water and create healthier urban environments. At the scale of a city or county, green infrastructure refers to the patchwork of natural areas that provides habitat, flood protection, cleaner air, and cleaner water. At the scale of a neighborhood or site, green infrastructure refers to stormwater management systems that mimic nature by soaking up and storing water, such as rain gardens, permeable pavement, and green roofs. These neighborhood or site-scale green infrastructure approaches are often referred to as “low impact development.”

EPA encourages the use of green infrastructure to help manage stormwater runoff. In April 2011, EPA renewed its commitment to green infrastructure with the release of the “Strategic Agenda to Protect Waters and Build More Livable Communities through Green Infrastructure.” The agenda identifies community partnerships as one of five key activities that EPA will pursue to accelerate the implementation of green infrastructure.

EPA announced partnerships with 10 “model communities” in April 2011. These communities have demonstrated how green infrastructure can supplement or substitute for single-purpose “gray” infrastructure investments such as storm sewers and detention ponds.

In February 2012, EPA announced the availability of $950,000 in technical assistance to a second set of partner communities to help overcome some of the most common barriers to green infrastructure. EPA received letters of interest from over 150 communities across the country. EPA selected 17 of these communities to receive assistance with code review, green infrastructure design, and cost-benefit assessments.

Through the assistance provided to the City of La Crosse, Wisconsin, EPA developed a detailed Storm Water Management Model of the Johnson Street Basin. The model was used to evaluate the potential for green infrastructure to mitigate peak flows and reduce associated flooding and pollutant loads. Porous pavement and bioretention were modeled in the street right of way at various levels of implementation. A series of performance curves was developed which summarizes the flood reduction effectiveness of the modeled green infrastructure and the cost-effectiveness of each scenario.

For more information, visit http://water.epa.gov/infrastructure/greeninfrastructure/gi_support.cfm

Acknowledgements

The City of La Crosse would like to recognize the following project partners for their contributions to this project:

Bernard Lenz, City of La Crosse
Yuri Nasonovs, City of La Crosse
Amy Peterson, City of La Crosse
Sally Kefer, Wisconsin DNR
David Liebl, University of Wisconsin
Bob Newport, EPA Region V
Jonathan Moody, EPA Region V
Tamara Mittman, U.S. EPA Headquarters
Christopher Kloss, U.S. EPA Headquarters
Jennifer Olson, Tetra Tech
George Remias, Tetra Tech
John Stein, Tetra Tech
Garrett Budd, Tetra Tech

This report was developed under EPA Contract No. EPA-C-11-009 as one of the 2012 EPA Green Infrastructure Community Partner Projects.

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Executive Summary

As climate change increases the frequency of intense rain events in the Midwest (USGCRP 2009), appropriate adaptation strategies are needed to manage the impacts of increased runoff volumes and rates. The City of La Crosse, Wisconsin offers an illustrative example. With its flat topography and long pipe network, the City's drainage infrastructure is very sensitive to increases in rainfall amounts and intensity. When intense storms occur, water either can't enter the storm sewer system or flows backward in topographically low areas, lifting storm sewer covers and forming geysers in the streets. The City has prioritized the Johnson Street Basin on the south side of the City for adaptation strategies, but lacks a plan beyond the standard practice of upsizing pipes.

At the same time, the City and County of La Crosse have identified several sustainability goals related to the City's transportation infrastructure. By providing greater access to bicycles and pedestrians, the City hopes to expand transportation choices, reduce fossil fuel consumption, and improve public health.

In seeking strategies to adapt to a changing climate and advance its sustainability goals, the City identified green streets as a promising alternative. Green streets integrate green infrastructure into the street and rights-of-way to intercept runoff from the street and adjacent parcels and reduce the burden on the storm sewer system. By reducing the urban heat island effect and improving aesthetics, green streets also enhance the bicycle and pedestrian environment.

This project evaluates the potential of green streets to mitigate flooding in the Johnson Street Basin. The project consisted of five steps. First, a detailed EPA Storm Water Management Model (SWMM) was developed to represent runoff generation and conveyance in the Johnson Street Basin. Second, three green street designs were selected for further analysis. One of the selected designs added bioretention to the right-of-way, while two of the selected designs added permeable pavement. Third, the applicability of each design within the basin was determined. While there was sufficient space to place bioretention along 30 percent of local roads, permeable pavement could be installed along 80 percent of major roads and 90 percent of local roads. Fourth, each design was simulated in the SWMM model across a range implementation levels. Finally, cost data were integrated to yield cost effectiveness curves.

The model results demonstrate the potential for green streets to significantly reduce localized flooding and mitigate the impacts of climate change. The three modeled systems had the capacity to nearly eliminate flooding from the 3-month, 24-hour event. Currently, 17% of manholes are predicted to flood during the 3-month, 24-hour event under existing conditions. Installing bioretention at all possible locations reduces flooding by 88%; installing permeable pavement at all possible locations eliminates flooding. Permeable pavement was also a lower cost option. The model indicated that permeable pavement was the most effective system for reducing the extent and duration of flooding associated with a large storm event (2.86 inches). Under current conditions, 63% of manholes are predicted to flood during a 2.86 inch event. Full implementation of permeable pavement with a storage depth of 4 feet is predicted to reduce flooding by 87%, resulting in fewer than 10% of manholes flooding during a large storm event.

Complete green infrastructure build-out is not required to positively impact local flooding. Modeling projects that install permeable pavement in 75% of appropriate locations showed that system flooding was reduced by 68% (with 20% of manholes flooding as opposed to current conditions of 63% of manholes).While this study evaluated basin-wide green infrastructure implementation, these results also suggest that prioritizing problem areas and optimizing implementation activities in priority areas would likely result in less costly solutions.

1. Project Goals

The City of La Crosse has identified climate change adaptation as a key priority. In 2012, the Sustainable La Crosse Commission conducted a workshop on climate change for the La Crosse area governments and community leaders. Attendees discussed the risks that climate change might pose to La Crosse, and identified a range of short- and long-term measures that could enhance the resiliency of human and natural systems. Building on the workshop, La Crosse worked with the Wisconsin Department of Natural Resources to complete a Climate Adaptation Study (Kefer 2013).

Among the highest adaptation priorities identified by La Crosse is reducing flood hazards. In the next half century, precipitation is expected to increase in the region, and storms are expected to become more severe (Sustainable La Crosse Commission 2012). With the City's flat topography and long pipe network, many areas of the City are very sensitive to increases in rainfall amounts or intensity. When intense storms occur, water either can't enter the storm sewer system or flows backward in topographically low areas, lifting storm sewer covers and forming geysers in the streets (Figure 1). In recent years, homes have collapsed due to saturated soils and standing water during flood events, and residents are filing more claims for property damage. The City has prioritized the Johnson Street Basin on the south side of La Crosse for mitigation, but currently lacks a plan beyond the standard practice of upsizing pipes.

Photo credit: Tetra Tech

Figure 1. Example of manhole that typically floods, note open grate which addresses safety concerns related to solid manhole covers being lifted due to force of water.

La Crosse and La Crosse County have also set a series of ambitious sustainability and public health goals. In 2009 the City and County adopted a Strategic Plan for Sustainability with goals and actions in the areas of energy consumption, transportation, purchasing decisions, waste generation, natural resource preservation, and community livability. Several of the actions address the City's transportation infrastructure, calling for more bicycle and pedestrian friendly streets. By providing greater access to bicycles and pedestrians, the City can expand transportation choices, reduce fossil fuel consumption, and improve public health.

In seeking strategies to adapt to a changing climate and advance its sustainability goals, the City identified green streets as a promising alternative. By absorbing and slowing the flow of water, green streets can reduce the burden on the storm sewer system and mitigate localized flooding. Also, by adding vegetation and permeable surfaces to the built environment, green streets can improve aesthetics, reduce the urban heat island effect, and create a more bicycle and pedestrian-friendly environment. Recognizing the promise of green streets and the importance of effective stormwater management, La Crosse adopted the first "Green Complete Streets" ordinance in Wisconsin, and is generating funds for infrastructure upgrades through a new stormwater utility. The City has also started implementing green infrastructure as part of road reconstruction projects.

The goal of this project is to assess the potential for green infrastructure in green streets to mitigate flooding in La Crosse. The study area selected for this project is the Johnson Street Basin, a high- density, residential area of the City that is experiencing flooding from more frequent and intense storms. The City plans to apply the project findings to install recommended facilities in the Johnson Street Basin and to build capacity for green infrastructure planning.

2. Study Area

La Crosse is a city of 51,000 located in western Wisconsin. Bordered to the west by the Mississippi River and to the east by 500 foot bluffs, the City is built on a broad alluvial plain formed at the confluence of the Black and La Crosse Rivers. Runoff from the bluffs and stormwater from the City are conveyed toward the rivers across this broad plain. Conventional stormwater facilities and best management practices (BMPs) are especially challenging given these topographical constraints.

The Johnson Street Basin is located entirely within La Crosse and drains to the Mississippi River through La Plume Slough (Figure 2). The 769 acre basin is fairly flat, ranging from a high point of 684.5 feet near the intersection of 14th Street and King Street to 663.0 feet near U.S. Route 14 and Johnson Street. Topography includes slight depressions near the southeast and northeastern corners (Figure 3), with an average slope of one percent.

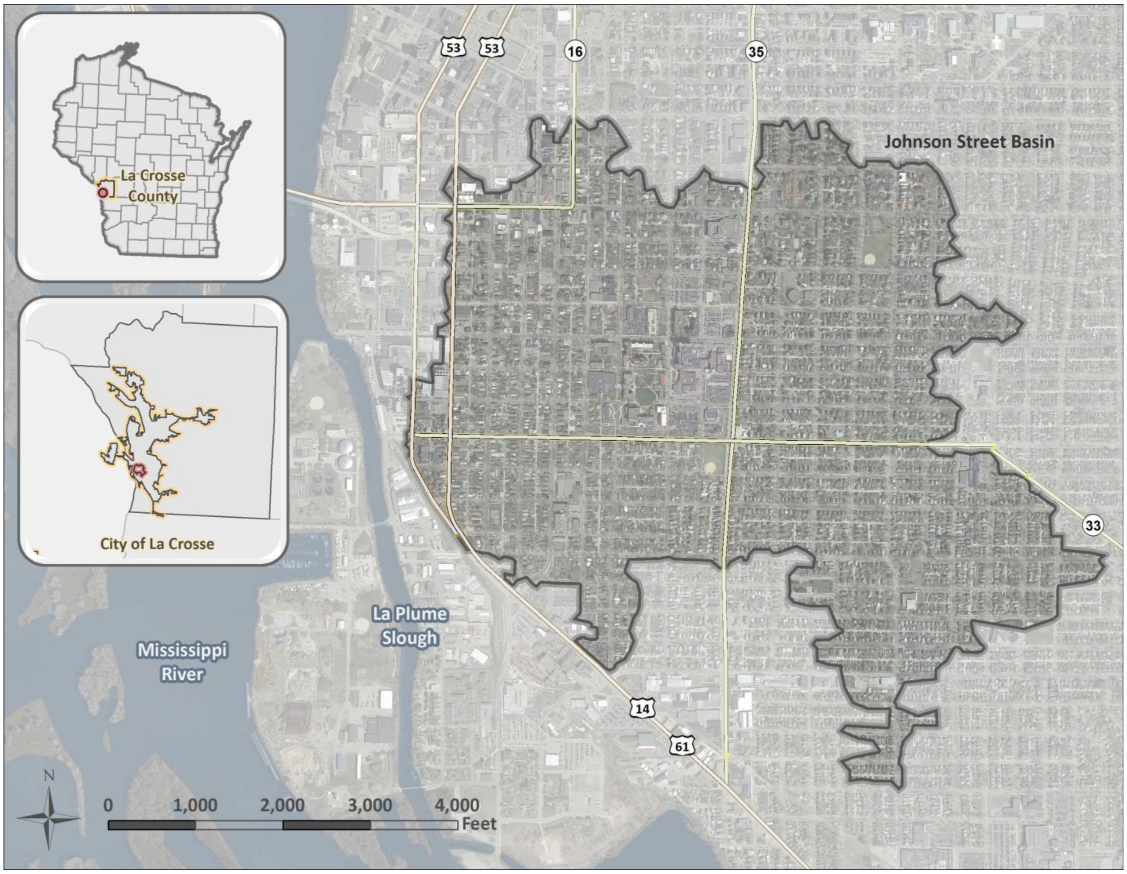

Figure 2. Johnson Street Basin watershed.

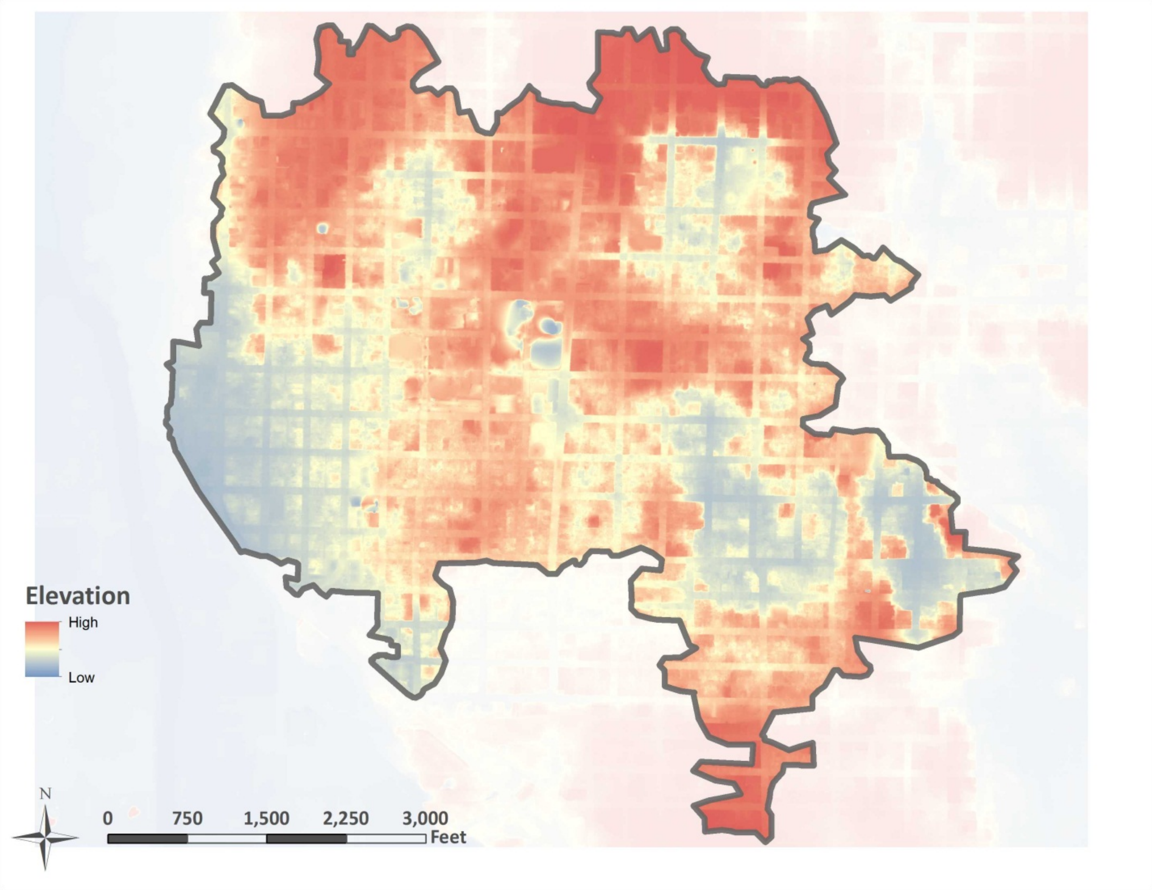

Figure 3. Johnson Street Basin topography.

Soils are formed on sand and gravel outwash deposits, and therefore exhibit high infiltration rates. The majority of the basin consists of residential land uses constructed between 1930 and 1950, encompassing 72 percent of the area (Figure 4 and Figure 5). Other land uses include industrial and commercial properties, churches, hospitals/clinics, and schools. Approximately two thirds of the basin (67.2 percent or 517 acres) is impervious, which includes approximately 38 acres of parking lots and 248 acres of road rights-of-way.

Field reconnaissance of the study area was conducted in October 2012. New development and re-development over the past couple of decades has resulted in significant hydrologic changes within the watershed, including increased runoff volumes and peak flows. For example, most of the City's gravel alleys have been paved. These alleys are now concrete-lined and sloped such that runoff leaves the site very quickly. While the storm sewer system was extended several times to accommodate the additional development, City design criteria (i.e., design of storm sewers to convey a 10-year, 24-hour storm) were not consistently followed.

Consequently, several locations within the study area frequently flood (Figure 6), and the time to drain the flooded area continues to increase as the runoff volume increases. To mitigate this flooding, the City has installed bioretention areas, disconnected downspouts, and installed underground storage in a few locations. The City has also intentionally undersized many storm sewers to allow surface flooding upstream and help minimize severe flooding downstream such as along Adams Street in the Johnson Street Basin.

Photo credit: Tetra Tech

Figure 4. Typical residential areas in the Johnson Street Basin.

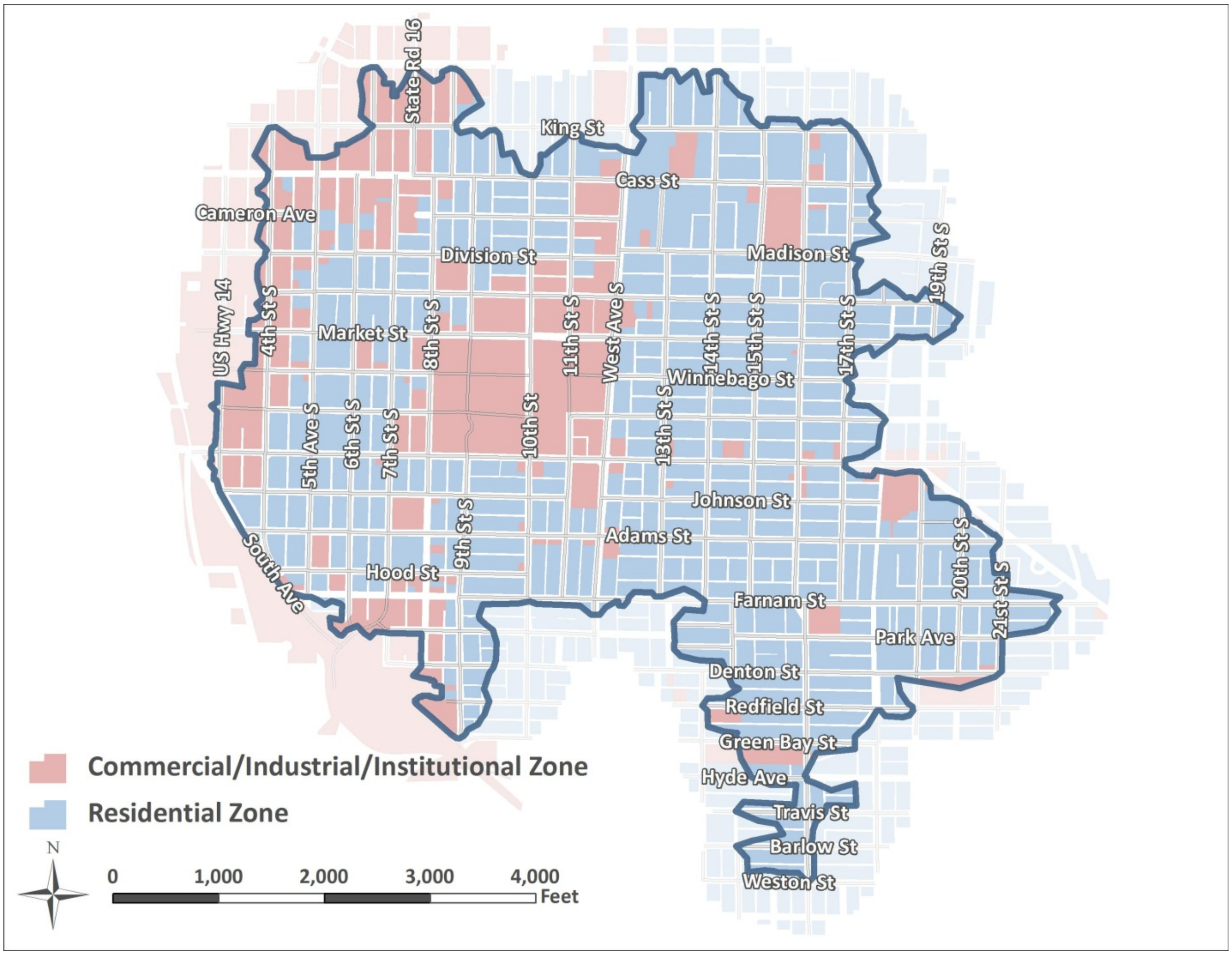

Figure 5. Johnson Street Basin land use.

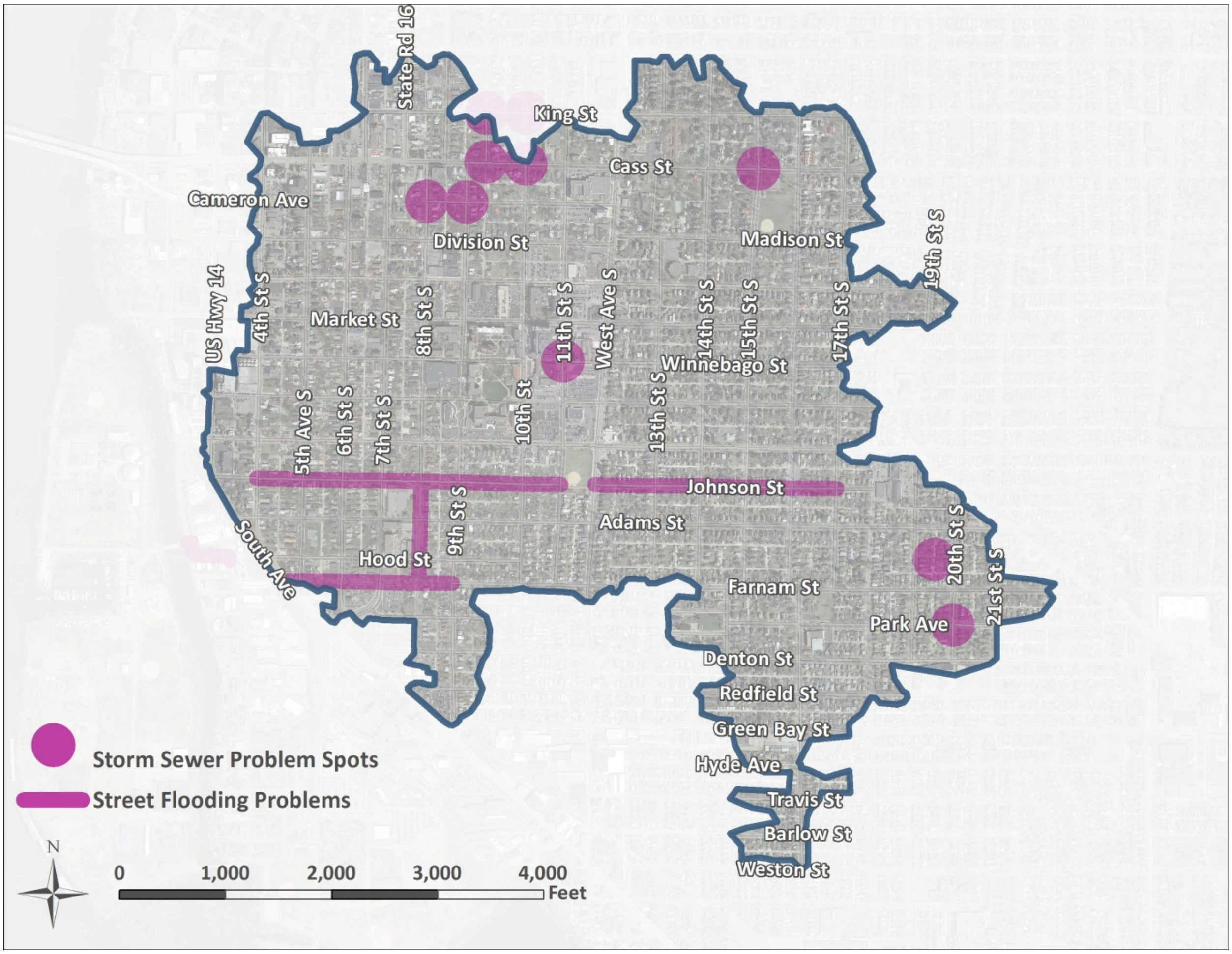

Figure 6. City reported flooding locations.

3. Model Development and Existing System Evaluation

EPA's Storm Water Management Model (SWMM; EPA 2008) was used to develop a hydrologic and hydraulic model of the Johnson Street Basin. SWMM is a dynamic hydrology-hydraulic-water quality model that simulates runoff quantity and quality from urban areas. SWMM can track the quantity and quality of runoff generated within each sub catchment, as well as the flow rate, flow depth, and quality of water in each pipe and channel. SWMM 5 can also model the hydrologic performance of several green infrastructure controls, including permeable pavement, rain gardens, green roofs, street planters, rain barrels, infiltration trenches, and vegetated swales.

Data required for this SWMM analysis include design storms to drive the model; catchment physical characteristics (topography, soils, land cover) to construct and parameterize the model; and observed flooding response to calibrate the model. The model construction, parameterization, and calibration are described in Appendix A, including the data sources for the design storms and catchment physical characteristics.

Once a SWMM model was developed for the Johnson Street Basin, the extent and duration of flooding in the existing system was evaluated. This evaluation was conducted to establish a baseline for comparison to the green street scenarios. As described in Appendix A, four design storm events were used to drive the SWMM model: a 3-month, 2-hour storm event to represent existing flooding conditions; a 1-year, 24-hour storm event to simulate a small, frequent storm event; a 10-year, 24-hour storm to represent design criteria listed in the La Crosse ordinance; and a 10-year, 2-hour climate change storm event to represent a potential short duration, high intensity climate change scenario. The 10-year, 2-hour climate change storm event was also identified by City staff as the targeted level of service, or the design storm event that should not cause flooding.

Significant flooding was predicted for each of the design storm events, with the duration and frequency of flooding generally increasing as the peak 1-hour depth and the total rainfall depth increase. Note that the duration of manholes flooded represents the accumulated duration of flooding over all the manholes in the system. As shown in Table 1, the percent of manholes flooded in the existing system ranged from 17% for the 3-month, 2-hour storm to 63% for the 10-year, 2 hour climate change storm. Similarly, the duration of manholes flooded ranged from 45 hours for the 3-month, 24-hour storm to 505 hours for the 10-year, 2 hour climate change storm. Figure 7 illustrates the widespread flooding that occurs in the existing system for the 10-year, 2-hour climate change storm event.

Table 1. SWMM predicted street flooding results

Design storm event	Total rainfall depth (inch)	Peak 1 hour depth (inch)	Manholes flooded (%)	Duration of manholes flooded (hours)	Flooded volume (million gallons)	Average peak flooding depth (inch)
3-month, 2 hour [a]	0.83	0.67	17	45	0.8	2
1-year, 24 hour [a]	2.23	1.05	36	130	3.0	3
10-year, 24 hour [a]	4.40	2.07	57	481	11.9	8
10-year, 2 hour climate change	2.86	2.32	63	505	14.7	9

a. Values are based Huff and Angel 1992

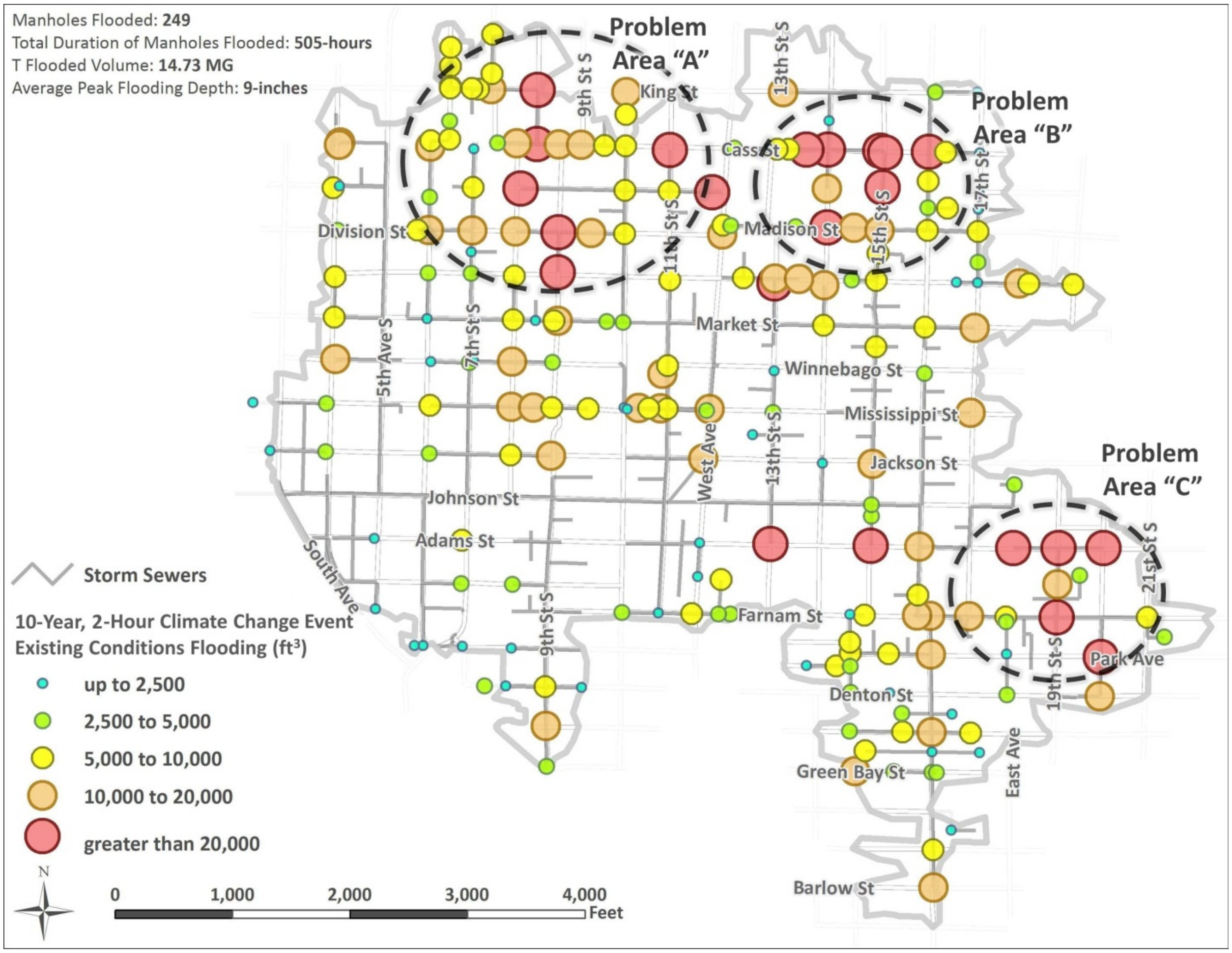

Figure 7. Modeled results showing surface flooding for the 10-year 2-hour event.

4. Green Street Scenarios

La Crosse is committed to implementing a green streets program to help mitigate flooding, promote water quality treatment, and advance its sustainability goals. To evaluate the impact of green streets on localized flooding in the Johnson Street Basin, several green street scenarios were simulated in the SWMM model described above. This section describes how key modeling inputs for each scenario were defined, including the green infrastructure practices selected, the assumed design parameters for each practice, and the extent of each practice within the Johnson Street Basin. The costs associated with these design parameters are also discussed.

4.1 Green Infrastructure Selection

Green streets implement green infrastructure within the street right-of-way to manage runoff from both the street and adjacent parcels. Green street features can include permeable paving (Figure 8), bioretention areas (Figure 9), sidewalk planters, landscaped medians, vegetated swales, and street trees. The most common approaches include bioretention areas located between the edge of the pavement and the edge of the right-of-way and permeable pavement installed in the parking lanes. Permeable pavement and bioretention were therefore selected for further analysis.

Permeable pavements work by allowing streets, parking lots, sidewalks, and other impervious covers to retain their natural infiltration capacity while maintaining the structural and functional features of the materials they replace. Permeable pavements contain small voids that allow water to drain through the pavement to an aggregate reservoir and then infiltrate into the soil. The depth of the gravel storage layer is an important design parameter.

Photo credit: Tetra Tech

Figure 8. Example permeable pavement (concrete pavers) application in parking lane on residential street

Bioretention typically consists of a shallow, vegetated basin that collects and absorbs runoff from impervious areas. These practices usually consist of a grass buffer strip, ponding area, mulch layer, and planting soil media. Similarly to permeable pavement, the depth of the soil media layer is an important design parameter.

Based on input from city staff, three green street systems were modeled for this study: a permeable pavement system with a storage depth of two feet, a permeable pavement system with a storage depth of four feet, and a bioretention system with a soil media depth of three feet. Additional design parameters for each practice are described and summarized in Appendix B.

Photo credits: Tetra Tech

Figure 9. Example bioretention areas: part of a complete street, linear feature between curb and sidewalk, and as a bump out.

4.2 Green Infrastructure Extent

To develop a series of green street scenarios representing different levels of implementation, the maximum extent of each practice was estimated along three categories of roads: 1) major roads, 2) local roads, and 3) alleys (Figure 10). The various road types in La Crosse are illustrated in Figure 11.

Based on input from city staff, review of aerial photos, and field reconnaissance, the maximum extent of permeable pavement was determined to be 80 percent along major roads, 90 percent along local roads, and 100 percent along alleys—corresponding to 286,000 linear feet of permeable pavement. This is because permeable pavement was determined to be feasible along the entire length of each road type with the exception of intersections.

In contrast, the maximum extent of bioretention was determined to be 30 percent along local roads only – corresponding to 85,000 linear feet of bioretention. This is because city staff considered bioretention to be infeasible along driveways and intersections (where bioretention could obstruct views or access) and along major roads and alleys (which consist of driving lanes only and lack space for bioretention).

Table 2 summarizes the road properties and maximum extent of green infrastructure for each road type, while Figure 12 illustrates a typical local road showing placement of green infrastructure.

Photo credit: Tetra Tech

Photo credit: Tetra Tech

Figure 10. Example of alley (top) and local road with two parking lanes (bottom) in Johnson Street Basin.

Once the maximum extent of permeable pavement and bioretention was known, green street scenarios were developed spanning 25%, 50%, 75%, and 100% of the maximum extent of implementation (Table 3). For the permeable pavement systems, two additional scenarios were developed – one in which permeable pavement was implemented in 100% of the feasible area as well as the entire width of the allies, and a second in which permeable pavement was implemented in 100% of the feasible areas, the entire width of the allies, and a portion of existing parking lots. Parking lots account for approximately 38 acres of impervious area in the watershed and are often located upstream of flood prone areas. Sixty percent of the parking lots were assumed to be converted to permeable pavement.

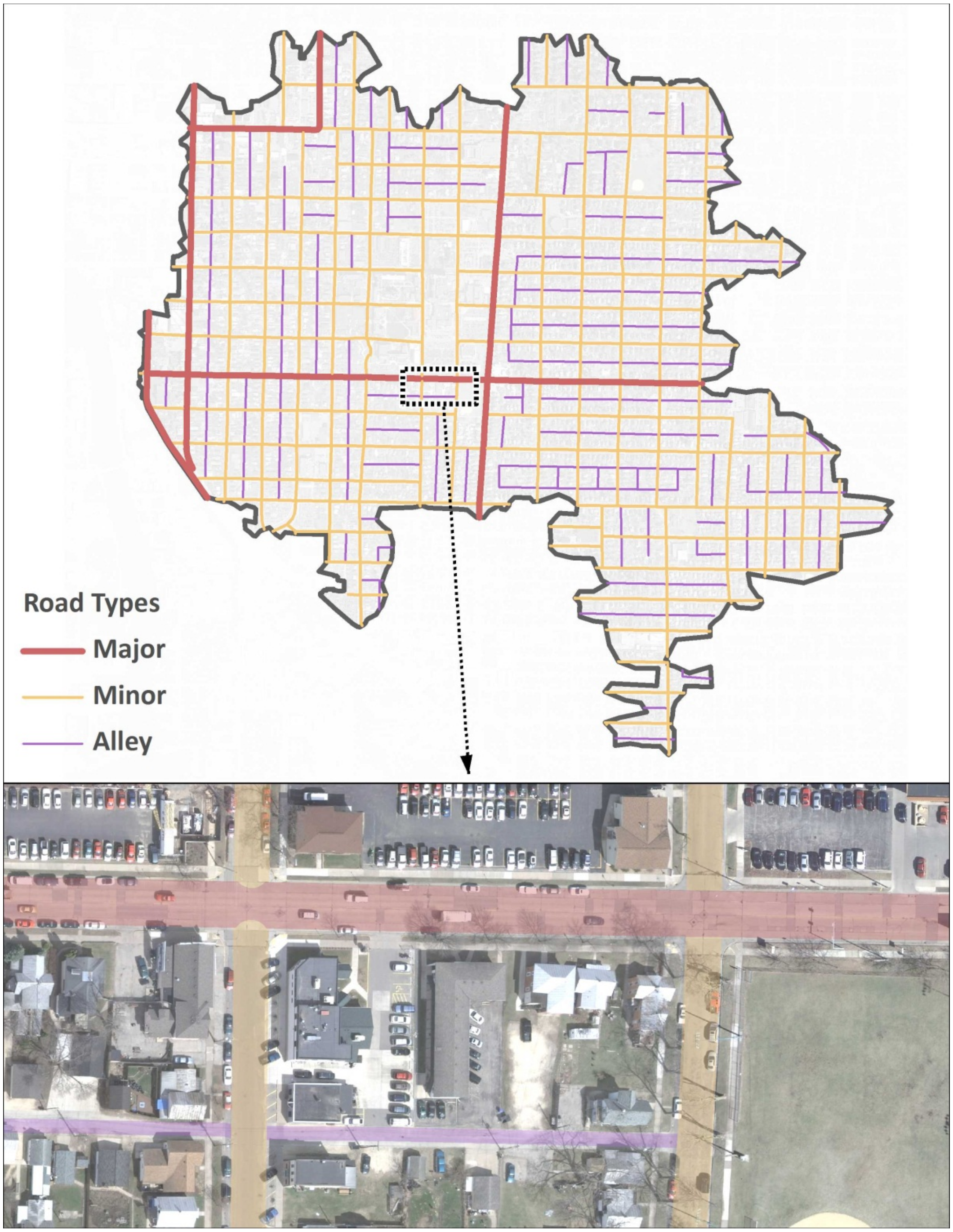

Figure 11. La Crosse road types.

Table 2. Street assumptions and green infrastructure applicability

Summary of Road Properties				
Category	**Unit**	**Major Roads**	**Local Roads**	**Alley**
Percent of street	(%)	8	63	29
Average width	(feet)	49	37	17
Number of driving lanes	(#)	4	2	1
Is there on-street parking?	(Yes or No)	Y	Y	N
Where is parking?		Within driving lanes	Dedicated parking lanes	NA
Parking on 1 or 2 sides?	(#)	2	2	NA
Maximum Extent of Bioretention				
Category	**Unit**	**Major Roads**	**Local Roads**	**Alley**
Percent street length converted to bioretention	(%)	None	30	0
Width of bioretention	(feet)	NA	8 each side of road	NA
Maximum Extent of Permeable Pavement				
Category	**Unit**	**Major Roads**	**Local Roads**	**Alley**
Percent street length converted to permeable pavement	(%)	80	90	100
Width of permeable pavement	(feet)	8-10	16	4

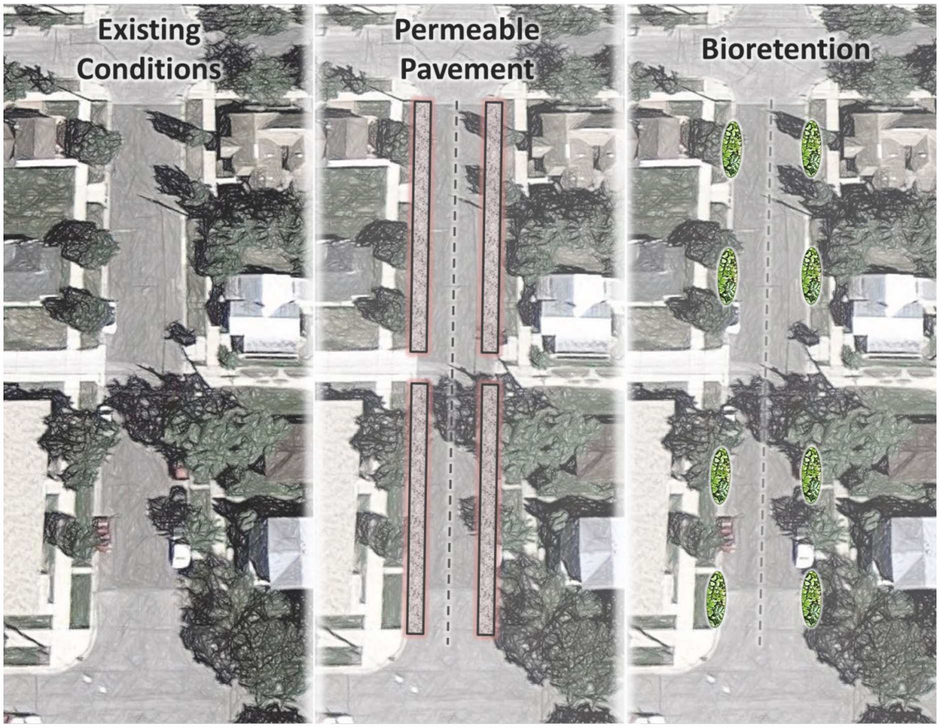

Figure 12. Conceptual placement of green infrastructure on a local road.

Table 3. Extent of green infrastructure for modeled scenarios

Implementation Scenario	Extent of Modeled Porous Pavement[a] (square feet)	Extent of Modeled Bioretention[a] (square feet)
Existing Conditions	0	0
25%	571,000	170,000
50%	1,142,000	340,000
75%	1,713,000	510,000
100%	2,284,000	680,000
100+Alleys	2,532,000	—
100+Alleys+Parking Lots	3,410,000	—

a. Assumes applicability based on Table 2.

4.3 Green Infrastructure Costs

Resource constraints may limit the type and number of practices that can be used to achieve program goals. Costs are evaluated with estimated reductions to select the final set of practices that are most cost-effective. There are three types of costs to consider over the life cycle of a green infrastructure intervention:

- Probable Construction Costs – the initial cost to construct
- Annual Operation and Maintenance – the annual costs to maintain
- Repair and Replacement Costs – the additional costs to repair or replace

The lifecycle period was defined as 20-years to account for costs for replacing some practices. No land, capital, administration, demolition, or legal cost factors were defined for any of the probable construction costs. Three unit costs were defined for each practice to represent an envelope of possible costs. A range of probable construction costs were used to represent low, median, and high construction costs. Construction costs have a high level of variability from project to project. The variability in costs can be attributed to the level of experience of the designers and contractors, the number of practices constructed in a given area, quality of the construction documents, and availability of special equipment or specific supplies (e.g., soil amendment or aggregate).

Operation and maintenance costs were held constant. Each unit cost was converted to 2012 dollars by applying a three percent inflation rate by the number of years from the published year of the cost data to 2012. A discount rate of 3 percent was used for converting annual operation and maintenance costs to present value. There were no repair and replacement costs included in this analysis since the life span of these practices is expected to exceed 20-years.

The following references were evaluated when determining appropriate costs for the Johnson Street Basin:

- BMP and Low Impact Development Whole Life Cost Models Version 2.0. Water Environment Research Foundation (WERF 2009)
- National Green Values Calculator, Center for Neighborhood Technology (Center for Neighborhood Technology 2009)
- The Cost and Effectiveness of Stormwater Management Practices, University of Minnesota (Weiss et al. 2005)

- Long-Term Hydrologic Impact Analysis Low Impact Development Version - 2.0
- Low Impact Development for Big Box Retailers. Prepared for U.S. Environmental Protection Agency (Low Impact Development Center 2005)
- Low Impact Development Manual for Michigan, Southeast Michigan Council of Governments

Table 4 presents the assumed lifecycle costs for each green street design. Note that these costs represent retrofit costs. The marginal costs of adding bioretention or permeable pavement to a planned street improvement project would be lower.

Table 4. Green infrastructure lifecycle cost assumptions (2012$)

Cost Parameter	Unit	Bioretention			Permeable Pavement		
		Low	Median	High	Low	Median	High
Net Present Value (NPV) = (A) + (B)	$/SF	$15	$23	$31	$12	$16	$20
(A) Probable Construction Costs NPV	$/SF	$8	$16	$24	$8	$12	$16
(B) O and M Present Value	$/SF	$7	$7	$7	$4	$4	$4
O and M Annual Costs	$/SF	$0.72	$0.72	$0.72	$0.28	$0.28	$0.28

5. Green Street Evaluation

As described above, three sets of green street scenarios were developed for the Johnson Street Basin, one representing permeable pavement with a storage depth of 2 feet, one representing permeable pavement with a storage depth of four feet, and one representing bioretention with a soil media depth of three feet. For each scenario, SWMM simulations were conducted for two design storms: the 3-month, 2-hour storm, and the 10-year, 2-hour climate change storm. These design storms were selected because the city was primarily interested in flooding associated with intense, short duration events.

5.1 Flood Mitigation

Modeling results indicate that all three green street designs significantly reduce the extent of flooding for the 3-month, 2-hour storm event (Figure 13 and Table 5). At 100% implementation, the percent of manholes flooded declines from 17% without green infrastructure to 2% with bioretention, and 0% for both permeable pavement systems. Flood reduction for the 10-year, 2-hour event, however, differs significantly between the bioretention and permeable pavement systems (Figure 14 and Table 6). At 100% implementation, the percent of the drainage system flooded declines 7.9% with bioretention, from 63% of manholes flooded to 58% of manholes flooded. In contrast, the percent of the system flooded declines 39% for permeable pavement with a storage depth of 2 feet, and 87% for permeable pavement with a storage depth of 4 feet. This is due to the limited extent of bioretention in this watershed (30 percent of street length for local roads only) when compared to the extent of permeable pavement (80 - 90 percent of all roads).

Figure 15 presents the volume of flooding for each scenario for the 10-year, 2-hour event and illustrates that although bioretention does not substantially reduce the number of manholes flooded (Figure 14 and Table 6); the volume of flooding is reduced. Figure 16 presents a hydrograph for the 10-year, 2-hour storm event showing existing conditions and three scenarios for a representative catchment consisting primarily of residential land uses. The hydrograph shows a small decrease in peak flows for bioretention with three feet of amended soil and permeable pavement with two feet of gravel storage although the duration and volume are both reduced. The permeable pavement design with 4 feet of gravel storage is the most effective green infrastructure system to reduce flooding for both rainfall events.

Flooding is further mitigated in the additional permeable pavement scenarios including greater implementation in alleys and parking areas. For the scenario in which permeable pavement with a storage depth of 4 feet is applied to all feasible areas, the entire width of alleys, and a portion of parking areas, the percent of manholes flooded is reduced from 63% without green infrastructure to 1% with green infrastructure. This demonstrates the capacity of intensive green infrastructure to achieve the city's targeted level of service.

Appendix C includes additional performance curves that were used to support the selection of the most effective practice including combinations of the system (manholes) flooded, volume flooded, duration of street flooding, average depth of flooding, costs, scenario, and green infrastructure area.

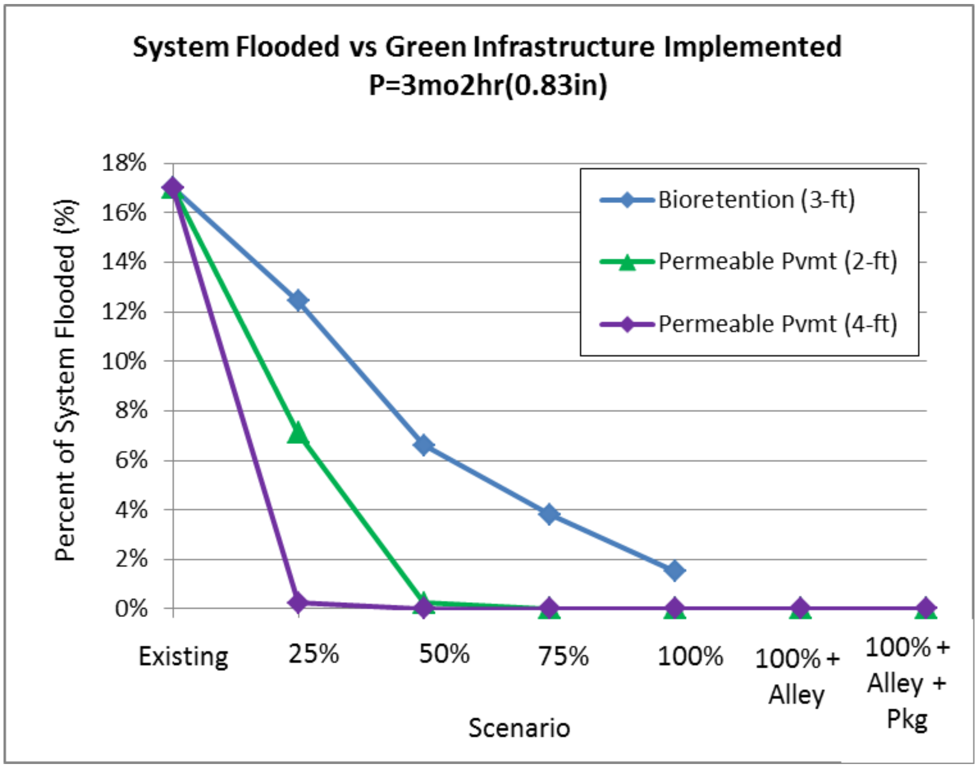

Figure 13. System flooded versus green infrastructure scenario, 3 month, 2-hour event.

Table 5. System flooded versus green infrastructure scenario, 3-month, 2-hour event

Green infrastructure scenario	Percent of system flooded		
	Bioretention (3 feet)	Permeable pavement (2 feet)	Permeable pavement (4 feet)
Existing conditions	17%	17%	17%
25 percent	12%	7%	0%
50 percent	7%	0%	0%
75 percent	4%	0%	0%
100 percent	2%	0%	0%
100 percent + Alleys	--	0%	0%
100 percent + Alleys + Parking Lots	--	0%	0%

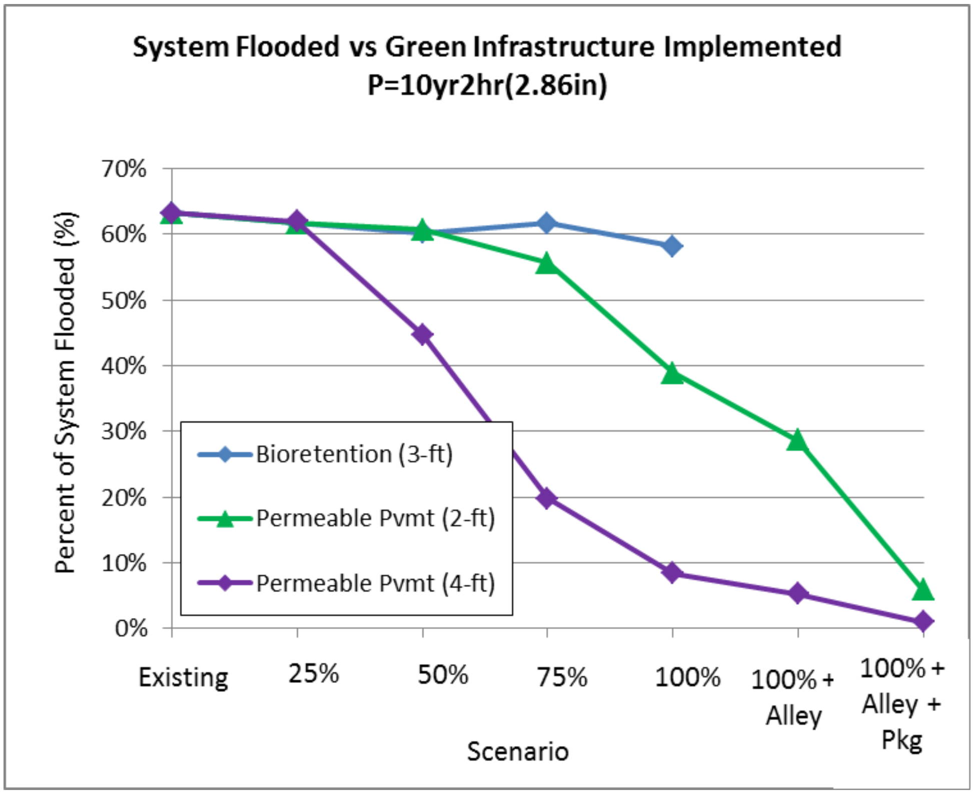

Figure 14. System flooded versus green infrastructure scenario, 10-year, 2-hour event.

Table 6. System flooded versus green infrastructure scenario, 10-year, 2-hour event

	Percent of system flooded		
Green infrastructure scenario	**Bioretention (3 feet)**	**Permeable pavement (2 feet)**	**Permeable pavement (4 feet)**
Existing conditions	63%	63%	63%
25 percent	62%	62%	62%
50 percent	60%	61%	45%
75 percent	62%	56%	20%
100 percent	58%	39%	8%
100 percent + Alleys	--	29%	5%
100 percent + Alleys + Parking Lots	--	6%	1%

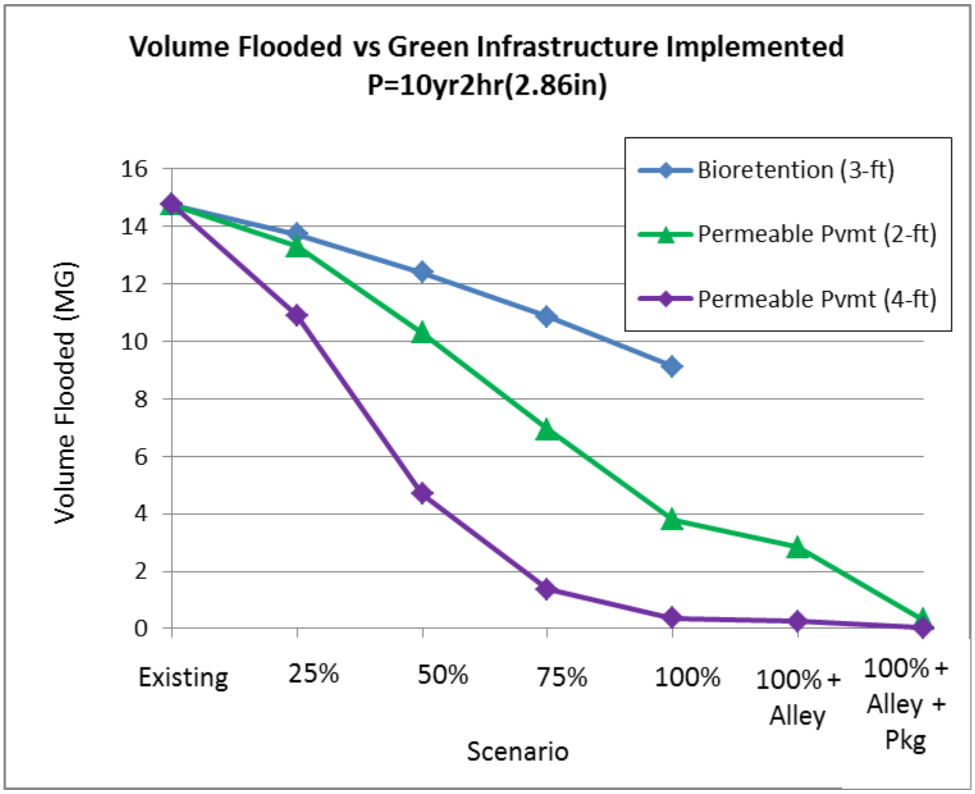

Figure 15. Volume flooded versus green infrastructure scenario, 10-year, 2-hour event.

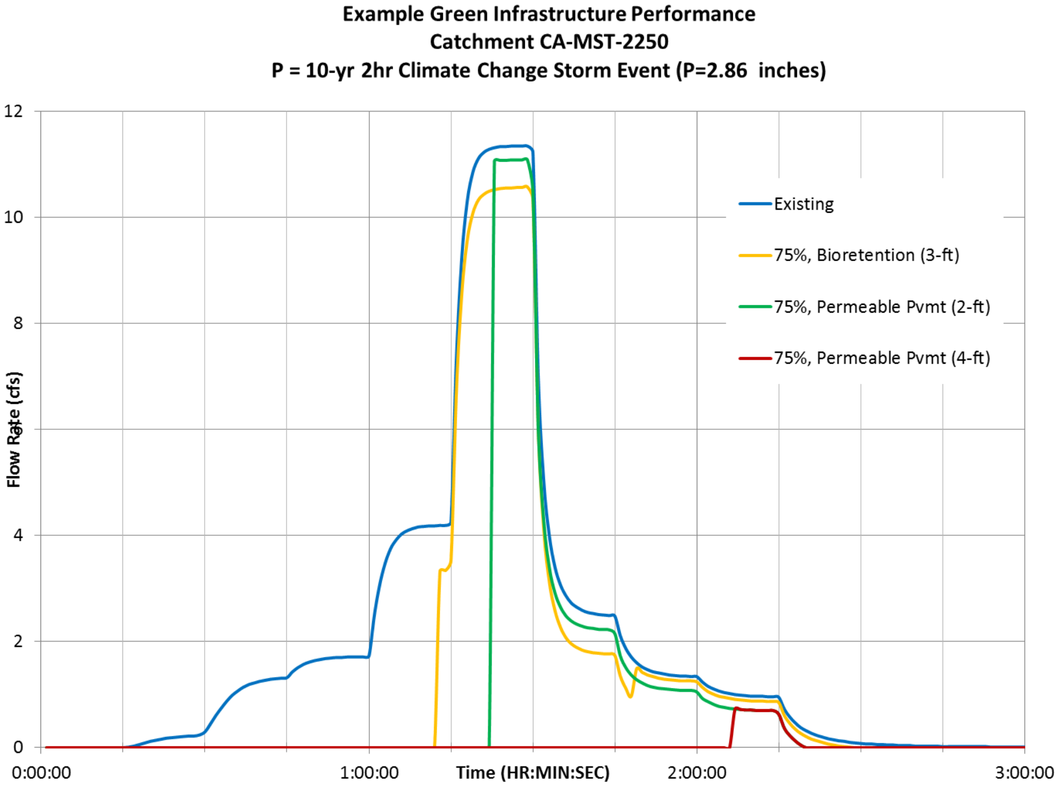

Figure 16. Example hydrograph for representative catchment, 10-year, 2 hour storm event.

5.2 Cost-Effectiveness Curves

Integrating cost information with effectiveness yields a cost-effectiveness curve (Figure 17 and Figure 18). Results for the small storm event (0.83 inches) indicate that all of the practices are similarly cost-effective; however the permeable pavement design with 4 feet of storage is slightly more cost-effective. In analyzing cost effectiveness curves it is often helpful to identify the "knee of the curve", or the point on the curve where additional costs to do not result in significant benefits. The knee of the curve solution for the permeable pavement design with 4 feet of storage occurs at a cost of $9 million and results in a 100% reduction in the extent of system flooding. This solution is the result of implementing permeable pavement in 25 percent of the applicable area.

Results for the large storm event differ in that permeable pavement is shown to be a much more cost-effective solution to significantly reduce flooding in this watershed. This is due to both the limited applicability of bioretention in the Johnson Street Basin, and the high intensity of the simulated event. The knee of the curve solution is the result of implementing permeable pavement in 75 percent of the applicable area. This solution occurs at a cost of $27 million and results in a 68% reduction in the extent of system flooding (from 63% of manholes flooded to 20% of manholes flooded). Increasing the level of implementation to 100 percent permeable pavement results in an 87% reduction in system flooding, but has a higher cost per unit benefit.

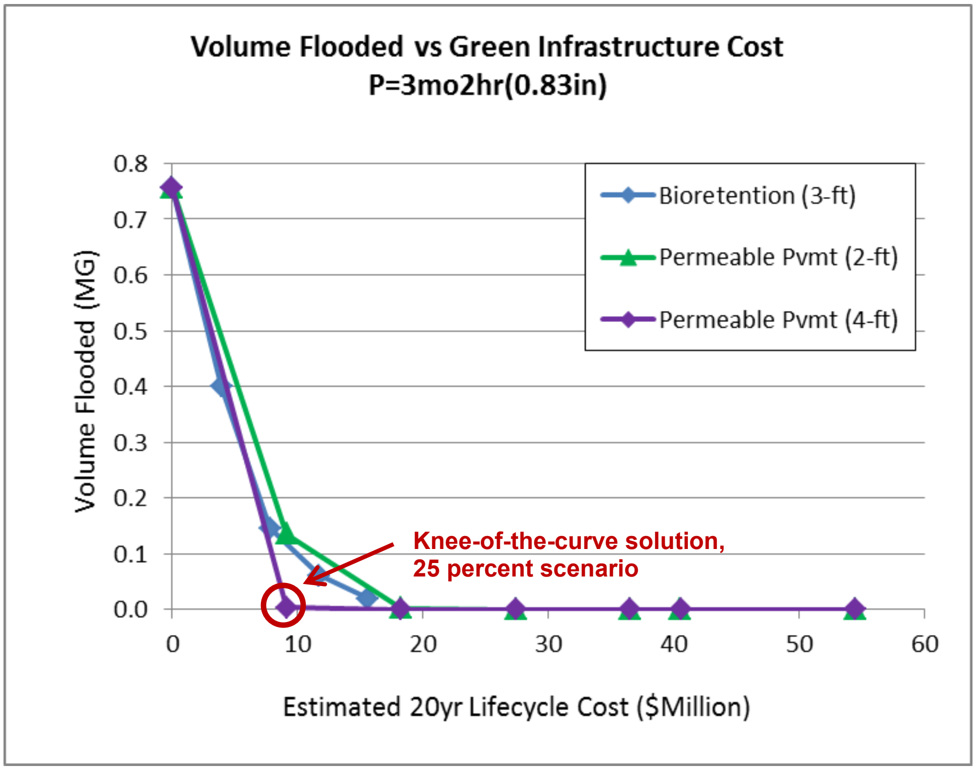

Figure 17. Cost-effectiveness curve, 3-month, 2 hour event.

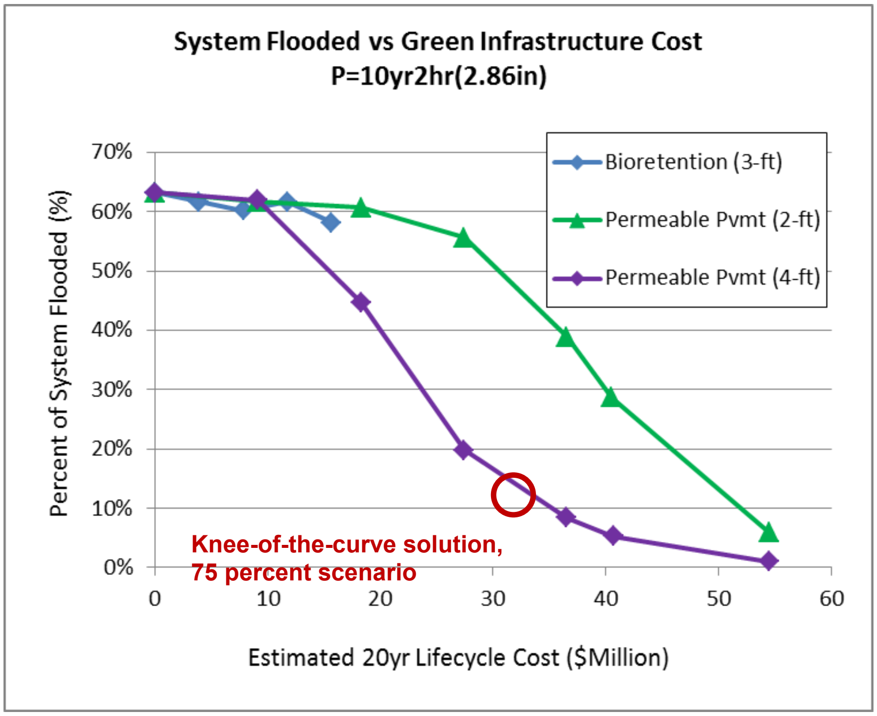

Figure 18. Cost-effectiveness curve, 10-year 2 hour event.

The cost data presented above represent an average life cycle cost. Figure 19 presents an example cost envelope which more realistically represents the range of potential costs. The cost envelope provides a low and high cost which takes into consideration variability and uncertainty of available cost data. Table 7 summarizes the life cycle cost range for each implementation scenario.

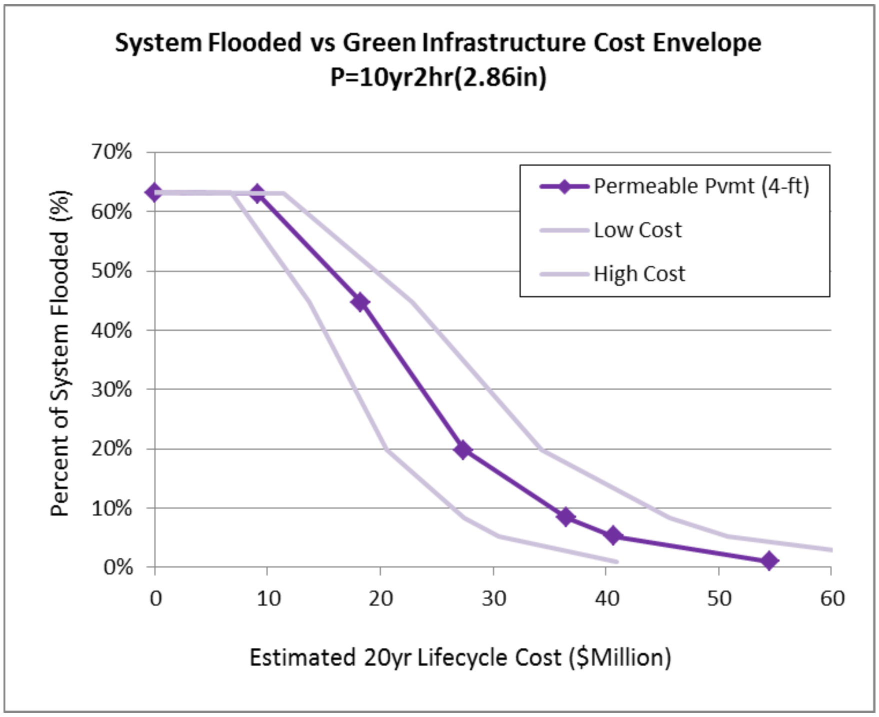

Figure 19. Cost envelope for implementing permeable pavement with four feet of grave storage in 75 percent of the watershed.

Table 7. Permeable pavement with 4 foot gravel storage cost range for each implementation scenario

Green infrastructure scenario	Estimated costs (Million $) [a]
25 percent	$6.9 – $11.4
50 percent	$13.7 – $22.8
75 percent	$20.6 - $34.3
100 percent	$27.4 - $45.7
100 percent + Alleys	$30.5 - $50.8
100 percent + Alleys + Parking Lots	$40.9 - $68.2

a. Costs are the same for both rainfall events, effectiveness varies

5.3 Pollutant Load Reduction

A summary of the pollutant load reductions for permeable pavement with four feet of gravel storage and 75 percent implementation is presented in Figure 20. All pollutants are attenuated for the small storm event (0.83 inches) and 100 percent of the runoff volume is captured and infiltrated. For the larger storm event (2.86 inches), 77 percent of the pollutants are removed and 76 percent of the runoff volume is infiltrated. All of the pollutant removal it attributed to volume control only; removal associated with detention prior to being routed downstream in bioretention areas is insignificant based on the model results.

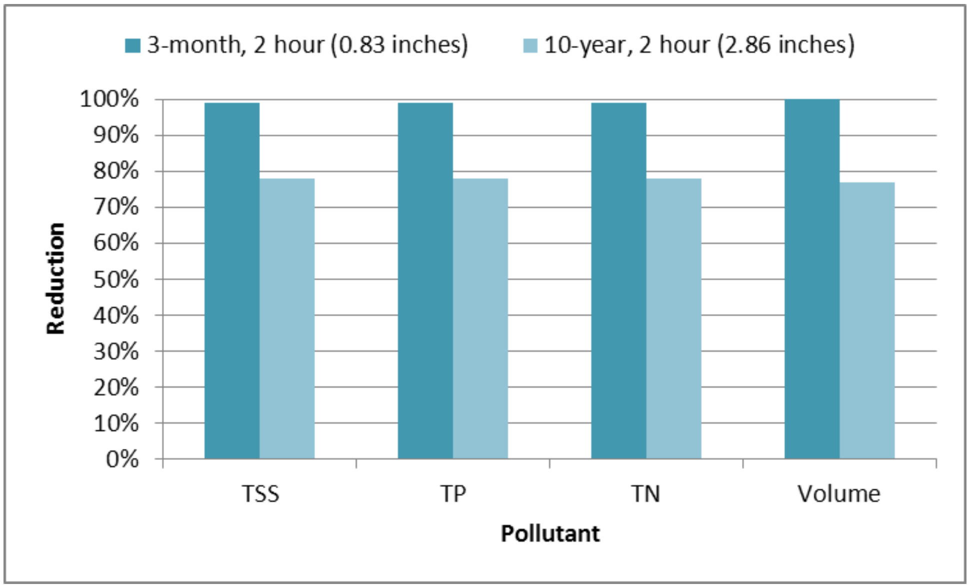

Figure 20. Pollutant and volume reductions for permeable pavement with four feet of storage, 75 percent scenario.

5.4 Recommended Implementation Scenario

The goal of this project was to evaluate feasible scenarios to provide flood control using permeable pavement and bioretention. Figure 21 presents the knee-of-the-curve solution for controlling flooding for the 10-year, 2-hour event. This represents the level of flooding present after implementation of permeable pavement with a storage depth of 4 feet in 75% of applicable areas. For comparison purposes, the existing conditions for the same rainfall event are presented in Figure 22.

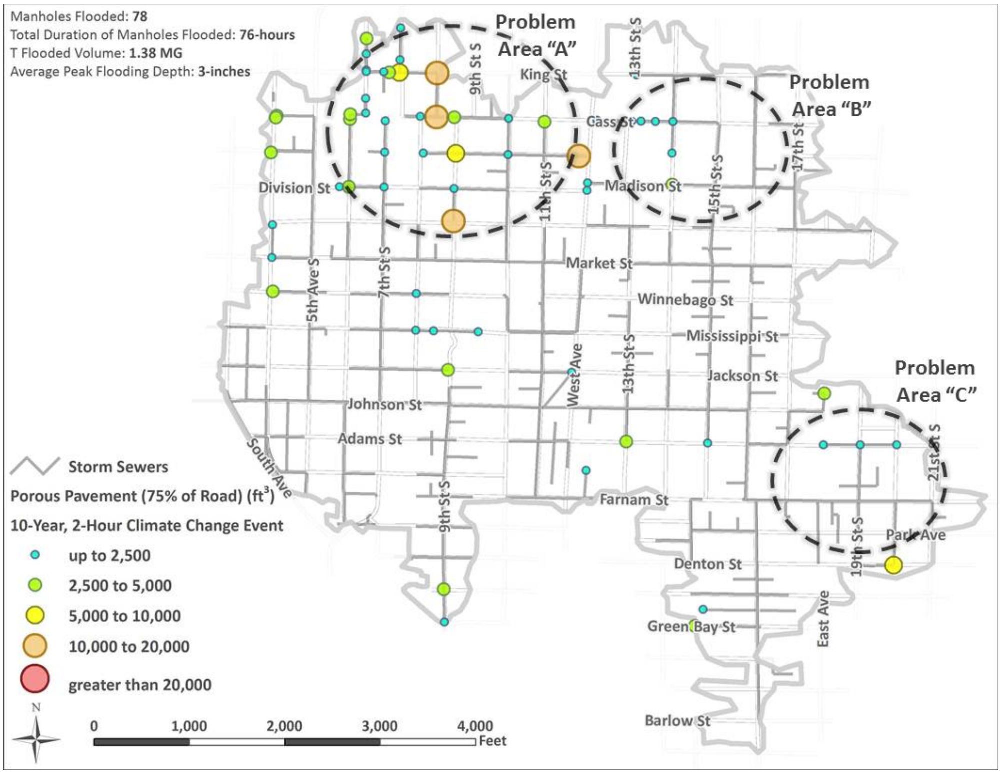

Figure 21. Recommended implementation scenario for green infrastructure, model results showing surface flooding for the 10-year, 2-hour event.

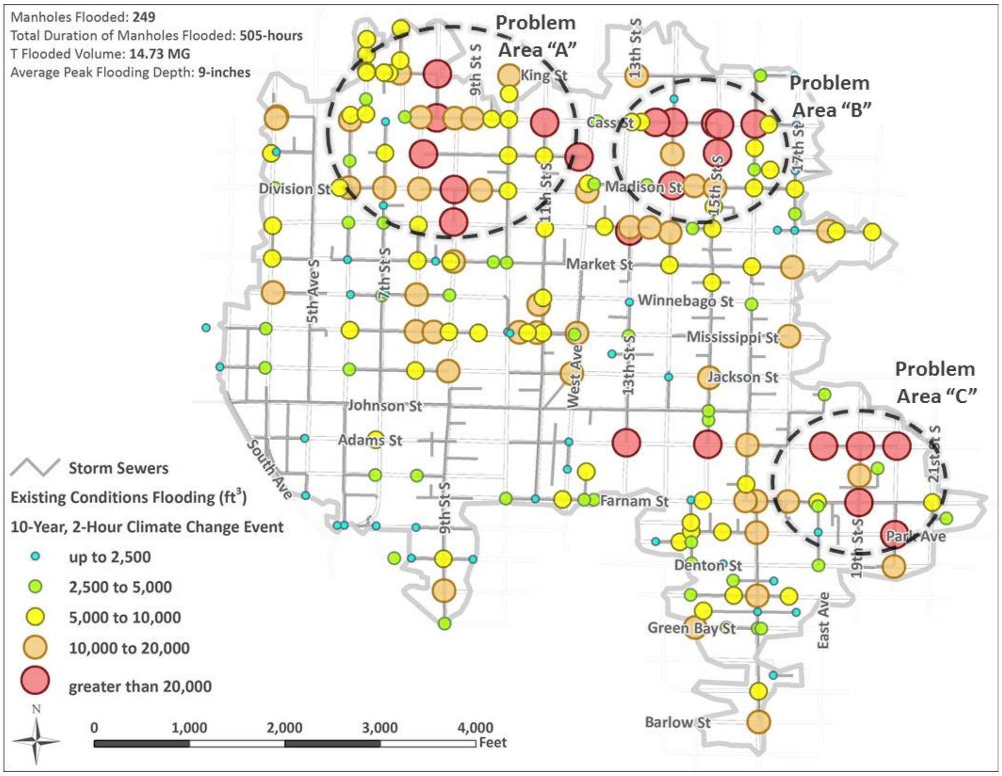

Figure 22. Modeled existing conditions showing surface flooding for the 10-year 2-hour event.

6. Findings and Conclusions

A detailed SWMM model was developed to help La Crosse select green street options that meet both flood mitigation and livability goals. Within the Johnson Street Basin, bioretention and permeable pavement were evaluated to determine their potential to mitigate existing flooding conditions. Findings are presented below:

- The three modeled systems had the capacity to nearly eliminate flooding from the 3-month, 24-hour event. Currently 17% of manholes are predicted to flood during the 3-month, 24-hour event under existing conditions. Installing bioretention at all possible locations reduces flooding by 88%; installing permeable pavement at all possible locations eliminates flooding. Permeable pavement was also a lower cost option.
- The model indicated that permeable pavement was the most effective system for reducing the extent and duration of flooding associated with a large storm event (2.86 inches). Under current conditions, 63% of manholes are predicted to flood during a 2.86 inch event. Full implementation of permeable pavement with a storage depth of 4 feet is predicted to reduce flooding by 87%, resulting in fewer than 10% of manholes flooding during a large storm event.
- The greater effectiveness of the permeable pavement systems is largely attributable to the greater area available for implementation of permeable pavement compared to bioretention. While permeable pavement can be installed along most of the roadway (or 286,000 linear feet of roadway), bioretention can only be installed along portions of the roadway where it will not obstruct views or access (or 85,000 linear feet of roadway). Given the ample space available for permeable pavement and the flood control objective for this basin, permeable pavement represents the most effective green street approach for the Johnson Street Basin.
- Permeable pavement with a 4 foot gravel storage bed was determined to be the highest performing system in the basin that can be used to meet the City's objectives for flood control.
- Implementing permeable pavement on 25 percent of the potential street area represents the knee-of-the-curve solution to mitigate flooding from the 3-month, 2-hour storm event.
- Implementing permeable pavement on 75 percent of the potential street represents the knee-of-the-curve solution to mitigate flooding from the 10-year, 2-hour storm event.

Focused implementation is recommended to address wide-spread flooding issues and problem areas identified in this report. At least one of the identified problem areas may require public-private partnerships to implement green infrastructure that addresses parking lot runoff in order to achieve flood reduction goals. Parking lots in problem areas should be further evaluated to determine potential for retrofits and alleys should be considered for permeable pavement retrofits since these areas are contributing to current flooding problems.

Implementation of green infrastructure should be focused on problem areas first, then address important low lying areas, and finally include wide-spread adoption throughout the watershed as needed. Adaptive management is needed, as is monitoring of results that can be used to refine modeling work and adjust implementation planning. The reality of focused implementation is dependent on capital improvement plans and road reconstruction activities that are underway or being planned. Intersecting these planning activities with high priority implementation activities is critical to ensuring a cost-effective management strategy.

Additional analysis could be completed to further optimize implementation activities based on priority areas and evaluate the potential impact of focused implementation activities, which would likely result in significantly lower costs.

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Appendix A: Model Construction, Parameterization, and Calibration

EPA's Storm Water Management Model (SWMM; EPA 2008) was used to develop a hydrologic and hydraulic model of the Johnson Street Basin. SWMM is a dynamic hydrology-hydraulic-water quality model that simulates runoff quantity and quality from urban areas. The runoff component operates on a collection of sub catchment areas that receive precipitation and generate runoff and pollutant loads. The routing component transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM can track the quantity and quality of runoff generated within each sub catchment, as well as the flow rate, flow depth, and quality of water in each pipe and channel. SWMM 5 can also model the hydrologic performance of several green infrastructure controls, including permeable pavement, rain gardens, green roofs, street planters, rain barrels, infiltration trenches, and vegetated swales.

Data required for this SWMM analysis include design storms to drive the model; catchment physical characteristics (topography, soils, land cover) to construct and parameterize the model; and observed flooding response to calibrate the model. This appendix describes the model construction, parameterization, and calibration, including the data sources and key modelling assumptions.

1. Climate Data

Four design storm events were used to drive the Johnson Street Basin SWMM model:

- A 3-month, 2-hour Atlas storm event (Precipitation = 0.83 inches; Peak 1-hour depth = 0.67 inches) to represent existing flooding conditions
- A 1-year, 24-hour Atlas storm event (Precipitation = 2.23 inches; Peak 1-hour depth = 1.05 inches) to simulate a small, frequent storm event
- A 10-year, 24-hour Atlas storm event (Precipitation = 4.40 inches; Peak 1-hour depth = 2.07 inches) to represent design criteria listed in the La Crosse ordinance
- A 10-year, 2-hour climate change storm event (Precipitation = 2.86 inches; Peak 1-hour depth = 2.32 inches) to represent a potential short duration, high intensity climate change scenario.

The first three storm events were derived from the Rainfall Frequency Atlas of the Midwest (Atlas; Huff and Angel 1992). The City currently references the Atlas as part of the City ordinance, and the 10-year, 24-hour design storm is used to size storm sewers. Each storm event was represented in the model with an SCS type II distribution, which is the standard distribution for this region.

The City was concerned, however, that the current Atlas did not account for the impact of climate change on recent storm events. Their observations suggest that intense short-duration storm events are currently occurring at a higher frequency than expected based on historic Atlas data. The City therefore asked that a 10-year, 2-hour climate change storm event be developed to evaluate street flooding. The 10-year frequency was chosen to match the frequency that the City currently uses for sizing storm sewers.

To develop a climate change storm event, this study consulted a recent EPA report on the potential impacts of climate change and urban development on watershed response (Butcher et al. 2013). As part of the report, a range of climate change scenarios was analyzed for rain gauges located across the country.

Since the report did not include a rain gauge located in La Crosse, rain gauges near La Crosse were selected for further evaluation. Based on comparisons of rainfall depths for a series of design storms, the rain gauge located in Titonka, Iowa was identified as most representative of rainfall patterns in La Crosse. Figure 1 compares the design storm depths for La Crosse derived from the Atlas to the design storm depths for Titonka. At all recurrence intervals, rainfall depths are very similar for the shorter duration events. Larger differences were identified for the 24-hour duration events, but since the goal was to derive a 10-year, 2-hour rainfall event, this difference was determined to be acceptable and the Titonka rain gauge was selected for use as a surrogate rain gauge for La Crosse.

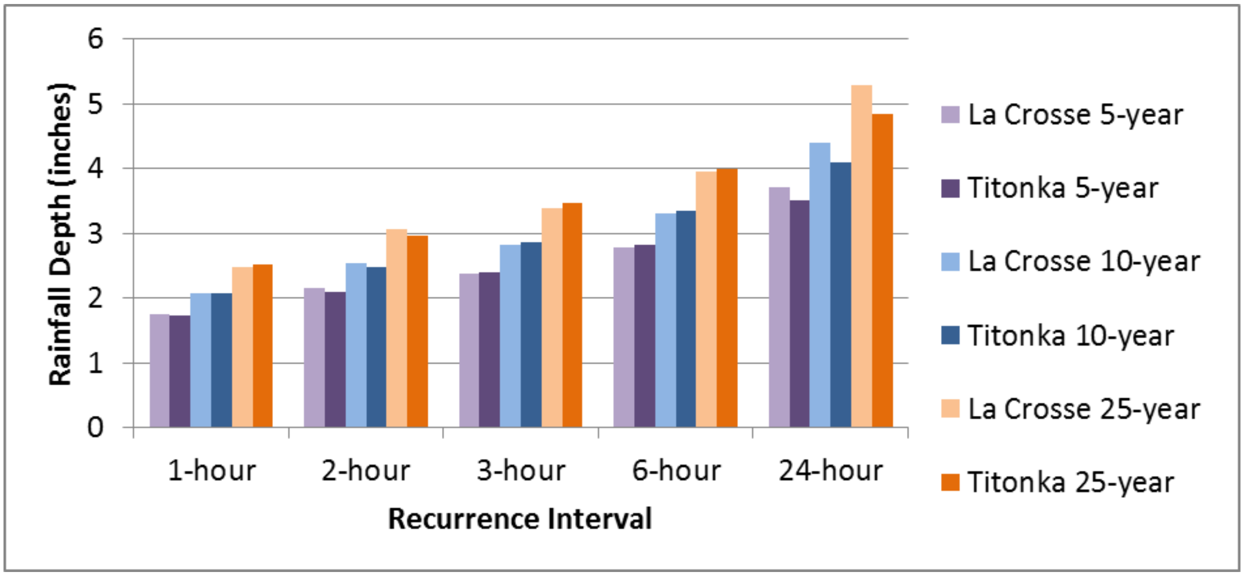

Figure 1. La Crosse Atlas rainfall values compared to Titonka rain gauge.

The EPA report evaluated six potential climate change scenarios for the period 2040-2070 developed from the North American Regional Climate Change Assessment Program's archive of dynamically downscaled climate products (Butcher et al. 2013). Once a surrogate gauge was selected for La Crosse, the 10-year, 2-hour storm event for each climate change scenario was compared to the 10-year, 2-hour storm event under existing conditions (Table 1). To produce a conservative estimate of existing system capacity, this study considered only the three climate change scenarios with the greatest percent increase in rainfall depth for the 10-year, 2-hour storm event. The average percent change for these three scenarios (12 percent) was then applied to the published Atlas 10-year, 2-hour rainfall depth (2.55 inches) to develop the climate change scenario (2.86 inches).

Table 1. Comparing climate change scenarios for 10-year, 2 hour discrete storm events to existing conditions

Climate change scenario	10-year, 2-hour storm event P (in) (based upon 2-hour discrete storm events) (inch)	Percent change from existing conditions (%)
Existing conditions	2.08	0%
crmcgcm3	2.36	13%
hrm3_hadcm3	2.21	6%
rcm3_gfdl_slice	2.25	8%
gfdl_slice	1.92	-8%
rcm3_cgcm3	2.37	14%
WRFG_ccsm	2.28	10%

Scenarios derived from North American Regional Climate Change Assessment Program

A SCS type II distribution was applied to this rainfall depth similar to the existing condition rainfall. A 12 percent increase was applied to each time step. This assumption is reasonable due to the short duration of the rainfall event. Table 2 presents the published values from the Atlas and how they were revised for the 10-year, 2-hour climate change rainfall event.

Table 2. 10-year, 2 hour rainfall event depths for existing conditions, climate change scenario

Duration	10-year, 2-hour rainfall (provided in the Atlas) (inch)	10-year, 2-hour climate change scenario (increase by 12-percent) (inch)
15 minute	1.19	1.33
30 minute	1.63	1.83
1 hour	2.07	2.32
2 hour	2.55	2.86

2. Hydrologic Model Development

To estimate the amount of precipitation infiltrated, stored in depressions, and converted to runoff, SWMM requires the user to define a set of hydrologic model parameters, including subcatchment drainage area, overland flow paths, percent imperviousness, slope, Manning’s n for pervious and impervious areas, depression storage, and soil infiltration characteristics (e.g., curve number). To define these hydrologic model parameters for the Johnson Street Basin, the following data sources were consulted:

- Subcatchment delineation as provided by the City of La Crosse
- SSURGO (for soil data)
- LiDAR data (for topography and slopes)
- Aerial photography, land use/ zoning maps, and impervious area maps (for land cover)

Based on these data sources, a SWMM model was developed to represent the hydrologic response within the Johnson Street Basin under existing conditions. The watershed is 769 acres in size, and the downstream model extent is located at the confluence between the Mississippi River and the Johnson Street Basin. The average subcatchment size is 3.4-acres.

Figure 2 presents the impervious area within the study area (67.2 percent impervious). The imperviousness that was considered directly connected was defined during a site visit and adjusted as needed during model verification.

The soil parameters were listed for the entire study as hydrologic soil group type B soils by reviewing the available soil (SSURGO) data. The Horton infiltration equation was used in SWMM to represent soil infiltration. Table 3 presents the model soil parameters used in SWMM. These values were derived from discussions with city staff and by reviewing literature including FDEP 2006 and Tetra Tech 2001, for applicable values.

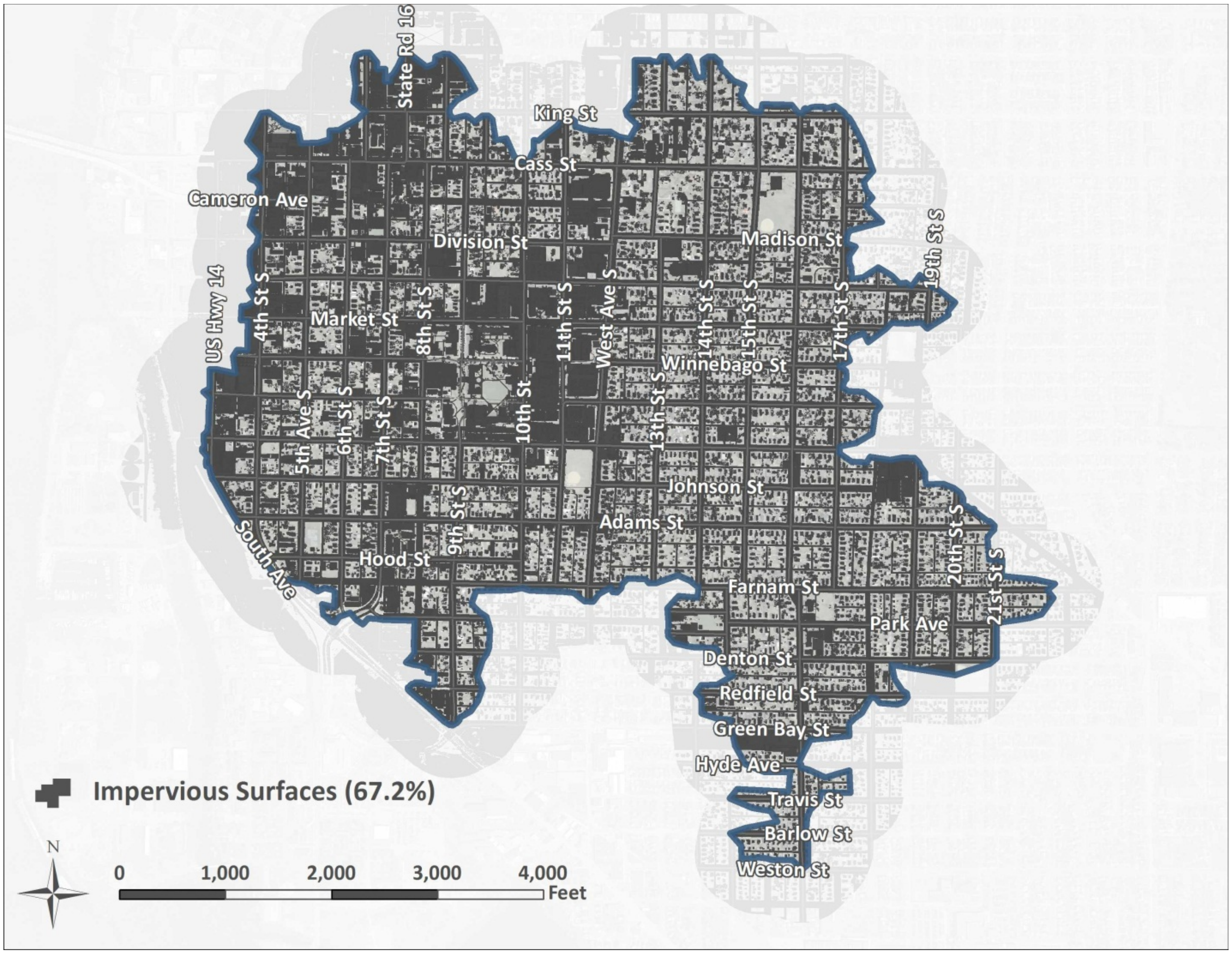

Figure 2. Johnson Street Basin watershed imperviousness.

Table 3. Soil parameters

Soil type (hydrologic soil group)	Maximum infiltration rate (inch/hour)	Minimum infiltration rate (inch/hour)	Maximum soil storage volume (inch)
B	9	0.5	5

Uncalibrated water quality pollutant loads for total suspended solids, total phosphorus, and total nitrogen were calculated in SWMM. Wash off pollutant loads were calculated by defining an event mean concentration (EMC) for total suspended solids, total nitrogen, and total phosphorus for each land use category, which was multiplied by the modeled runoff to estimate pollutant loads. Dynamic buildup and wash-off for these pollutants were not modeled. Land use categories were assigned to each modeled subcatchment using the City zoning map. Table 4 presents the land use categories and EMC values utilized for this study which were selected from the Nationwide Urban Runoff Program summary report (EPA 1983). The EMCs represent median concentration and are applied as constants for all storm sizes.

Table 4. Land use event mean concentrations

Land use	TSS (mg/l)	TP (mg/l)	TN (mg/l)
Residential	101	0.383	2.636
Non-residential	69	0.201	1.751

Source: EPA 1983

3. Hydraulic Model Development

A dynamic wave SWMM model was developed to represent the hydraulic routing of the hydrographs generated from the SWMM hydrologic model within the Johnson Street Basin storm sewer network under existing conditions (Figure 3). The model extents include almost every 12-inch diameter pipe in the watershed as provided by the City and extends to the confluence of the Mississippi River and Johnson Street Basin. The SWMM hydraulic model includes 424 links and nodes. Discussions with City staff indicated that backwater impacts from the Mississippi River are considered minimal to negligible. Therefore, the SWMM outfall boundary is modeled as a free flow boundary condition.

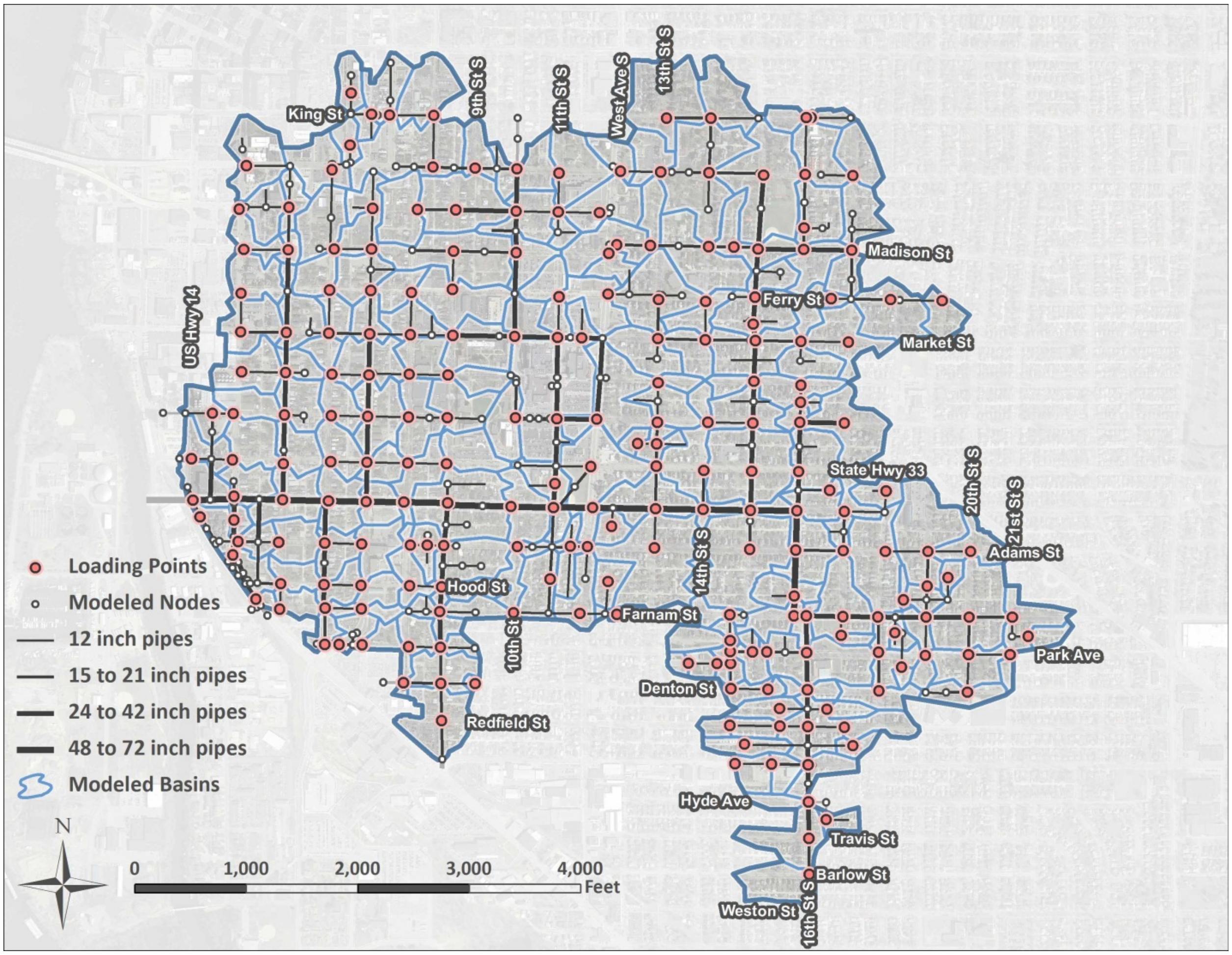

Figure 3. Modeled storm sewer network for the Johnson Street Basin.

4. Model Debug and Verification

Model debugging and verification was performed to improve model credibility and confidence in results. A series of quality control procedures were conducted to verify that the model is a reasonable representation of the Johnson Street Basin and its stormwater system, including flow and volume checks. Similarly, the SWMM model was checked to be free of various types of instabilities inherent to the numerical calculation schemes the model uses to approximate real-world conditions. Due to the detail and complexity of this SWMM model, flooded nodes were not modeled using overland flow paths that are routed to other modeled nodes. Instead, each flooded node was modeled using a general ponded area assumption (10,000 square feet per foot) that generally represents the area within the public right-of-way between manholes, and the flooded runoff volume was routed into the modeled storm sewer network when capacity was available.

City staff provided input on three separate occasions to ensure the model predictions matched historical flooding conditions prior to completing model verification. City staff also indicated that short, intense storm events were typically what led to observed flooding. The City proposed utilizing a 2-inch, 2-hour storm event to compare to observed flooding problems. To test model response and sensitivity, a series of short duration, high intensity storm events were identified by referencing the Atlas (Huff and Angel 1992). Storm events ranged from less than 1 inch (3-month, 2-hour storm) to greater than 2 inches (10-year, 2-hour storm). Model results were compared to City reported flooding, and model parameters were adjusted until there was reasonable agreement between the observed flooding conditions and model results.

Reviewing the model results during the sensitivity analysis, the common flooded areas reported by the City occurred when the peak intensity exceeded 0.50 inches over a 30-minute period, which is essentially the same as the 2-inch, 2-hour storm the City suggested using for the model verification purposes. City staff confirmed that the frequency, severity, and location of modeled flooding problems generally corresponded to observed flooding problems, and concluded that the model provides a sufficiently accurate approximation of observed conditions. Figure 4 presents a summary of the areas where the existing storm sewer network floods during the 3-month, 2-hour (0.83 inch) storm event with a SCS type II distribution and presents the cubic feet of flooding occurring at each location. Results for the 3-month, 2-hour rainfall event include 67 flooded manholes for a duration of 45 hours. The average peak flooding depth is 2 inches for a total flood volume of 0.76 million gallons.

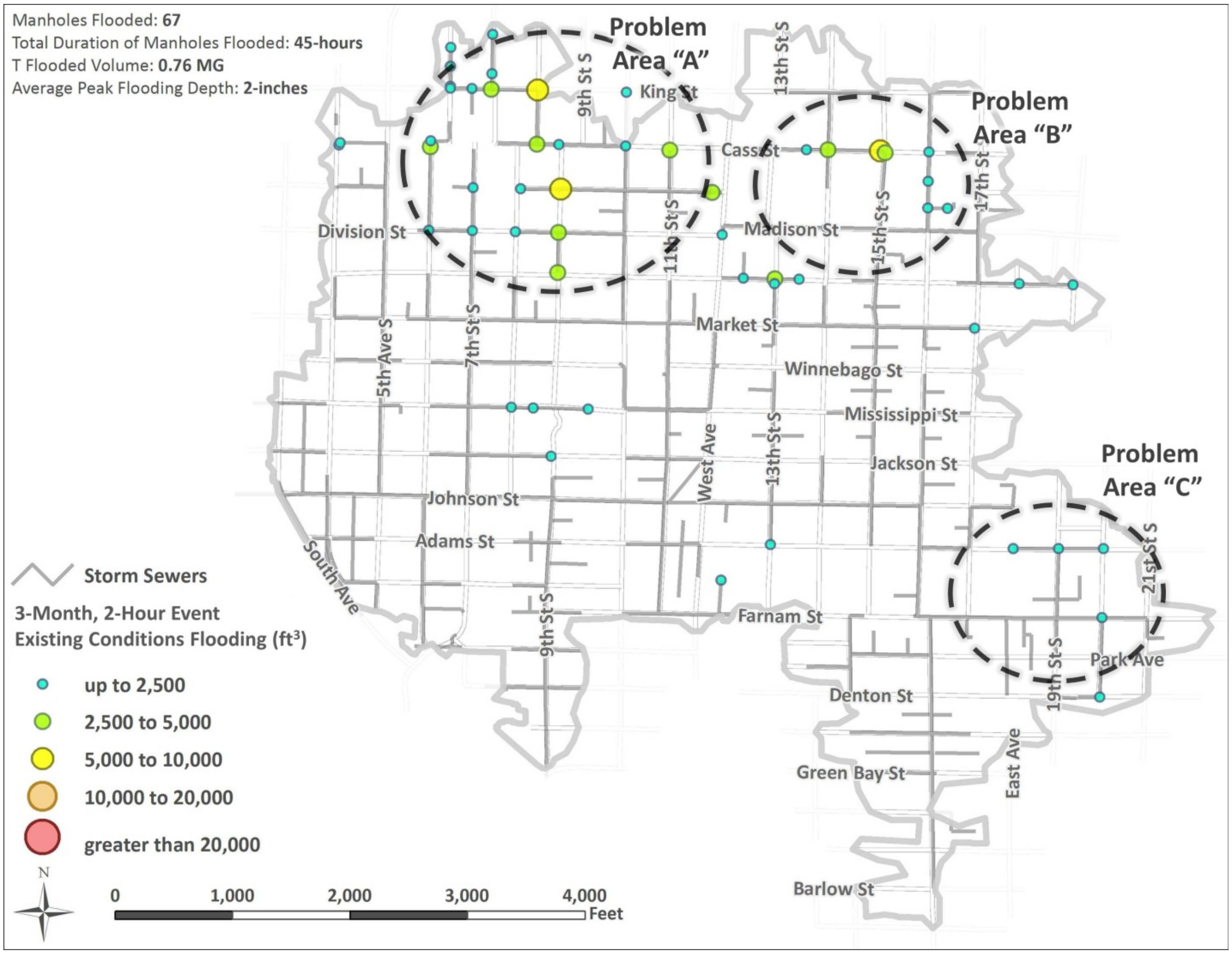

Figure 4. Existing conditions flooding, 3-month 2-hour event.

The most extensive flooding is concentrated in a few areas (Problem Areas A, B, and C in Figure 4). Reviewing some of these problems led to the following observations regarding the hydrology and storm sewer network:

- **Problem Area A** (King Street and Cass Street between 6th and 8th) has a very high imperviousness (70 percent) and is mostly non-residential with several parking lots that do not have stormwater control measures. The storm sewer network consists primarily of a 12-inch diameter pipe, which appears to be significantly less than needed.
- **Problem Area B** (King Street and Cass Street between 13th Street and 15th Street) has relatively high impervious area (greater than 50 percent) in a primarily residential area with only a modest amount of parking lots. When visiting the study area, most of the residential houses appeared to have disconnected rooftops, which helps reduce the peak flow. At the intersection of 15th Street and Cass Street is a constricting 1.75-ft diameter pipe, which leads to frequent surcharging and backup. Similarly, further downstream along 15th Street between Winnebago Street and State Street are a couple of pipe segments where the pipe slope appears to be zero percent, which results in pipe surcharging upstream.
- **Problem Area C** (Adams Street and Farnum Street between 18th Street and 20thStreet) is located in a predominantly residential area with an average imperviousness of 50 percent. However, the

City has intentionally undersized pipes along Adams Street and Farnum Street to help reduce the flooding elsewhere. Along Farnum Street near the intersection with 16th Street, a 3-foot diameter pipe along Farnum Street and a 3-foot diameter pipe along 16th Street intersect and discharge into a single 3-foot diameter pipe, resulting in street flooding upstream.

Appendix B: Additional Green Infrastructure Design Parameters

Green infrastructure is modeled in SWMM using a combination of vertical layers whose properties are defined on a per-unit-area basis. The entire catchment impervious area was routed to the green infrastructure. The vertical layers can include a surface layer, pavement layer, soil layer, storage layer, and underdrain layer. Depending on the physical composition of each green infrastructure practice, various combinations of layers were applied. Figure 1 shows the vertical layers that can be used in SWMM to represent green infrastructure practices. Table 1 shows the vertical layers that were used in this analysis to represent bioretention and permeable pavement.

Each vertical layer within a bioretention or permeable pavement area is characterized by several design parameters that determine the hydrologic function of the practice. These design parameters include the depth of the layer, the porosity or void ratio, and other parameters that define the rate at which water can flow through the layer. The green infrastructure design parameters assumed for this analysis are presented in Table 2. Soil infiltration parameters required for the soil layer and storage layer were determined on the basis of the assumed soil substrate. The infiltration rate into the bioretention media (6 inches per hour) is derived from Washington State Department of Ecology for bioretention soil mixes with an assumed safety factor of 2 (Washington State University 2009).

The bioretention soil layer shown in Figure 1 is modeled in SWMM using the Green Ampt equation. While bioretention uses the soil layer for detaining stormwater, permeable pavement detains stormwater in the storage layer. Referring to Table 1, neither bioretention nor the permeable pavement was modeled in SWMM with an underdrain, since La Crosse soils have a high enough infiltration rate not to warrant an underdrain.

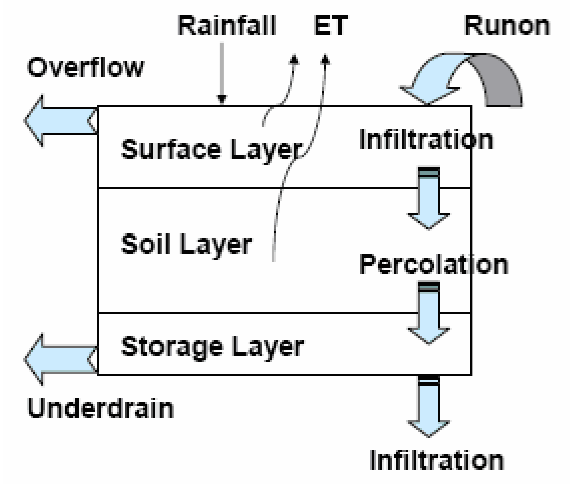

Figure 1. General schematic of SWMM BMP layers (pavement layer is substituted for soil layer for permeable pavement).

Table 1. SWMM Vertical layers

BMP type	Surface	Pavement	Soil	Storage	Underdrain
Bioretention	Yes	NA	Yes	No [a]	No
Permeable Pavement	Yes	Yes	NA	Yes	No

a. Bioretention storage is included in soil layer

Table 2. BMP layer parameters

SWMM parameter	Unit	Bioretention	Permeable pavement
Surface layer parameters			
Storage Depth	inch	12	0
Vegetation Volume Fraction (storage volume removed due to vegetation volume)	dimensionless	0.1	0
Surface Roughness	dimensionless	0.35	0.011
Surface Slope	%	1	1
Swale Side Slope	horizontal : vertical	2	NA
Soil layer parameters			
Thickness	inch	36	NA
Porosity	fraction	0.4	NA
Field Capacity	fraction	0.25	NA
Wilting Point	fraction	0.1	NA
Conductivity	inch/hour	6	NA
Conductivity Slope	dimensionless	7.5	NA
Suction Head	inches	2.4	NA
Pavement layer parameters			
Thickness	inches	NA	6
Void Ratio (not porosity)	fraction	NA	0.2
Impervious Surface Fraction (impervious vs porous surface)	ratio	NA	0 (continuous)
Permeability	inch/hour	NA	100
Clogging Factor	NA	NA	NA
Storage layer parameters			
Height	inches	NA	24 and 48
Void Ratio	fraction	0.67	0.67
Infiltration Rate	inch/hour	1	1
Clogging Factor	NA	NA	NA

Appendix C: Performance Curves Supporting Selection of the Most Effective Practice

3-month, 2-hour Performance Curves

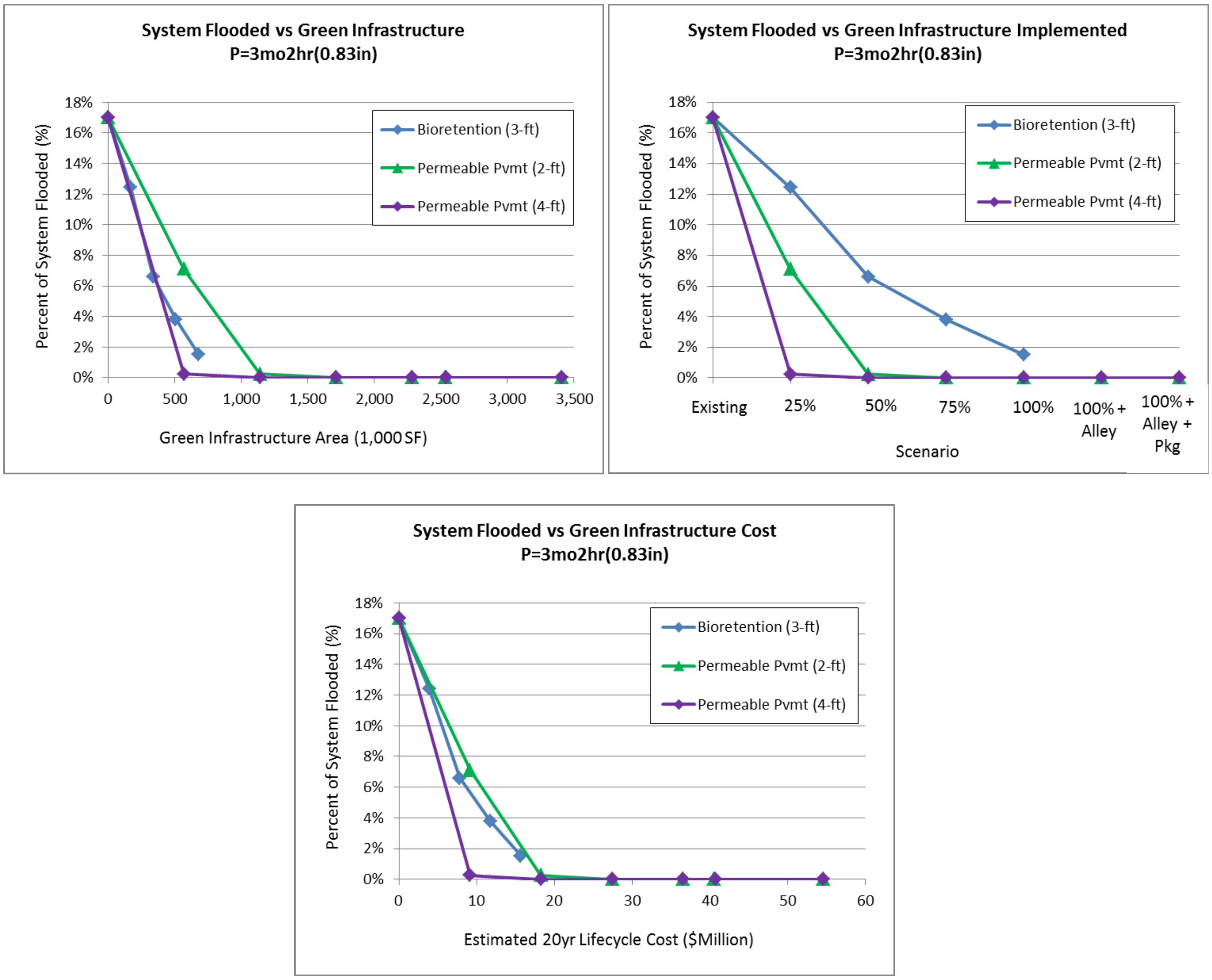

Figure C-1. System flooded performance curves, 3-month, 2-hour storm event.

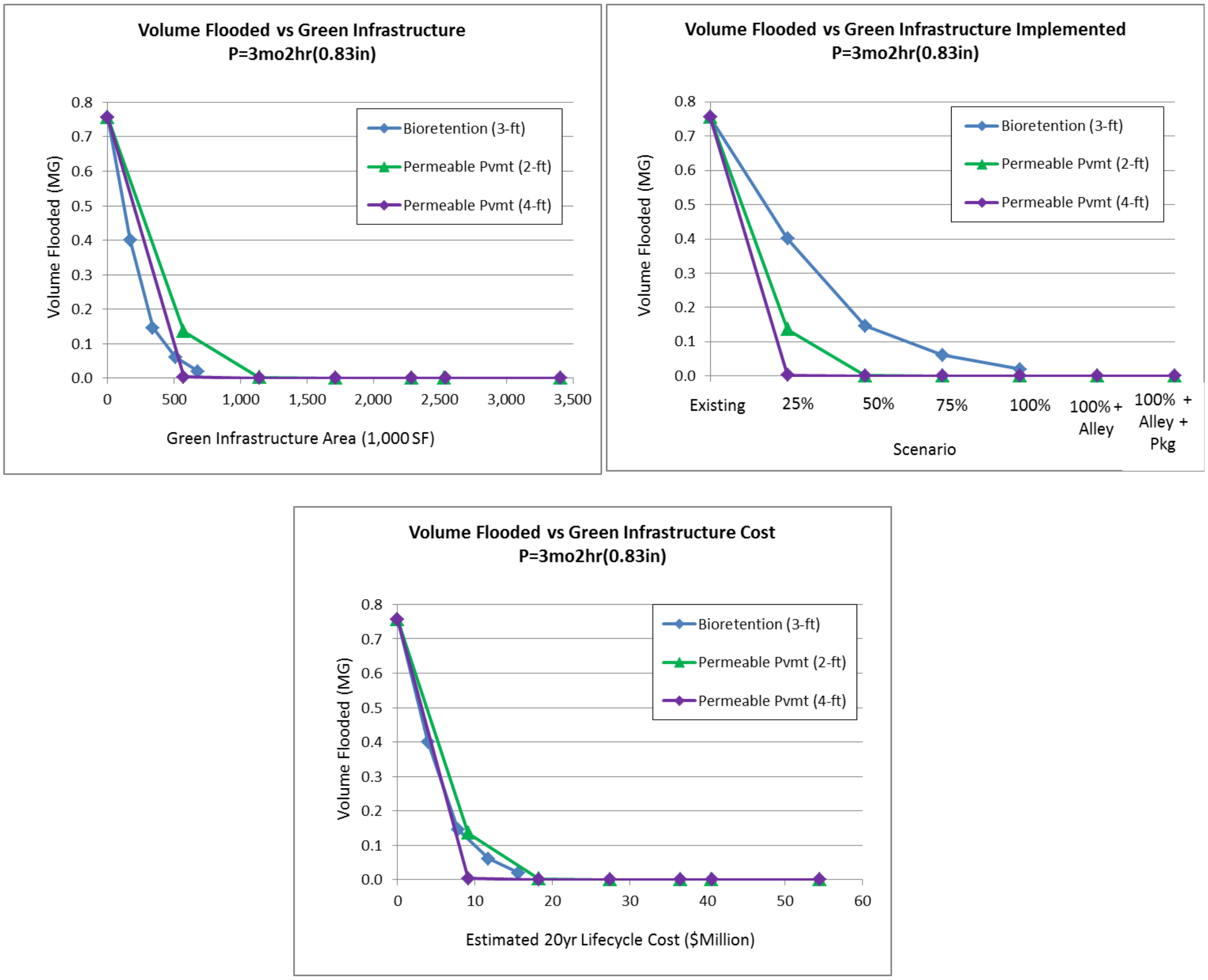

Figure C-2. Volume flooded performance curves, 3-month, 2-hour storm event.

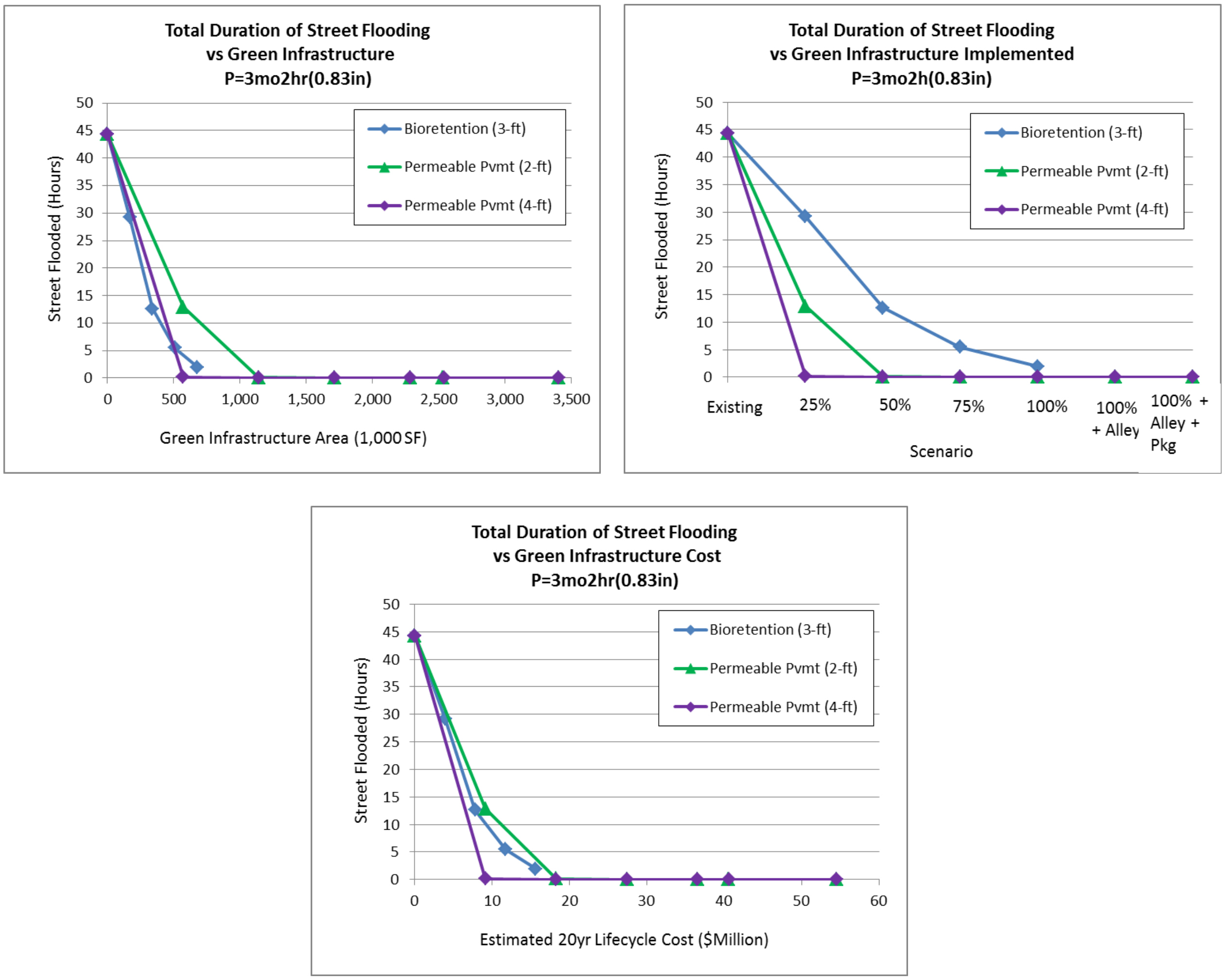

Figure C-3. Total duration of street flooding performance curves, 3-month, 2-hour storm event.

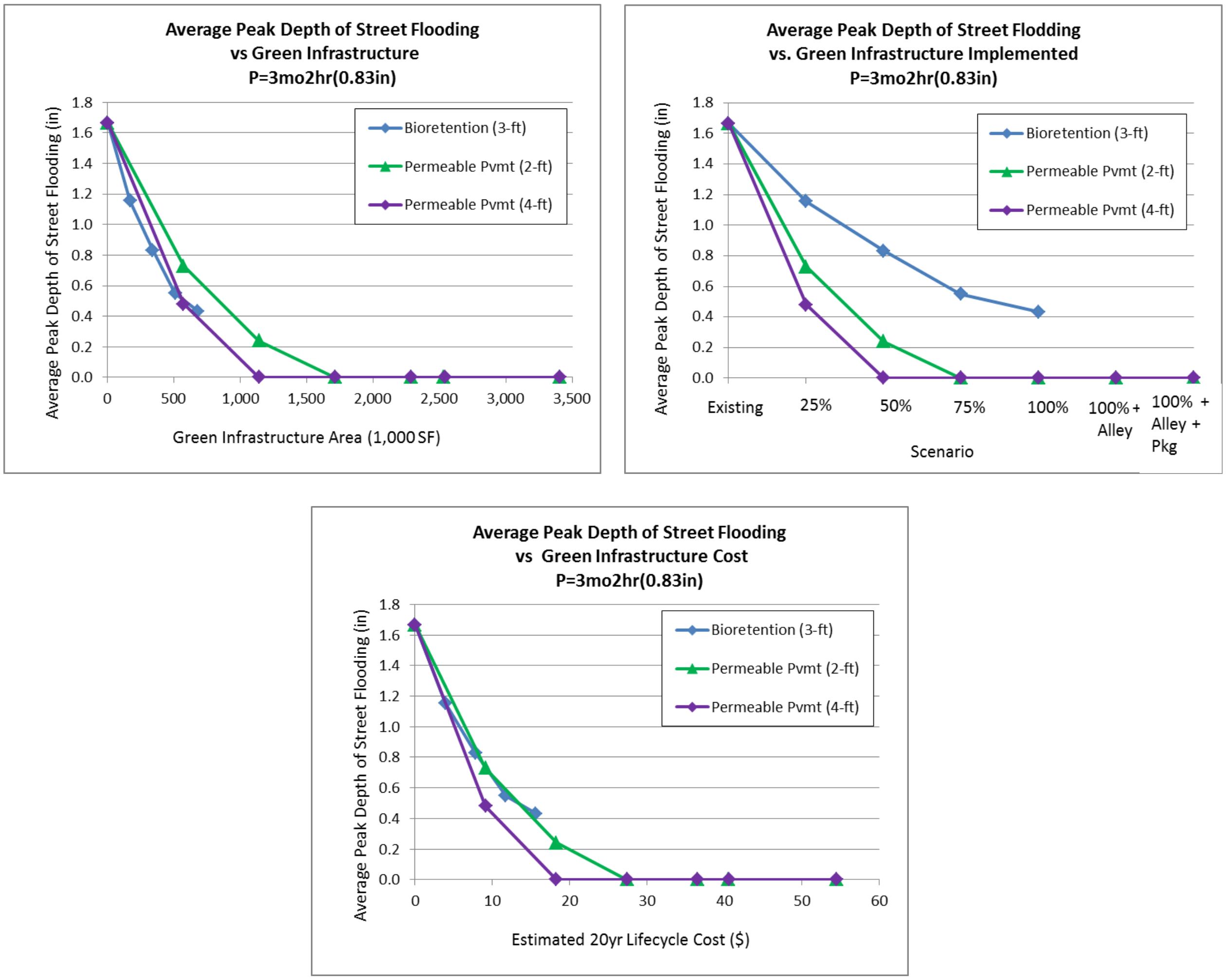

Figure C-4. Average peak depth of street flooding performance curves, 3-month, 2-hour storm event.

10-year, 2-hour Performance Curves

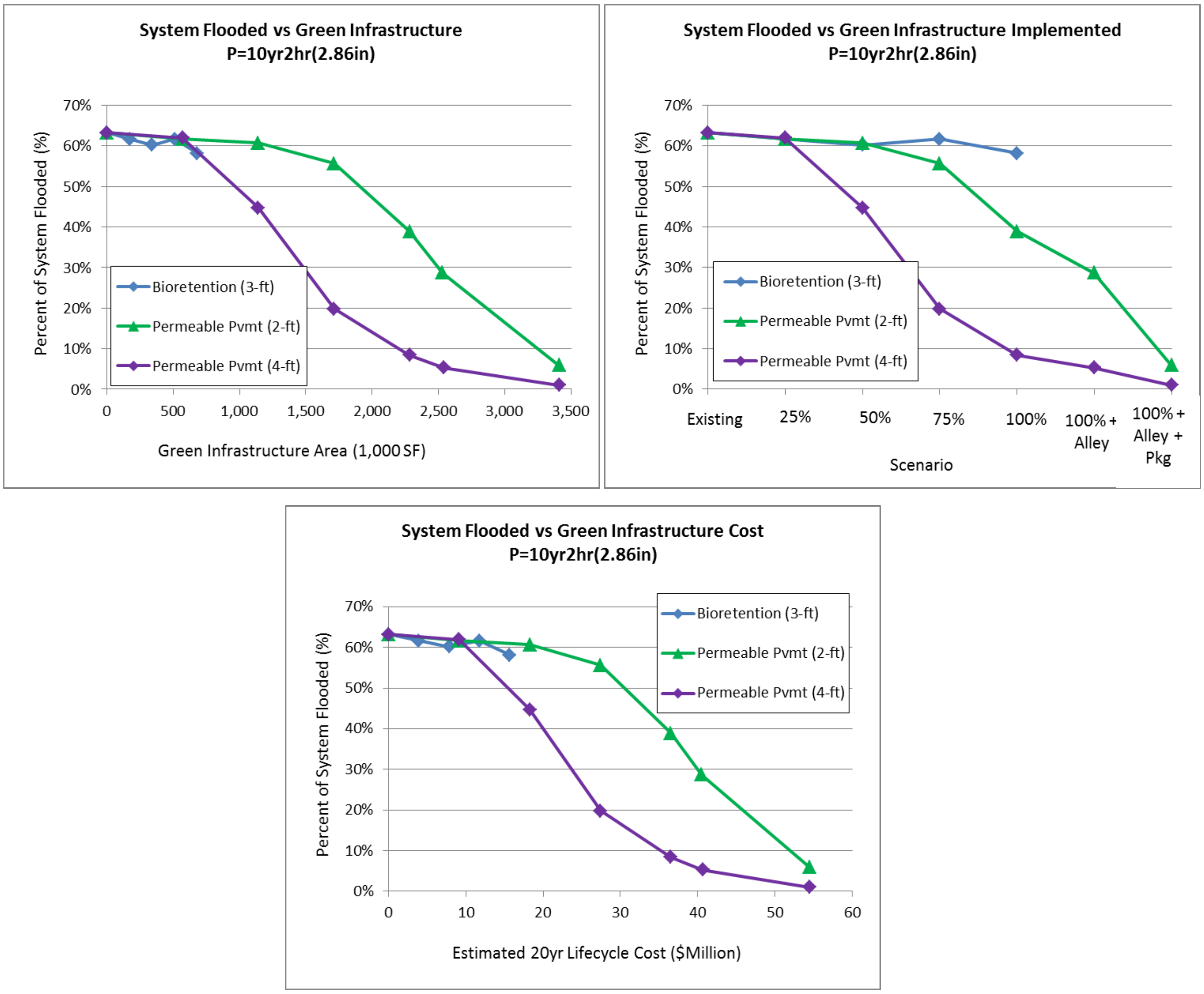

Figure C-5. System flooded performance curves, 10-year, 2-hour storm event.

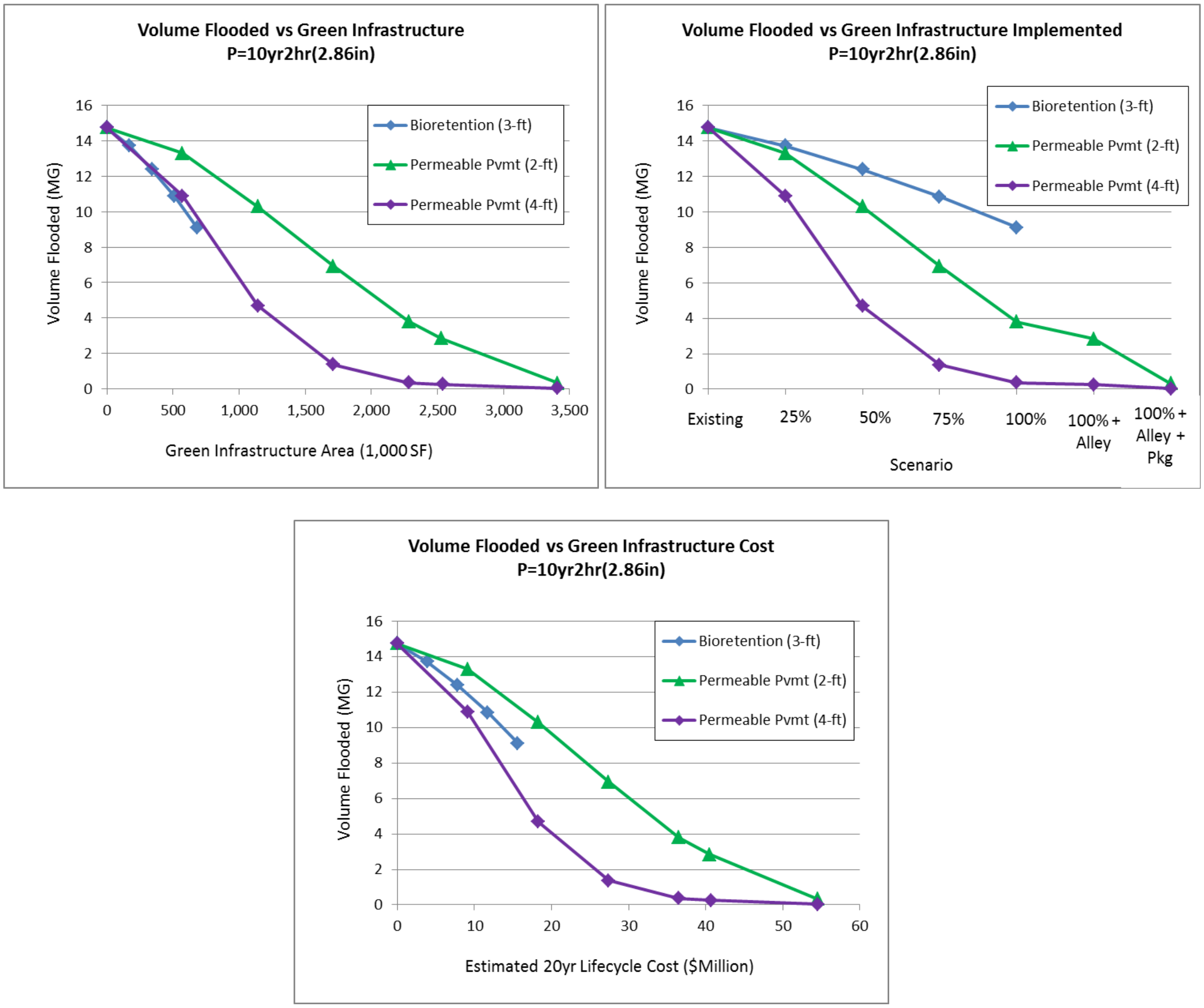

Figure C-6. Volume flooded performance curves, 10-year, 2-hour storm event.

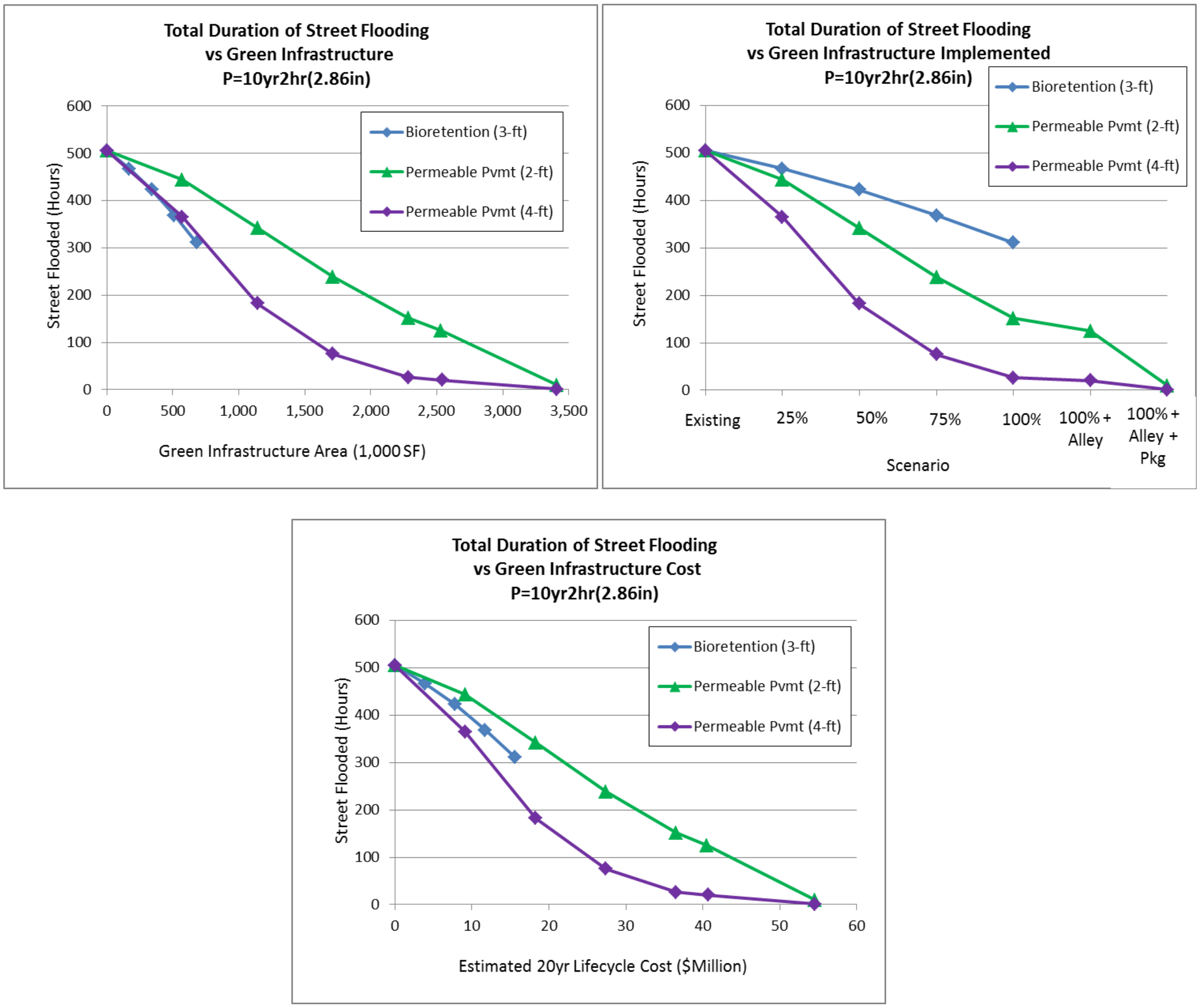

Figure C-7. Total duration of street flooding performance curves, 10-year, 2-hour storm event.

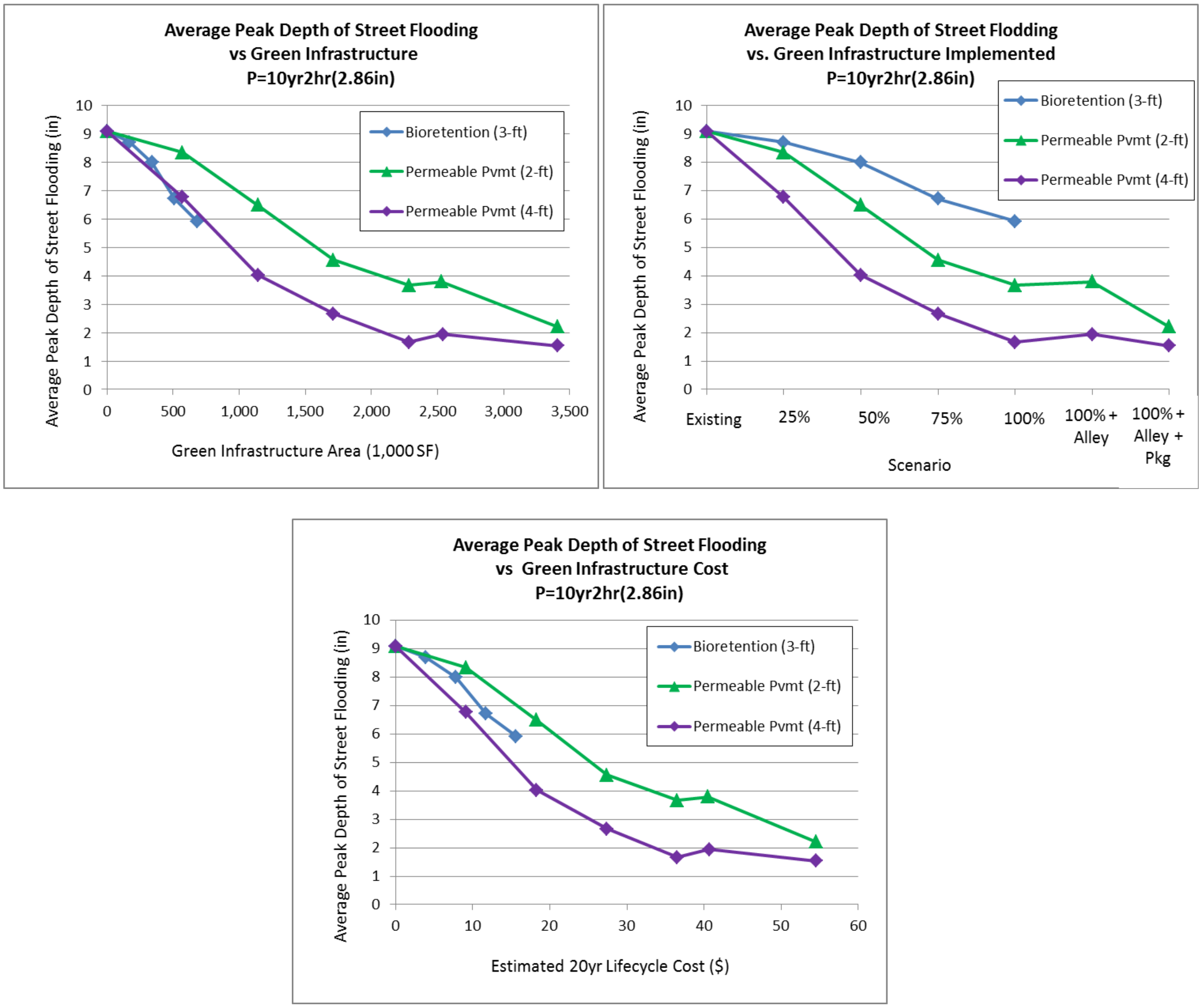

Figure C-8. Average peak depth of street flooding performance curves, 10-year, 2-hour storm event.