# Storm Water Control Management and Monitoring

Temple University Master Agreement

Contract No. 4400011166

Work Order TEM 006

**Task 9: Final Report**

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# Executive Summary

## Statement of task

The Pennsylvania Department of Transportation (PennDOT) is incorporating extensive green stormwater infrastructure into the redesign of the I-95 corridor in Philadelphia, which will take place over the next 25 years. These stormwater management practices (SMPs) are designed to capture the first inch or more of stormwater that falls on the highway and allow it to infiltrate rather than enter the storm sewer network. The use of SMPs to manage stormwater runoff stems from requirements of the Pennsylvania Department of Environmental Protection and the Philadelphia Water Department's *Green City, Clean Waters* program, which were designed to address combined sewer overflow problems in Philadelphia. SMPs are also expected to improve runoff water quality and mitigate spills on roadways. The latter will help PennDOT comply with the permitting requirements of the National Pollutant Discharge Elimination System (NPDES) of the Clean Water Act.

Scientists and engineers at Temple and Villanova Universities collected monitoring and assessment data along the Girard Avenue Interchange (GIR) to evaluate the performance of current stormwater control, design and maintenance practices. This group has worked together since 2005 to advance the knowledge base of stormwater management in the Philadelphia region and nationally. The research program includes monitoring, modeling, and assessment, with the goal of providing data-driven recommendations to PennDOT and its consultants for improving SMP design and maintenance practices. While SMPs have been used in transportation projects throughout the United States, the technology is still evolving. The magnitude of the I-95 stormwater infrastructure design, which will contain as many as 75-80 SMPs, presents an opportunity to conduct a rigorous evaluation of the first phase of construction to ensure that future SMPs are located, designed, and maintained to function optimally.

This report covers the first year of study on the I-95/GIR SMPs, specifically SMPs A, C, D, and G (also known as basins A, C, D, and G). The Temple and Villanova teams addressed the following critical areas: (1) characterization of the groundwater table along the corridor, (2) impact of urban soil and fill, (3) hydrologic performance and stormflow characterization, (4) geochemical characterization of stormwater runoff, (4) plant performance, and (5) maintenance strategies. The initial period involved monitoring design and installation of equipment. Approximately seven months of hydrologic monitoring is described, together with nine months of plant monitoring and maintenance; periods vary by basin. In addition, to supplement natural storm events, simulated runoff tests (SRTs) were conducted in three basins to evaluate their response to a large volume event. The runoff was simulated by releasing water from fire hydrants at the SMP inlet pipes. These tests were conducted in cooperation with the Philadelphia Water Department.

This executive summary provides highlights of findings and recommendations from the first year of study; more detailed data and discussion are included in the main report. While a great deal has been learned in this initial monitoring period, there are also limitations to the study. The findings are based on short-term behavior in the basins; additional understanding of basin behavior will require a longer period of monitoring.

**Storms monitored and estimated capture areas**

This executive summary provides an overview of the observed rainfall, observed inflows spanning the monitoring period, and different estimates of basin capture areas. Every SMP is designed to capture and infiltrate a specific quantity of water. The performance of a basin can in part be evaluated by comparing the planned and realized capture (or drainage) areas. Actual capture areas are calculated by dividing measured inflow by rainfall amounts (Table E-1) and assuming a uniform distribution of rain during an event. The actual capture areas for individual inlet structures is presented as a percentage of the designed drainage areas for each inlet to evaluate how much water was received for each storm.

Almost all of the basins monitored received lower volumes than expected. A consequence of lower capture volumes was 100% removal efficiency (no outflow) in SMPs C and D during the monitoring period (as discussed in the next section). With the exception of inlet N9 (within SMP A), realized capture areas were substantially smaller than their designed capture areas. Percentages ranged from 1-80% for SMP A (Table E-1a) and from 2-50% for SMPs C, D, and G (Table E-1b, also reported in Chapter 6). Inlet N9 sometimes had volumes greater than 100%, probably as a result of water from N8 being redirected to N9.

The large variation in captured volumes for each inlet across storms suggests that the drainage areas were not constant through the period of study. It is likely that this variation was due to changing conditions in the drained region of the highway. For example, the grate over one of the highway inlets draining to SMPs D and G was blocked by construction equipment, but the length of time it was blocked is unknown. For N8 the observed drainage area was less than 7% of what was expected for ten of the reported 12 storms, leading to the conclusion that the piping system was blocked as a temporary construction measure or leaking. Values were 20% and 13.8% for the remaining two events. Both of these are larger rain events, suggesting changes in stormwater capture area may have increased flow. As mentioned above, flow recorded at N9 exceeds the volumes expected from the drainage areas based on design plans in some cases (showing capture areas >100%). It may be that water crossed a flow divide or piping restrictions were overcome in these storm events. Clearly, monitoring is important to evaluate such changes during and after construction to identify and remove blockages and to take into account variations in system performance.

A detailed microtopographical analysis was conducted to more precisely determine why observed stormwater capture areas differed from those expected from planning documents. Accurate drainage area values were also needed to carry out sediment and contaminant loading estimates (next section) and provide watershed areas for modeling. LiDAR surveys of the highway provided elevation data that were used together with updated inlet coordinates to calculate flow routing and estimate capture areas with ArcGIS (Figures E-1-4). These were then compared to areas from design plans (Table E-2). The data presented here supersede values presented in Chapter 6 of the report. However, design plans were used for modeling SMPs C, D, and G in Chapter 6.

The maps of capture area show separate drainage to the N inlets along the sidewall and M inlets in the center of the highway due to the variation in microtopography mapped with LiDAR. In SMP A (Figure E-1 and E-2), several small drainage areas leading to several of the M inlets connect to the N8 inlet before entering SMP A. According to the LiDAR-based flow paths, a substantial area bypasses the inlets for SMP A. Note that the drainage area of the small ramp traveling down the embankment to SMP A has not yet been evaluated, and could raise the capture area by another 0.1 acre. In Figures E-3 and E-4, the large maroon area is piped to N7 (SMP C), and the smaller pale blue area is piped to N5 (SMP G). AECOM recently discovered that a revised plan set showed this blue drainage was split between two pipes, which would reduce the area by about half.

Barriers placed on the highway during construction have openings that allow stormwater runoff to reach drains, but these openings can easily become clogged. Thus, the highway rainfall capture areas were calculated both without barriers (Figures E1 and E-3) and with the barriers restricting flow (Figures E-2 and E-4). Diversion of stormwater due to the barriers had the largest effect on Basin A, reducing the capture area from 0.39 to 0.24 acres (summing N8, N9, and N10 in Table E-2). The arrangement of the barriers near Basin C lead to a slight increase in capture area from 0.24 to 0.29 acres as water diverted from Basin D flowed into Basin C instead (Figure E4, enlarged green area). There was no diversion near Basin G.

The largest difference between design and LiDAR-derived capture areas occurred for Basin A which captured about one third of the designed stormwater. The estimated drainage areas were closer to design in SMPs C, D, and G, but were still smaller. These capture areas should be reevaluated using LiDAR after construction is finished and compared to observed inflow monitoring data.

While surface grading reduced effective capture areas, this does not entirely account for the lower observed inflows to the basin (Table E-1). Adjusting the stormwater capture area estimates by eliminating piping from the center drains provides a closer match to measured volumes. As mentioned above, it is possible that drains in the middle of the highway are blocked as a temporary construction practice or they may be leaking. However, the drains cannot be physically checked without shutting down the highway. Further exploration by remote monitoring will be conducted. Note that the roadway surface will not receive final grading until sometime in the future, when it is expected that the drainage areas will be more similar to those specified in the design plans.

For loading calculations, areas included only the LiDAR estimated surfaces that drain directly to the N inlets (LiDAR_DA directly to inlet reduced by barriers in Table E-2) without the central drainage pipes. The areas reduced by barriers reflect the best estimate of drainage areas during the construction phase conditions during most of the monitoring period. Using an area less than the designed capture areas is based on: (a) the low flows observed in the basin (Table E-1, Chapter 3, Appendix 2), (b) flow storm routing accumulations predicted by digital elevation models from the LiDAR surveys (Chapter 5 and updated in this section), and (c) direct observations of stormwater runoff rerouting during rain events. These results emphasize the importance of understanding the construction effect on the drainage areas. Small changes in road cross slope, temporary pipe obstructions, and barriers such as washing structures placed on inlets effect drainage patterns. It also highlights the importance of monitoring, which will be continued under the District 6 funding through AECOM.

*Table E-1a: Contributing areas from measured flow in Basin A compared to the design drainage area for individual storms.*

| Date | Rainfall (inches) | N10 Contributing Area (%) | N9 Contributing Area (%) | N8 Contributing Area (%) |
|---|---|---|---|---|
| 07/22/2017 | 0.53 | 5.4 | 23.6 | 4.8 |
| 07/23/2017 | 1.16 | 8.3 | 28.3 | 1.0 |
| 07/24/2017 | 0.54 | 60.4 | 155.0 | 20.0 |
| 08/02/2017 | 0.65 | 13.2 | 47.9 | 5.2 |
| 08/05/2017 | 0.94 | 15.2 | 42.7 | 6.4 |
| 08/18/2017 | 0.73 | 16.4 | 31.7 | 2.8 |
| 08/22/2017 | 0.75 | 29.6 | 53.4 | 5.6 |
| 08/29/2017 | 0.76 | 79.9 | 148.1 | 4.3 |
| 09/02/2017 | 0.41 | 69.3 | 153.4 | 4.1 |
| 09/06/2017 | 0.74 | 60.2 | 138.0 | 6.2 |
| 09/16/2017 | 1.14 | 12.4 | 21.6 | 5.5 |
| 10/29/2017 | 2.61 | 25.7 | 39.7 | 13.8 |

*Table E-1b: Contributing areas from measured flow in Basin C, D, and G compared to the design drainage area for individual storms.*

| Date | Rainfall (mm) | C Contributing Area (%) | D Contributing Area (%) | G Contributing Area (%) |
|---|---|---|---|---|
| 03/30/2017 | 1.67 | 2 | 36 | 1 |
| 04/25/2017 | 0.71 | 14 | 47 | 5 |
| 05/05/2017h | 1.12 | 24 | 33 | 8 |
| 05/13/2017 | 1.90 | 30 | 13 | 5 |
| 05/25/2017 (B2B)* | 1.71 | 28 | 7 | 7 |
| 06/06/2017 | 0.57 | 20 | 10 | 7 |
| 06/24/2017 | 1.10 | 14 | 7 | 8 |

* B2B Stands for a combined back to back storm.

*Table E-2: Drainage area (DA) estimates for each basin based on LiDAR surveys and design plans.*

| SMP | Inlet | LiDAR_DA Directly to inlet without barriers (acres) | LiDAR_DA Directly to inlet reduced by barriers (acres)** | LiDAR_DA Piped from M inlets (acres) | Sum LiDAR Areas reduced by barriers (acres) | AECOM DA Estimates (ROAD ONLY)* |
|---|---|---|---|---|---|---|
| A | N8 | 0.21 | 0.12 | 0.34 | 0.46 | 1.50 |
| | N9 | 0.15 | 0.09 | -- | 0.09 | 0.22 |
| | N10 | 0.03 | 0.03 | -- | 0.03 | 0.17 |
| C | N7 | 0.24 | 0.29 | 0.66 | 0.95 | 0.98 |
| D | N6 | 0.24 | 0.18 | -- | 0.18 | 0.24 |
| G | N5 | 0.18 | 0.18 | 0.07*** | 0.25 | 0.30 |

* AECOM DA Estimates are based on Drawing SHEET#92B OF129 and drawing titled DRAINAGE AREA 2 -POST DEVELOPMENT STORMWATER MANAGEMENT SHEET#
** Used in loading estimates
*** Adjusted by 50% to match revised plans

*Figure E-1: Drainage areas for Basin A calculated from flow routing of LiDAR elevation surveys without consideration of highway barriers. The location of the highway drains was used as the capture point for outflow. The central highway drains currently appear to be blocked so those areas are not included in operational (construction-phase) capture areas.*

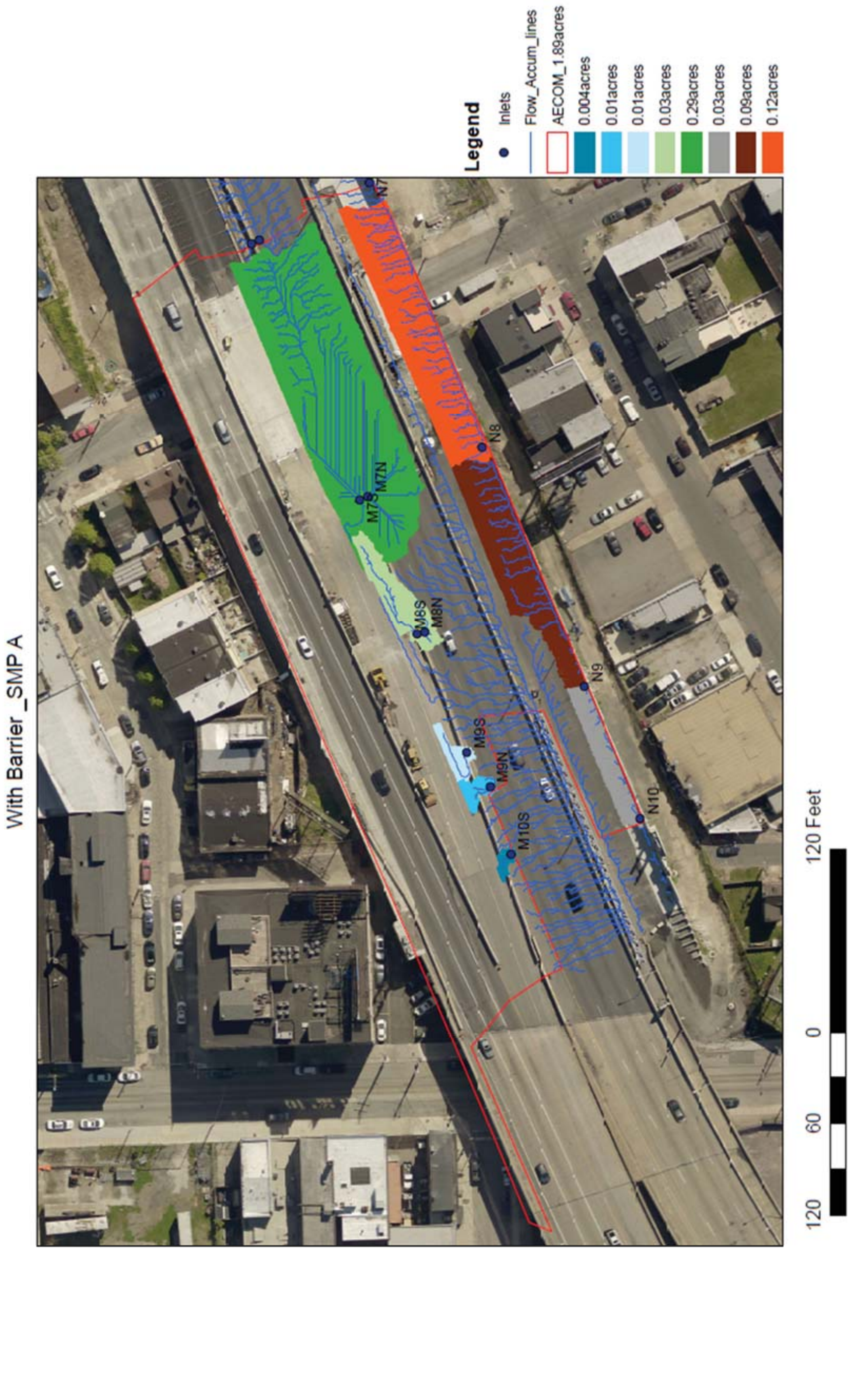


*Figure E-2: Drainage areas for Basin A calculated from flow routing of LiDAR elevation surveys including rerouting due to highway barriers. These barriers were in place for most of the storms in the monitoring period. The location of the highway drains was used as the capture point for outflow. The central highway drains currently appear to be blocked so those areas are not included in operational (construction-phase) capture areas.*

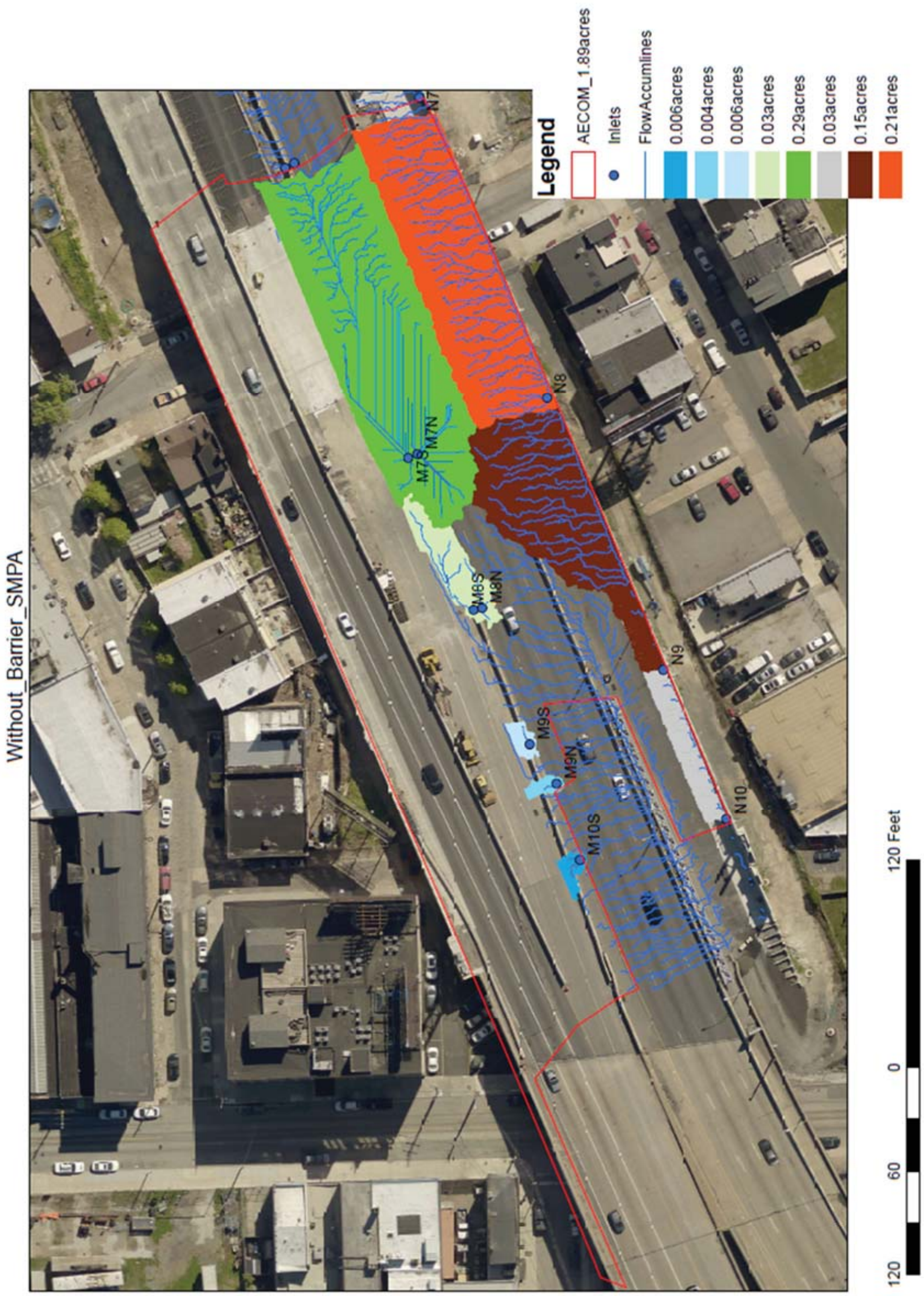


*Figure E-3: Drainage areas for Basins C, D, and G, calculated from flow routing of LiDAR elevation surveys without consideration of highway barriers. The location of the highway drains was used as the capture point for outflow. The central highway drains currently appear to be blocked so those areas are not included in operational (construction-phase) capture areas.*

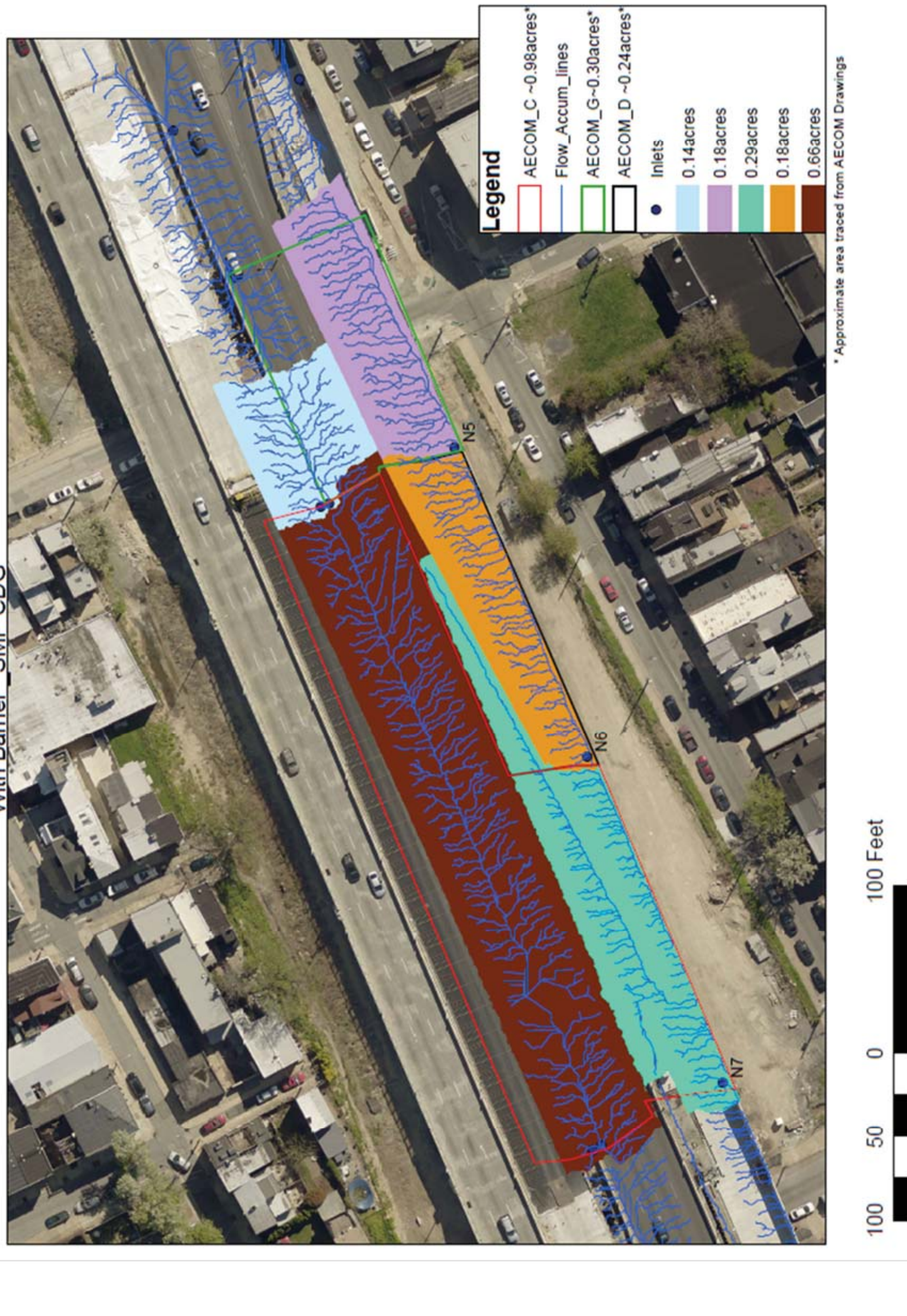
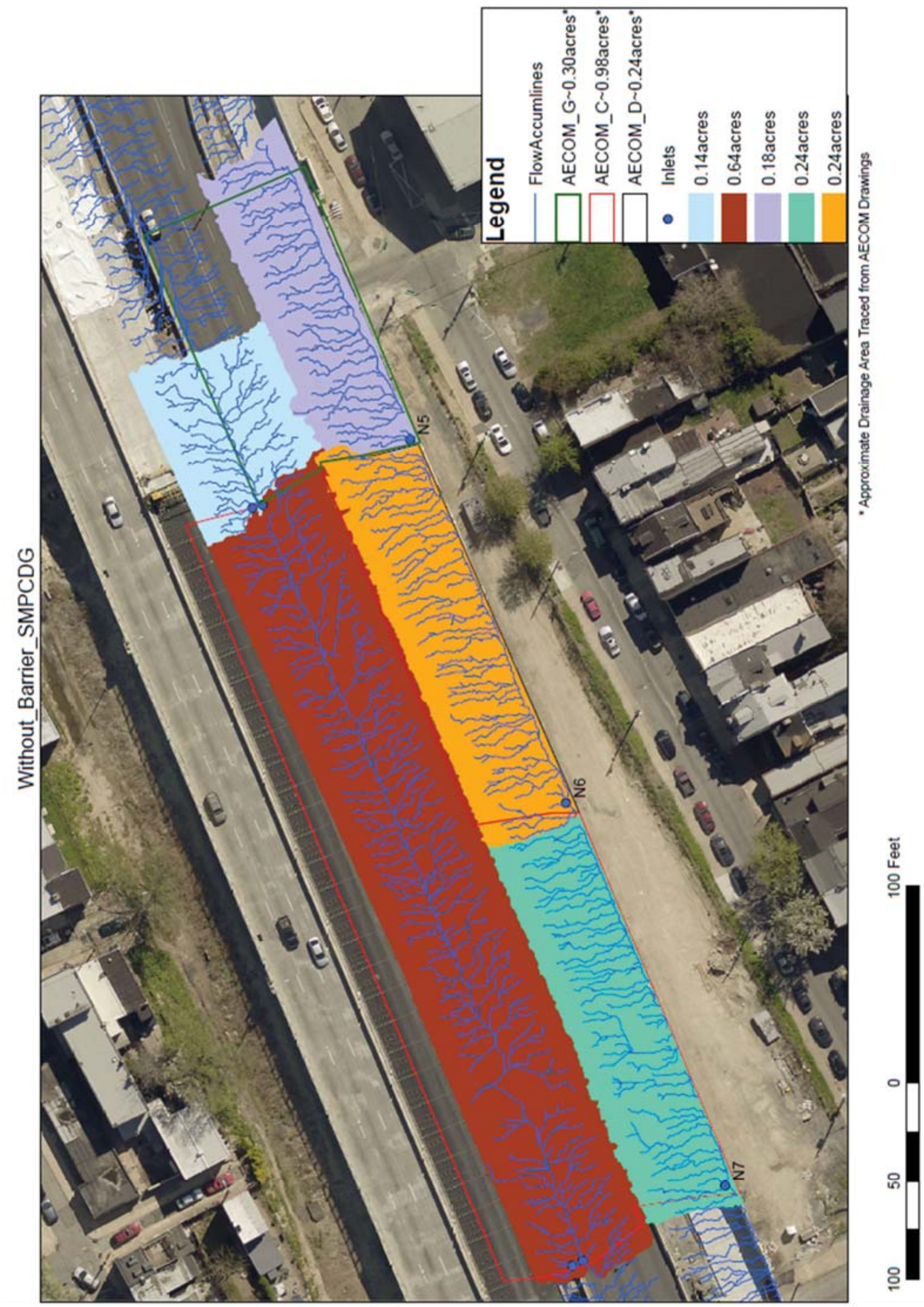


*Figure E-4: Drainage areas for Basins C, D, and G, calculated from flow routing of LiDAR elevation surveys including rerouting due to highway barriers. These barriers were in place for most of the storms in the monitoring period. The location of the highway drains was used as the capture point for outflow. The central highway drains currently appear to be blocked so those areas are not included in operational (construction-phase) capture areas.*



**Loading calculations**

Loading calculations were updated and summarized for the first year of study. Along with the ranges in influent concentrations, these data help evaluate initial performance in the basins and provide comparisons with literature values. The total loads (mass) for each storm sampled in Basins C and D were calculated using an estimated event mean concentration (EMC), total rainfall depth and runoff area (Eq. E-1).

$$Storm\ Load\ = EMC\ \times Rainfall\ \times Area \qquad \text{Eq. E-1}$$

The EMC is the flow-weighted average concentration sampled over the course of a storm (Appendix 3). In this equation, the drainage area for each basin was the capture area for corresponding inlet pipes (N7 to Basin C and N6 to Basin D; Table E-2 and Figure E-4). This table updates previous calculations in the main report. The annual load (mass per year) was estimated by summing the loads of the sampled storms then normalizing the rainfall of the sampled storms to the annual rainfall (Eq E-2). Normalization was needed because not all storms in the year were measured. The annual loads were divided by the basin surface areas for comparison with literature values reported in load per unit area.

$$Annual\ Load\ = \sum Storm\ Load\ \times \frac{Average\ Annual\ Rainfall}{Rainfall\ for\ Storms\ Sampled} \qquad \text{Eq. E-2}$$

Contaminant concentrations measured in influent to the SMPs were compared with values reported in the literature (International BMP Database, 2016). The concentrations of suspended solids and total phosphorous measured in the study were within the range reported in the literature, and within the lowest quartile. The nitrate concentration exceeded the values reported in the literature, presumably because of the particular nature of the influent at this site. Nitrate in stormwater runoff from highways is reported to be higher than in residential areas (Burton and Pitt, 2002).

The calculated annual loadings were compared to literature values for urban runoff (EPA, 1976) and to loads per unit area reported in Burton and Pitt (2002) and Shaver et al., (2007). The loads per unit area reported in these studies were multiplied by the Basin C and D basin areas similar to Eq E-2 for comparison (Appendix 3). Note that the units for the EPA data base were ambiguous in that they reported Total N, but did not specify whether it was inorganic N only (which would be mostly nitrate) or both inorganic and organic. The more recent data on nitrate loadings from Burton and Pitt and Shaver fell in the same range, so it may be that the EPA data are inorganic N and comparable. However, given this uncertainty caution is needed in comparing the literature loading values for nitrogen. Suspended solids and total phosphorus loads in Basin C were on the lower end of the reported range while nitrate loads exceeded the maximum reported value. In Basin D, suspended solids were below the minimum reported value, total phosphorus was on the low end of the reported range and nitrate was in the middle of the reported range.

Typical removal efficiencies for bioswales (National Pollutant Removal Performance Database, 2007) are provided for context only because the absence of outlet flows from the SMPs precludes the calculation of removal efficiencies. In effect, the resulting removal efficiency in Basins C and D was 100%. Literature values for removal efficiency range up to 65 to 98%, but can be much lower. Note that negative efficiency occurs when the outlet concentration (or load) is greater than the inlet concentration (or load).

*Table E-3: Median concentrations and annual loads observed in Basins C and D, based on storms captured bet Aug 29, 2017. Literature values for concentration and efficiency reported from the International BMP database*

| Contaminant | Conc. measured in SMP[a] (mg/L) ***median [min-max]*** | Conc. reported in literature[b] (mg/L) ***median [min-max]*** | Load measured in SMP[c] (lbs) ***median [min-max]*** | Total load measured in SMP[d] (lbs) | Predicted annual load[e] (lbs/yr) | Annual load per surface area measured in SMP (lbs/yr/ac) | Annual loa per area reported in literature f urban run (lbs/yr/ac) ***mean [min max]*** |
|---|---|---|---|---|---|---|---|
| **SMP C Contributing Drainage Area[h] = 0.29 ac Basin Surface Area = 0.1 ac** | | | | | | | |
| **Suspended Solids** | 80 [0.0-845] | 40.6 [2-1200] | 0.54 [0.02-2.7] | 7.7 | 79.5 | 274.2 | 1784 [441-4461] |
| **Nitrate or TN** | 1.83 [0.63-7.17] Nitrate | 0.35 [0.06-1.2] Nitrate | 0.01 [0.001-0.04] Nitrate | 0.1 Nitrate | 1.3 Nitrate | 4.7 Nitrate | 4.5 [1.8-18] TN |
| **Total Phosphorus** | 0.22 [0.066-0.83] | 0.13 [0.01-2.0] | 0.001 [0.00007-0.004] | 0.01 | 0.2 | 0.7 | 0.7 [0.2-4.5] |
| **SMP D Contributing Drainage Area[h] = 0.18 ac Basin Surface Area = 0.05 ac** | | | | | | | |
| **Suspended Solids** | 41 [0.0-600] | 40.6 [2-1200] | 0.22 [0.009-1.7] | 3.4 | 35.7 | 198.5 | 1784 [441-4461] |
| **Nitrate or TN** | 1.07 [0.13-6.63] Nitrate | 0.35 [0.06-1.2] Nitrate | 0.004 [0.0006-0.01] Nitrate | 0.04 Nitrate | 0.5 Nitrate | 2.7 Nitrate | 4.5 [1.8-18] TN |
| **Total Phosphorus** | 0.11 [0.057-0.83] | 0.13 [0.01-2.0] | 0.0006 [0.00004-0.002] | 0.005 | 0.1 | 0.5 | 0.7 [0.2-4.5] |

a. Influent concentrations for storms sampled from Oct 27, 2016 to Aug 29, 2017.

b. Source: International BMP Database (2016).

c. Median [minimum-maximum] load for storms sampled from Oct 27, 2016 to Aug 29, 2017 and calculated using the ope (construction phase) contributing drainage areas.

d. Total load for the storms sampled from Oct 27, 2016 to Aug 29, 2017.

e. Annual load estimated based on average annual rainfall in the Philadelphia area.

f. Source: EPA (1976), Burton and Pitt (2002), Shaver et al., (2007) Nitrogen concentrations reported in the EPA report di
they included organic nitrogen or inorganic only so numbers are gray to indicate literature values may be higher than for n

g. Source: National Pollutant Removal Performance Database (2007).

h. Drainage area determined by LiDAR measurement.

**Plants and maintenance**
Species selection and placement are critical to maximizing plant performance (i.e., survival, growth, health, and flowering) in vegetated SMPs. We conducted two sets of studies assessing plant performance in the SMPs within GR2. First, we inventoried the intentionally planted vegetation in basins A, C, D, G, E and part of F to assess survival and health of the 56 species present. Over 8100 plants were included in the inventories, which occurred twice: approximately one year after planting and then after the plants had experienced two winters in the SMPs. The overall survival rate was approximately 80%, though varied considerably across plant life forms, species, and locations within the SMPs.

Second, we conducted in-depth investigations of the growth and physiological health of nine species that spanned the gradient of exposure to stormwater within the basins. Based on the information from the two studies (detailed in Chapter 7) and additional reports of the species' preferences from other sources, we report here ratings of the suitability of each species for placement in low elevation and mid to high elevation areas within PennDOT's SMPs (Table E-4). We rate suitability separately by elevation because environmental conditions can vary substantially within basins, with low elevation areas experiencing much greater inundation and exposure to salts, trace metals, and other contaminants, and higher elevation areas experiencing limited water availability. Continued monitoring would make it possible to evaluate the effects of long-term exposure to environmental stressors and to differentiate the effects of stressors on widely used species.

Temple University hired a landscaping contractor (Terraquabor, LLC) to carry out the maintenance and inspection needs of the five SMPs in GR2. Maintenance included weeding, pruning, trash and debris removal, as well as re-mulching as needed. The cost of their services provides a means of projecting maintenance and inspection costs into the future (Table E-5). However, one of the recommendations we make is to increase the frequency of some aspects of maintenance, including weeding and trash collection, which will inevitably increase the cost. We also recommended adjusting the timing of some maintenance tasks (Table E-6). We note that cost estimates do not account for reconstruction or major replanting, which will be necessary intermittently.

*Table E-4: Species rankings and suggested species for different environments within the basin. The rating syste… (green), moderately suited (yellow) and not well suited (red) to the conditions listed.*

| *Inventoried Plant Species* | | | | | |
|---|---|---|---|---|---|
| **Code** | **Plant type** | **Scientific name** | **Common name** | **Suitability at mid to high elevation** | **Suitability at low elevation** |
| N | Bulb | *Narcissus* 'Ice follies' | Daffodil | Green | Red |
| KA | Graminoid | *Calamagrostis × acutiflora* 'Karl Foerster' | Karl foersters feather reed grass | Green | Yellow |
| CL | Graminoid | *Carex lupulina* | Hop sedge | Yellow | Green |
| CVA | Graminoid | *Carex muskingumensis* 'Oehme' | Variegated palm sedge | Yellow | Green |
| CV | Graminoid | *Carex vulpinoidea* | Fox sedge | Yellow | Green |
| PA | Graminoid | *Pennisetum alopecuroides* 'Hameln' | Dwarf fountain grass | Green | Red |
| AC | Perennial | *Achillea millefolium* 'Coronation gold' | Yellow yarrow | Green | Red |
| AF | Perennial | *Achillea millefolium* 'Fireland' | Fireland yarrow | Green | Red |
| AI | Perennial | *Asclepias incarnata* 'Ice ballet' | Swamp milkweed | Yellow | Yellow |
| AN | Perennial | *Aster novae-angliae* 'Purple dome' | New england aster | Green | Red |
| CH | Perennial | *Cimicifuga ramosa* 'Hillside black beauty' | Autumn snakeroot | Red | Red |
| EP | Perennial | *Echinacea purpurea* | Purple cone flower | Green | Red |
| GG | Perennial | *Gaillardia × grandiflora* 'Kobold' | Indian blanket | Green | Red |
| GM | Perennial | *Geranium maculatum* | Wild geranium | Red | Red |
| HM | Perennial | *Helenium autumnale 'Mardi gras'* | Mardi gras perennial sunflower | Green | Red |
| HHR | Perennial | *Hemerocallis* 'Happy returns' | Happy returns daylily | Green | Yellow |
| HRR | Perennial | *Hemerocallis* 'Rosy returns' | Rosy returns daylily | Green | Yellow |
| HI | Perennial | *Hosta* 'Ice follies' | Ice follies hosta | Green | Red |
| HR | Perennial | *Hosta* 'Royal standard' | Royal standard standard hosta | Yellow | Red |
| IP | Perennial | *Iris pseudacorus* 'Variegata' | Variegated water iris | Yellow | Green |
| IS | Perennial | *Iris sibirica* 'Caesar's brother' | Caesar's brother iris | Yellow | Green |
| IV | Perennial | *Iris versicolor* | American blue flag iris | Yellow | Yellow |
| LS | Perennial | *Liatris spicata* | Blazing star | Green | Red |
| MA | Perennial | *Matteuccia struthiopteris* | Ostrich fern | Red | Red |
| MC | Perennial | *Monarda* 'Cambridge scarlet' | Cambridge scarlet beebalm | Green | Red |
| RF | Perennial | *Rudbeckia fulgida var. sullivantii* 'Goldsturm' | Black-eyed Susan | Green | Red |
| TO | Perennial | *Tradescantia ohiensis* | Ohio spiderwort | Green | Red |
| AM | Shrub | *Aronia melanocarpa* 'Autumn magic' | Autumn magic black chokeberry | Green | Green |
| BT | Shrub | *Berberis thunbergii atropurpurea* | Crimson pygmy barberry | Red | Red |
| LB | Shrub | *Calycanthus floridus* | Carolina allspice | Green | Red |
| CA | Shrub | *Cornus alba* 'Sibirica' | Red twig dogwood | Green | Yellow |
| CS | Shrub | *Cornus sericea* 'Cardinal' | Red-osier dogwood | Green | Yellow |

*Table E-4 (continued)*

| ***Inventoried Plant Species*** | | | | | |
|---|---|---|---|---|---|
| **Code** | **Plant type** | **Scientific name** | **Common name** | **Suitability at mid to high elevation** | **Suitability at lo elevation** |
| FS | Shrub | *Forsythia suspensa sieboldii* | Siebold weeping forsythia | 🔴 | 🔴 |
| HV | Shrub | *Hamamelis vernalis* | Vernal witchhazel | 🟢 | 🔴 |
| IH | Shrub | *Itea virginica* 'Little Henry' | Virginia sweetspire dwarf | 🟢 | 🟡 |
| JH | Shrub | *Juniperus horizontalis* 'Blue chip' | Blue chip juniper | 🟢 | 🔴 |
| KJ | Shrub | *Kerria japonica* 'Pleniflora' | Japanese kerria | 🔴 | 🔴 |
| RH | Shrub | *Rhus aromatica* | Fragrant sumac | 🟢 | 🔴 |
| RR | Shrub | *Rosa rugosa* | Rugosa rose | 🟢 | 🔴 |
| VT | Shrub | *Viburnum trilobum* 'Wentworth' | American cranberrybush | 🟢 | 🟡 |
| YB | Shrub | *Yucca* × 'Bright edge' | Variegated adam's needle | 🟢 | 🔴 |
| AP | Tree | *Acer platanoides* 'Crimson king' | Crimson king maple | 🟢 | 🔴 |
| AA | Tree | *Amelanchier arborea* | Common serviceberry | 🟢 | 🔴 |
| AG | Tree | *Amelanchier* × *grandiflora* 'Autumn brilliance' | Autumn brilliance serviceberry | 🟢 | 🔴 |
| BN | Tree | *Betula nigra* 'Heritage' | Heritage river birch | 🟢 | 🟡 |
| CC | Tree | *Cercis canadensis* | Redbud | 🟢 | 🔴 |
| CP | Tree | *Crataegus phaenopyrum* | Washington hawthorne | 🟢 | 🔴 |
| CW | Tree | *Crataegus viridis* 'Winter king' | Winter king hawthorne | 🟢 | 🔴 |
| FJ | Tree | *Juniperus chinensis 'Hetzii columnaris'* | Fairview juniper | 🟢 | 🔴 |
| PP | Tree | *Picea pungens* | Colorado spruce | 🟢 | 🔴 |
| PN | Tree | *Pinus nigra* | Austrian pine | 🟢 | 🔴 |
| TE | Tree | *Thuja occidentalis* 'Emerald green' | Emerald green arborvitae | 🟢 | 🔴 |
| TH | Tree | *Thuja occidentalis* 'Holmstrup' | Holmstrup arborvitae | 🟢 | 🔴 |
| TW | Tree | *Thuja occidentalis* 'Wintergreen' | Wingergreen arborvitae | 🟢 | 🔴 |

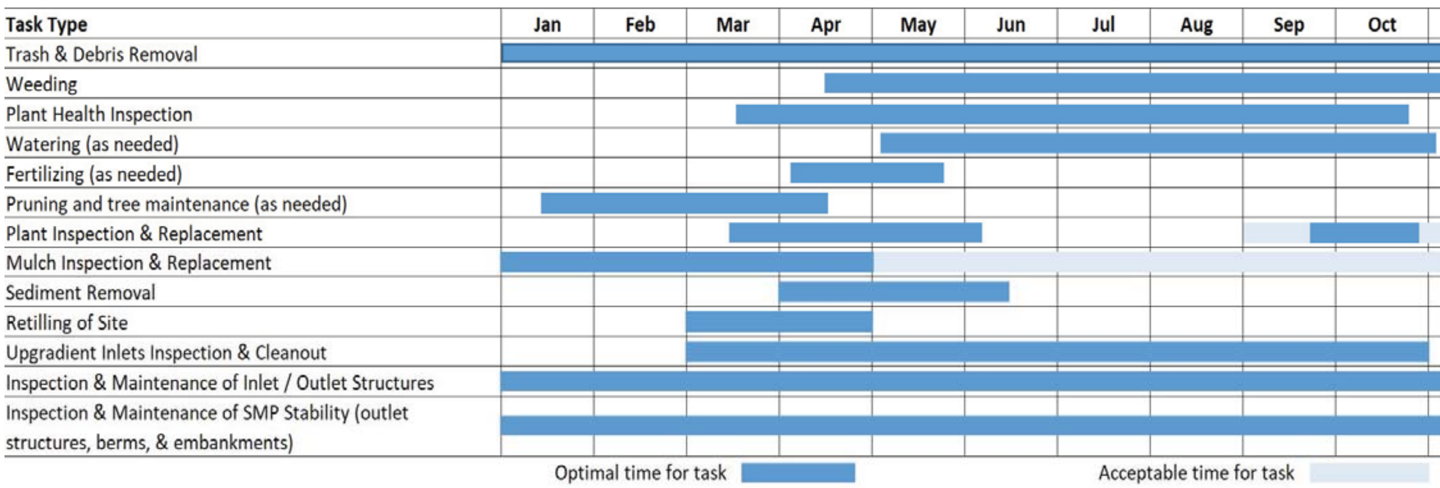
*Table E-4 (continued)*

| ***Suggested Plant Species*** | | | | | |
|---|---|---|---|---|---|
| **Species type** | **Scientific name** | **Common name** | **Suitability at mid to high elevation** | **Suitability at low elevation** | **Notes** |
| Graminoid | *Acorus calamus* | Sweetflag | ● (red) | ● (green) | Requires freq |
| Graminoid | *Ammophila brevigulata* | Beach grass | ● (green) | ● (yellow) | Requires sanc |
| Graminoid | *Carex stricta* | Tussock sedge | ● (red) | ● (green) | |
| Graminoid | *Juncus effusus* | Common rush | ● (red) | ● (green) | |
| Graminoid | *Panicum amarum* | Bitter panic grass | ● (green) | ● (red) | Salt tolerant |
| Graminoid | *Panicum virgatum* | Switch grass | ● (green) | ● (green) | Salt tolerant |
| Graminoid | *Scirpus cyperinus* | Woolgrass | ● (red) | ● (green) | |
| Perennial | *Chelone glabra* | Turtlehead | ● (yellow) | ● (green) | |
| Perennial | *Helianthus angustifolius* | Swamp sunflower | ● (yellow) | ● (green) | |
| Perennial | *Hibiscus moscheutos* | Rose mallow | ● (yellow) | ● (green) | Salt tolerant |
| Perennial | *Lobelia siphilitica* | Great blue lobelia | ● (yellow) | ● (green) | |
| Perennial | *Physostegia virginiana* | Obedient plant | ● (green) | ● (yellow) | |
| Perennial | *Pycnanthemum virginianum* | Virginia mountain mint | ● (yellow) | ● (green) | |
| Perennial | *Solidago sempervirens* | Seaside goldenrod | ● (yellow) | ● (green) | Salt tolerant |
| Shrub | *Baccharis halimifolia* | Eastern baccharis | ● (green) | ● (green) | |
| Shrub | *Clethra alnifolia* | Sweet pepperbush | ● (yellow) | ● (green) | Salt tolerant |
| Shrub | *Myrica pensylvanica* | Bayberry | ● (green) | ● (yellow) | Salt tolerant |
| Shrub | *Physocarpus opulifolius* | Ninebark | ● (green) | ● (red) | |
| Shrub | *Prunus maritima* | Beach plum | ● (green) | ● (red) | Salt tolerant |
| Shrub | *Rhododendron viscosum* | Swamp azalea | ● (yellow) | ● (green) | |
| Shrub | *Rhus copallinum* | Winged sumac | ● (green) | ● (red) | Salt tolerant |
| Shrub | *Rosa palustris* | Swamp rose | ● (yellow) | ● (green) | |
| Shrub | *Salix discolor* | Pussy willow | ● (yellow) | ● (green) | Salt tolerant |
| Shrub | *Sambucus canadensis* | Elderberry | ● (yellow) | ● (green) | Salt tolerant |
| Tree | *Salix nigra* | Black willow | ● (yellow) | ● (green) | |

*Table E-5: Maintenance costs for landscaping contractor working on five basins.*

| | Current | Projected |
|---|---|---|
| Annual cost | $70,000 | $100,000 |
| Weeding frequency | 1/month | 2/month, April-Sept |
| Trash collection frequency | 1/month | 2/month, Year-round |

*Table E-6: Recommended maintenance schedule by month.*



**Highlights of recommendations after the first year of study**

- We recommend that drainage system design include consideration of performance during the intermediate construction stages for long term projects, and not just the final design requirements.
- We recommend that designers locate inlets where slight changes of slope will not cause stormwater to bypass inlets.
- We recommend that LiDAR and monitoring be used to demonstrate that constructed surfaces are within tolerance before project acceptance, and for adjustments to correct for construction changes.
- We recommend that SRTs or rain event monitoring be required as part of SMP acceptance.
- We recommend that SMP's be designed to support instrumentation for temporary monitoring of performance and maintenance activities.
- SMP media can be replaced or managed to prioritize infiltration performance and underlying water quality rather than concerns of remobilization within the SMP
- The observation of preferential flow paths emphasizes the importance of planting vegetation in the basins to reduce preferential flow paths and render the flow more turbulent, thereby increasing mixing and reducing the magnitude of surface water hotspots.
- Based on the plant survival data collected thus far, there are three species whose use should be avoided or reserved for shaded and minimally stressful regions of the SMPs. These are *Cimicifuga ramosa*, *Geranium maculatum*, and *Matteuccia struthiopteris*
- Given the difficult growing conditions found at the lowest elevations within SMPs, we recommend planting additional species that are known to tolerate periodic inundation.
- Regardless of the reason, many installers will replace individuals that die within a year of planting; we recommend that this provision be noted when contracting with installers and that it be enforced.
- We recommend avoiding the use of known invasives in SMP plantings
- We recommend accommodating foot traffic in the design strategy to reduce erosion, soil compaction, and damage to plants.
- We recommend that the depth of amended soil in upper areas of SMPs be increased, which could be accomplished by ensuring that the current design specification is enacted.
- We recommend that weeding be conducted every two weeks, and that the maintenance manual be updated to reflect this. However, frequent weeding (perhaps even weekly) along the fences of neighboring residences and businesses could be an important way to maintain positive relations with neighbors.
- We recommend that motorized weeding devices be allowed during restricted hours of the day in certain cases where weed removal is prohibitively difficult with manual tools and hand pulling and that targeted herbicide application be used.
- We recommend that inflow pipes continue to be elevated where possible, and that a low-cost, maintenance-friendly trash collection system be developed to capture small pieces of trash.
- With respect to larger litter and debris items, the maintenance manual currently specifies that they should be removed monthly; we recommend increasing the frequency to at least every two weeks in this highly urban setting.

- Adding signage about dog waste negatively impacting water quality would inform the community and making it as easy as possible for dog owners to collect and dispose of their dog's waste could also help mitigate the problem
- We recommend modifying inlet spillways to be able to dissipate energy and reduce water velocities.
- We recommend decreasing the slopes of SMP sidewalls when they are initially dug out to better support root establishment.
- In future installations, we recommend that a more thorough evaluation of subsoil conditions be conducted prior to the installation of amended soil
- Actively engaging the community in SMP management could be an effective strategy for both increasing the person-hours dedicated to maintaining the vegetation and litter in BMPs and decreasing the labor costs.

The SMPs along the Girard Avenue Interchange have proven to be successful in many ways. They are capturing stormwater together with the contaminants it carries, thereby preventing either from entering the municipal stormwater system and being released into the Delaware River. Moreover, much of the vegetation has successfully established and promises to beautify the neighborhood for years to come. Our data-intensive investigation has highlighted several ways in which the design and maintenance of SMPs can be improved while minimizing the associated costs. The analyses and recommendations provided here are an initial synthesis of our ongoing effort; we expect the empirical and modeling processes that we have developed to facilitate many further insights and suggestions that can be put into practice in future phases of SMP design, installation, and management.

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