# BROADVIEW GREEN GRID NATURAL DRAINAGE SYSTEM

# PERFORMANCE MONITORING

Prepared for

Seattle Public Utilities

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PROJECT DESCRIPTIONS

Seattle Public Utilities (SPU) has been building various natural drainage systems to reduce peak runoff rates and volumes and improve stormwater quality. Natural drainage systems (NDS) are vegetated water retention areas and swales designed to infiltrate runoff into the soil or evaporate or transpire it to the atmosphere as a vapor, and to improve the water quality of any remaining runoff before it reaches the receiving water body. Often called bioretention, this technique is a central component of any low impact development (LID) program. The ultimate goal is to bring about an urban hydrology resembling predeveloped conditions, targeting a predeveloped pasture condition (City of Seattle 2006).

Seattle's NDS initiative began with retrofits in the northwestern area of the City where drainage is mostly in open street ditches instead of below-ground pipes. Three natural systems (2nd Avenue NW Street Edge Alternatives (SEA) Street, Viewlands Cascade, and NW 110th Street Cascade) have been in service for 45-7 years. The Broadview Green Grid was completed in stages over the two years, with full completion in spring 2005. Additional systems are being considered for the NW 120th Street area. Outside the Pipers Creek watershed, SPU installed similar natural drainage systems in the redeveloped High Point Seattle Housing Authority project in the Longfellow Creek Watershed and in the Pinehurst area of the Thornton Creek watershed.

The first SEA Street project, located on 2nd Avenue NW between NW 117th and NW 120th Streets, set the tone for projects of this type. The street was redesigned to reduce impervious cover, as well as traffic speeds, while converting previous asphalt and gravel right of way to vegetated swales and detention areas. Built largely in compost-amended soils, this natural drainage system was designed to reduce peak runoff rates and volumes conveyed to the creek, and also convey the peak 25-yr, 24-hour storm event. While providing these environmental benefits, the system landscaping was also intended to offer a neighborhood aesthetic benefit.

The Viewlands Cascade, located on NW 105th Street between 3rd Avenue NW and 5th Avenue NW, is designed to convey flows up to the 25-year, 24-hour peak rate and route them to an existing inlet. An open channel design with check dams was selected to attenuate peak flows to prevent overflows into a natural ravine. Unlike the SEA Streets project, the Viewlands Cascade had no soil amendment. Although not a specific design objective, both projects were expected to provide water quality benefits through contact with the vegetation and soil in the swale, as well as by loading reduction in association with the infiltration and evapotranspiration losses.

A second cascade was built during 2002 and 2003 along NW 110th Avenue between Greenwood Avenue N and 3rd Avenue NW. Soils were amended in this case with the hope of improving runoff peak flow rate and volume attenuation. The principal flow to this system is from the Greenwood Avenue N arterial, but it also gets runoff from the adjacent north-south avenues and NW 110th Street. The 110th Cascade began receiving runoff in 2003.

The next project was a network of natural drainage systems in the SEA Streets style built on the relatively flat north-south avenues north of NW 107th Street. This network is known as the

Broadview Green Grid (BGG). It drains to another cascade designed similarly to the NW 110$^{th}$ Cascade and was installed along NW 107$^{th}$ in 2005. This report covers flow and water quality monitoring at the discharge end of the NW 107$^{th}$ Street Cascade. This station represents the output of the combined Broadview Green Grid and NW 107$^{th}$ Cascade system.

## PERFORMANCE MONITORING

The University of Washington (UW) began flow monitoring at 2$^{nd}$ Avenue NW and Viewlands in 2000. The initial 2$^{nd}$ Avenue NW monitoring measured discharge from the original street, before the SEA Street project was built, and thus represents the baseline period for comparison with flows from the new street. That construction finished in early 2001. Flow monitoring commenced again immediately and continued through June 2007.

The Viewlands Cascade was built before any baseline monitoring could occur. For more than two years both inflows and outflows were monitored, until the performance of that system was well demonstrated. From that point on, only inflows were monitored (through June 2007), to assist in hydrologic model development. Reports by Miller (2001); Miller, Burges, and Horner (2001); and Horner, Lim, and Burges (2002, 2004) cover performance monitoring of these first two natural drainage systems.

From 2002 to 2004 the UW turned to monitoring at NW 107$^{th}$, NW 120$^{th}$, and NW 122$^{nd}$ Streets. This work provided baselines for the natural drainage systems subsequently constructed upstream from the NW 107$^{th}$ Street monitoring point and planned, but not yet built in the vicinity of NW 120$^{th}$ and NW 122$^{nd}$ Streets. The NW 107$^{th}$ and NW 120$^{th}$ Street stations, both at low elevations in their respective watersheds, also provided information on the quality of storm runoff from conventional drainage systems. The NW 122$^{nd}$ Street site represents runoff water quality at a point near where it flows off Greenwood Avenue N, the major traffic arterial in the area, and enters these systems. Engstrom (2004) provided the data collected during the 2002-2004 period. Chapman (2006) continued monitoring at NW 120$^{th}$ Street and updated the data collected there.

The first monitoring effort on a finished Seattle natural drainage system project to include both flow and water quality measurements was on the NW 110$^{th}$ Street Cascade during the years 2004 to 2006. Chapman (2006) is the source for complete details and the full database on that monitoring, which was summarized by Horner and Chapman (2007).

In the fall of 2006 the UW returned to work at NW 107$^{th}$ Street to monitor the performance of the Broadview Green Grid and new cascade over the succeeding two years. This report presents the results of that study.

## BROADVIEW GREEN GRID AND NW 107$^{TH}$ STREET CASCADE MONITORING OBJECTIVES

The NW 107$^{th}$ Street monitoring program was structured to determine:

- The effectiveness of the combined Broadview Green Grid and NW 107$^{th}$ Cascade system at reducing the volumes and peak flow rates of both wet-season and dry-season storms; and

- The effectiveness of the system at reducing water pollutant discharges, and how its discharges compare to those from a conventional drainage system.

## MONITORING LOCATIONS AND METHODS

## DESCRIPTION OF THE BROADVIEW GREEN GRID AND NW 107$^{TH}$ STREET CASCADE AND THE DRAINAGE CATCHMENT

The BGG is a network of natural drainage systems that were constructed between Phinney Avenue N and 4$^{th}$ Avenue NW along the north-south avenues between NW 107$^{th}$ Street and NW 110$^{th}$ Street. The north-south avenues were constructed in a style similar to the SEA Street project, reducing impervious area and traffic speeds while creating swale areas for conveyance and bioretention. The network drains to a cascade along NW 107$^{th}$ Street, which has an open channel design with check dams, designed primarily with biofiltration concepts but with 3-6 inches (7.6-15.2 cm) of permanent pool storage below the water quality flow-through depth. Cascades are used primarily in steep areas where substantial weirs are needed to create relatively flat-bottomed vegetated swale cells. Because of high flow velocities and the potential for scouring, the surface of the amended soils area was covered with approximately 3 inches (7.6 cm) of rock. The entire BGG and NW 107$^{th}$ Cascade system drains approximately 32 acres (13 hectares) (http://www.seattle.gov/util/About_SPU/Drainage_&_Sewer_System/Natural_Drainage_Systems/Broadview_Green_Grid_Project/index.asp). The system was designed to reduce peak runoff rates and volumes and provide water quality benefits through infiltration and evapotranspiration promoted by runoff contact with vegetation and compost-amended soils, as well as offer neighborhood aesthetic advantages through system landscaping.

Figures 1 and 2 provide an aerial photograph and street map of the BGG area, respectively. The overall catchment contributing drainage to the system extends generally along the entire lengths running between NW 107$^{th}$ and 110$^{th}$ Streets of the north-south Phinney N, Palatine N, 1$^{st}$ NW, and 2$^{nd}$ NW Avenues and half or more of Greenwood N and 3$^{rd}$ NW Avenues, as well as all along NW 107$^{th}$ from its center crown north.

Figures 1 and 2 show the locations of flow monitoring stations NS003-007. NS003 is located in a pipe in the Cascade system along N 107$^{th}$ Street between Phinney Avenue N and Greenwood Avenue N. It measures upstream flow in the Cascade and the incoming flow from the Phinney Avenue N. SEA Street. NS004 is beneath a weir in the Cascade system along N 107$^{th}$ Street between Greenwood Avenue N and Palatine Avenue N and measures upstream flow in the Cascade and flow from Greenwood Avenue N. NS005 is located in a pipe in the SEA Street system along 2$^{nd}$ Avenue NW that outlets into the Cascade system along NW 107$^{th}$ Street. It measures flow on 2$^{nd}$ Avenue NW between NW 110$^{th}$ Street and NW 107$^{th}$ Street. NS007 is in an outfall at the end of the Cascades system at the northeast corner of NW 107$^{th}$ Street and 4$^{th}$ Avenue NW. It measures all upstream flow into the Cascade. NS006, downstream of the Cascade on the west side of 4$^{th}$ Avenue NW, houses automated water sampling equipment and an associated flow meter. It is subject to an unmeasured flow, untreated by a natural drainage system, from a catchment area of approximately 0.5 acre (0.2 hectare) running north along 4$^{th}$ Avenue NW and west along NW 107$^{th}$.

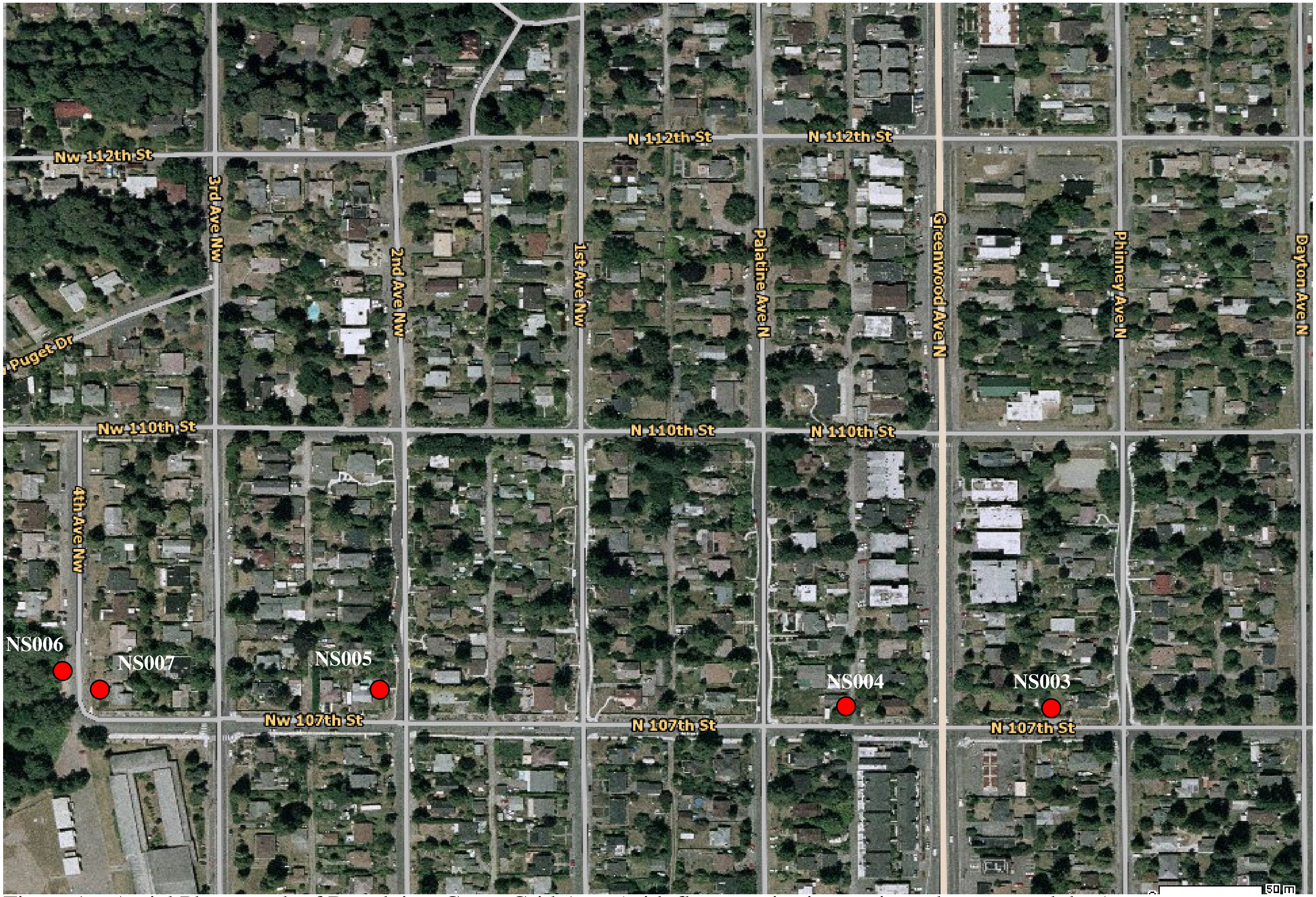

Figure 1. Aerial Photograph of Broadview Green Grid Area (with flow monitoring stations shown as red dots)

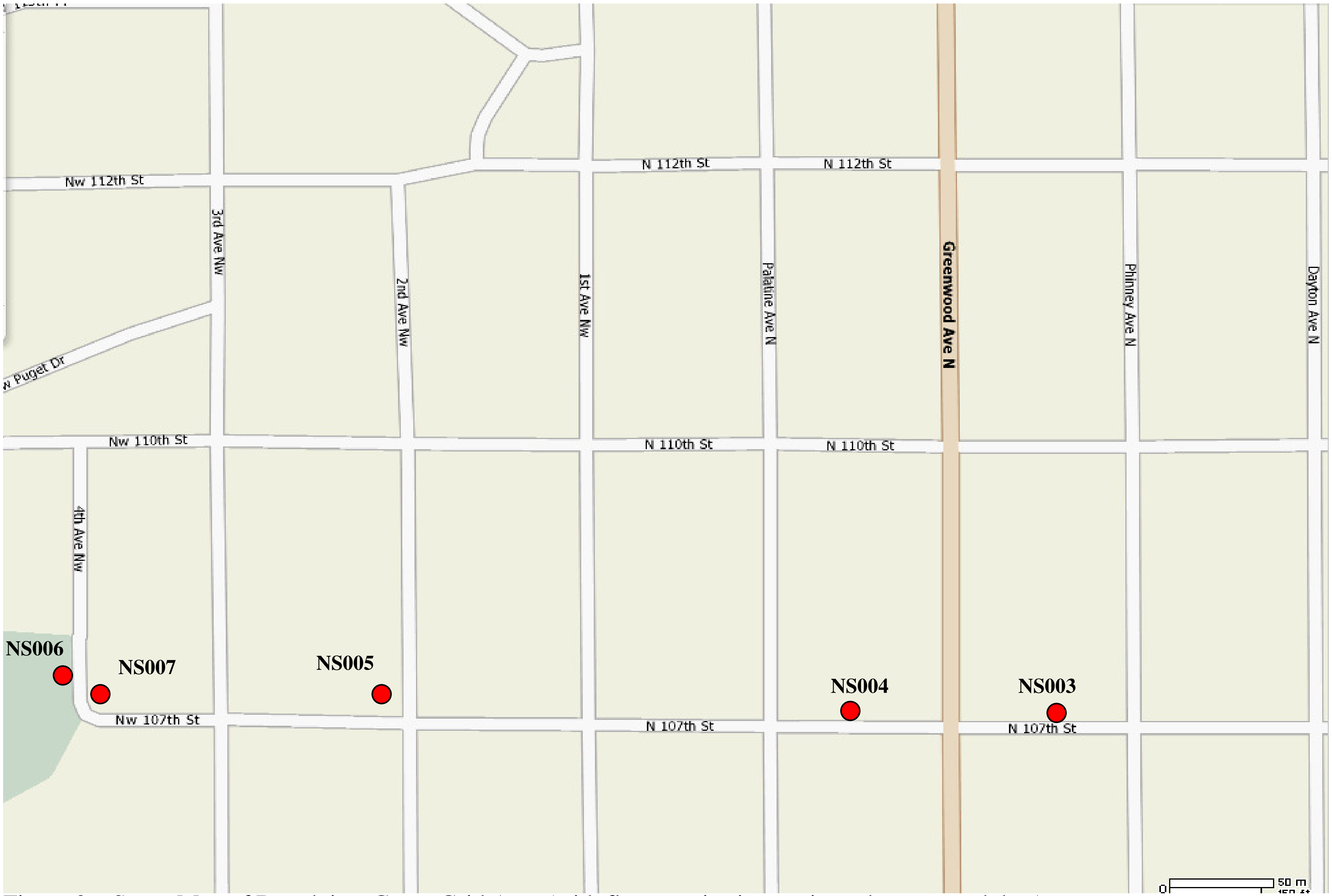


Figure 2. Street Map of Broadview Green Grid Area (with flow monitoring stations shown as red dots)

# MONITORING EQUIPMENT AND PROCEDURES

## Flow Measurement

Stations NS003-005 and 007 utilized Druck pressure transducer data recorded by Campbell Scientific model CR10x data loggers. Flow at station NS006 was measured with an ISCO Model 730 bubbler flow module, also used to pace the automatic water sampler.

## Flow-Weighted Composite Water Sampling

Monitoring equipment at station NS006 consisted of an ISCO Model 6700 automatic sampler, in addition to the ISCO Model 730 bubbler flow module. Run by a twelve-volt battery, each instrument has a programmable computer to, respectively, specify sample collection parameters and calculate and store flow data. The sampler computer operates a pump that takes water samples through a stainless steel strainer at programmed intervals and conveys them via Teflon-lined Tygon tubing to four one-gallon (3.79 L) jars held within the equipment housing. Flow modules collected continuous flow data at 5-minute intervals, whether or not the sampler was in operation.

For this sampling effort, a valid storm event was defined as follows:

- Total precipitation—minimum 0.15 inch (3.8 mm);
- Antecedent dry period—12 hours with less than 0.04 inch (1 mm) of rain; and
- Minimum storm duration—1 hour.

Samplers were programmed to collect flow-weighted composite samples, meaning a set sample volume was drawn each time a specific flow quantity was registered. This monitoring strategy truly represents overall storm event mean pollutant concentrations (EMCs, mass per unit volume) and mass loadings (mass per unit time). A valid sample was considered to be one consisting of a minimum of 10 sample aliquots representing at least 75 percent of the runoff hydrograph. Every effort was made to sample from the beginning of storms and meet these criteria.

The monitoring program operated from November 2006 through March 2008. Relatively few precipitation events created discharge during that period, and the resulting database hence was limited. Also, it is likely that the discharges that occurred were heavily influenced by the untreated and unmeasured inflow entering between the end of the Cascade and station NS006, which would compromise achieving the second objective set for the program.

## Water Quality Analyses

### *General Analyses and Methods*

Composite samples were analyzed for the following water quality variables according to the methods cited (American Public Health Association 2005 unless otherwise indicated):

- Field—Temperature (Hanna 9023C pH/temperature meter);
  pH (Hanna 9023C pH/temperature meter);

- Laboratory—Total suspended solids (TSS, 2540-D gravimetric);
  Total hardness (TH, 2340-B);
  Total phosphorus (TP, 4500-PF automated ascorbic acid);
  Soluble reactive phosphorus (SRP, 4500-PF automated ascorbic acid after filtering);
  Total (persulfate) nitrogen (TN, 4500-N);
  Total petroleum hydrocarbons (Diesel and motor oil, Washington Department of Ecology 1997); and
  Total recoverable and dissolved metals (copper, Cu; lead, Pb; zinc, Zn; U.S. Environmental Protection Agency 1983 200.8 inductively coupled plasma-mass spectrometry).

*Quality Assurance/Quality Control*

The monitoring work followed extensive quality assurance/quality control (QA/QC) procedures in both the field and the laboratory to ensure the validity of results. The full QA/QC program is described in the City of Seattle's (2006) Quality Assurance Project Plan. The major quantitative components were analyses of field and laboratory duplicates, laboratory spike samples, and equipment rinsate blanks.

Rainfall Data

Rainfall measurements were obtained from the existing rain gauges operated by the UW for SPU at Viewlands Elementary School, located near the intersection of 3rd Avenue NW and NW 105th Street. The station has two tipping bucket rain gauges, one flush with ground level and the other standing above ground level to judge wind effects, and a non-recording gauge for total rainfall. Installed in 2000, this station records other meteorological information (temperature, wind speed, relative humidity, net solar radiation, pan evaporation) in addition to rainfall.

## MONITORING RESULTS

### RUNOFF VOLUME AND PEAK FLOW RATE REDUCTION

Flow results are reported for station NS007, which is at the discharge of the BGG and NW 107$^{th}$ Cascade system and avoids the unmeasured side flow present at station NS006. In baseline monitoring before construction of the system, 80 of 105 storms (76.2 percent) discharged runoff. Monitoring of 274 storms after the system was in operation recorded discharge in 166, a reduction to 60.6 percent. Before construction, the existing street ditch network discharged more than 100 ft$^3$ (2.83 m$^3$) of runoff in 67.6 percent of the total storms and more than 1000 ft$^3$ (28.3 m$^3$) in 30.5 percent. The BGG and Cascade cut these percentages to 43.4 and 16.4 percent, respectively.

In the pre-construction monitoring period, 41.22 inches (1047 mm) of rain produced 343,111 ft$^3$ (9723 m$^3$) of discharge volume, a unit discharge ratio of 8324 ft$^3$/inch of rainfall (9.29 m$^3$/mm). The post-construction monitoring period had 112.83 inches (2866 mm) of precipitation and produced 278,858 ft$^3$ (7902 m$^3$) of discharge. The ratio of 2471 ft$^3$/inch (2.76 m$^3$/mm) was just 29.7 percent of production before the BGG and Cascade system went into service.

The overall runoff coefficients (ratio of discharge to rainfall) before and after construction were assessed by computing the total rainfall volumes over the 32-acre (13-hectare) watershed in the two periods and dividing by the measured discharge volumes. The results are 0.07 pre-construction and 0.02 post-construction, a decline the same as the drop in unit discharge ratio. These findings are notable not only for how much the BGG/Cascade system decreased the runoff coefficient but how low it was already in this medium-density urban neighborhood.

It was well established in the NW 110$^{th}$ Cascade monitoring program that the runoff coefficient in that adjacent neighborhood was 0.10-0.11 with the cascade in place (Horner and Chapman 2007). Without baseline monitoring in that catchment, the pre-construction runoff coefficient is unknown. It was obviously substantially higher than in the BGG area, but likely not as high as would ordinarily be expected in a neighborhood of this type. The NW 110$^{th}$ Cascade is not backed by a SEA-Streets type grid, and its catchment probably did not experience as great a drop in runoff coefficient as occurred in the BGG.

It should be noted, however, that potentially a significant portion of the rooftops may be connected to the sanitary sewer system. The drainage area is technically a fully separated basin, meaning that only wastewater can be plumbed into the sewer system. However, recent sanitary sewer system evaluation indicates that up to 50 percent of the rooftops may be connected to the sanitary sewer. SPU is evaluating this situation further and will establish if initial analysis is correct, and if a rooftop disconnection program will be pursued in this basin to reduce sewer overflows (Tackett, personal communication).

Another view of the performance of the natural drainage system is afforded by comparing it to the predecessor conventional network in relatively dry and wet antecedent conditions. Relatively dry was defined as ≤ 0.1 inches (2.5 mm) of rain in the 7 days preceding a storm, relatively wet as 0.5-1.5 inches (13-38 mm) in that period, and very wet as > 1.5 inch (38 mm) in the past week.  In relatively dry conditions the former drainage system always discharged with an event of 0.077 inch (2.0 mm) or more, in 91.6 percent of the cases producing at least 298 $ft^3$ (8.4 $m^3$) of volume.  With the BGG and Cascade it took at least 0.12 inch (3.0 mm) of rain to produce a discharge, which was no more than 105 $ft^3$ (3.0 $m^3$) in 50 percent of the cases.  After a relatively wet antecedent period the old and new systems did not act very differently from the standpoint of the minimum rainfall to create a discharge (0.06-0.07 inches [1.5-1.8 mm] in both cases). However, the unit discharge ratio differed by a factor of 1.33, at 5446 $ft^3$/inch of rain (6.07 $m^3$/mm) for the old system and 4090 $ft^3$/inch (4.56 $m^3$/mm) for the new one.  That advantage of the BGG/Cascade was accentuated further in very wet conditions, with the unit discharge rising to 6278 $ft^3$/inch (7.00 $m^3$/mm) in the former drainage network but dropping to 3513 $ft^3$/inch (3.92 $m^3$/mm) in the natural drainage system.  This difference represents a factor of 1.79.

In assessing these results it is seen that the rebuilt drainage is functioning to reduce the number of occasions when discharge occurs, but even more to cut the quantities discharged to Pipers Creek.  Moreover, the advantage of the natural drainage over the conventional system increases in the larger storms and wetter antecedent conditions, when it is most important to protect the stream from elevated flows.

As would be expected in considering the results reported thus far, the BGG and Cascade system also generally discharges lower peak flow rates than its predecessor.  Figures 3 and 4 plot peak flow rates versus event rainfall for the pre- and post-construction periods, respectively.  To provide a visual basis for comparison, each graph has a 45° line.  In the post-construction plot only one point falls well above the line, whereas many do in the pre-construction data set.

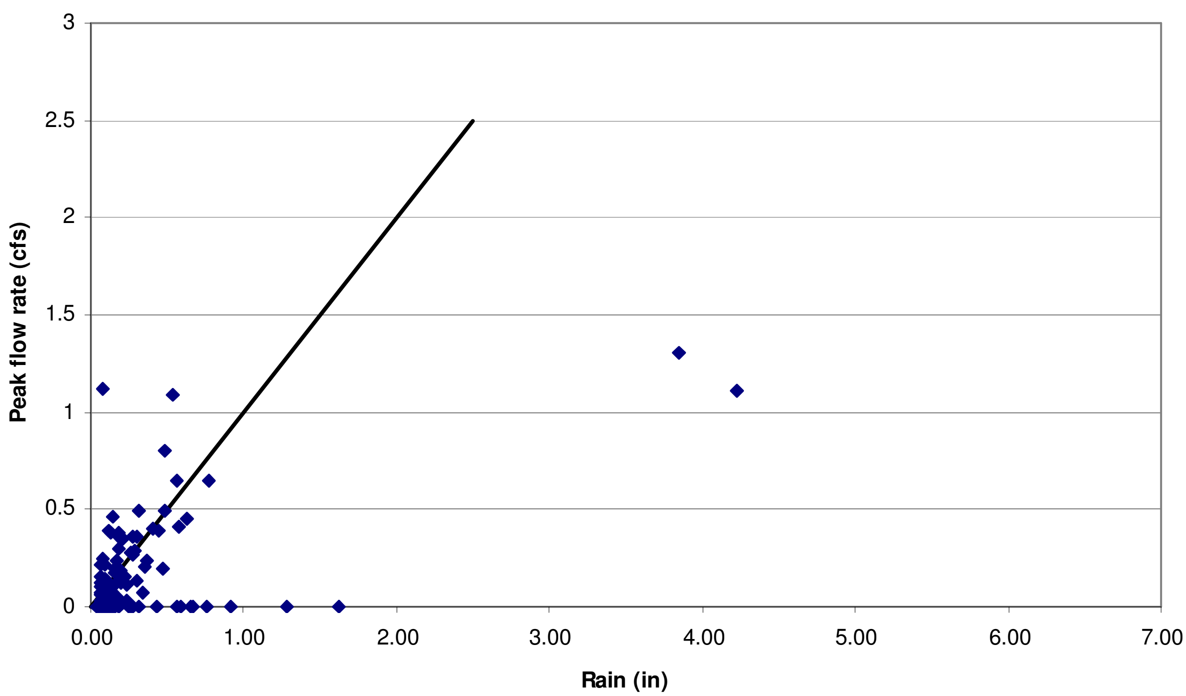


Figure 3.  Discharge Peak Flow Rates Relative to Event Rainfall for the Original Drainage System (The diagonal is a 45° line.)

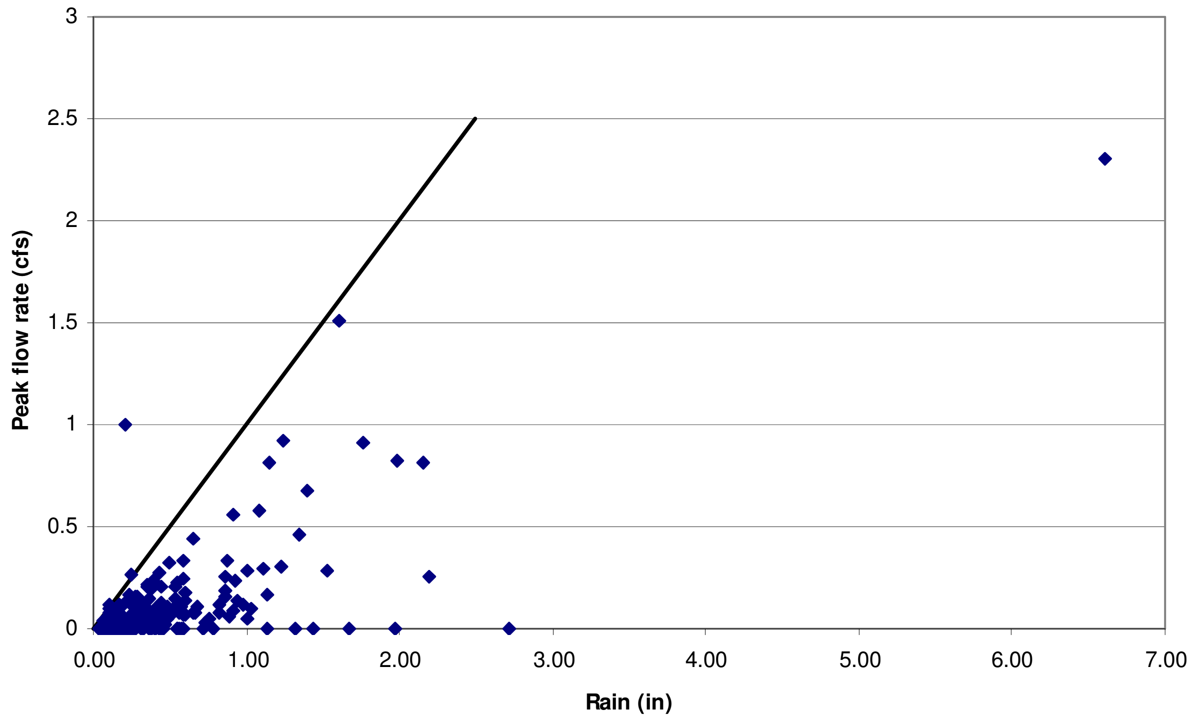


Figure 4. Discharge Peak Flow Rates Relative to Event Rainfall for the Broadview Green Grid and NW 107th Cascade Natural Drainage System (The diagonal is a 45° line.)

An analysis was attempted to compare total discharge volume, peak flow rate, and time to reach peak discharge for comparable storms at the BGG/NW 107th Cascade discharge point before and after construction of the system. Most interest was in performance during events occurring with approximately 1- to 2-year frequencies and having approximately 24 hour durations, representing common design bases for stormwater treatment systems. Unfortunately, there were no events of this description during pre-construction monitoring, and the two periods experienced storms generally differing in character. Therefore, this analysis did not add to the portrait of system performance presented here but is summarized in Appendix A. With the absence of comparable precipitation patterns, modeling would have to be performed to make the desired comparison between the BGG/NW 107th Cascade and the preexisting drainage system.

## WATER QUALITY PERFORMANCE

During the water quality monitoring period the NW 107th Cascade usually either did not flow to the end or discharged small quantities of runoff. Hence, there were limited opportunities to obtain samples, and only four were collected. This small number, coupled with variance in the data, produced relatively high coefficients of variation (ratio of standard deviation to mean), more than 0.5 for the majority of the water quality variables. The original intention was to make statistical comparisons between the BGG/Cascade and other nearby Pipers Creek subbasins monitored both before and after installation of natural drainage systems. However, the limited data set, for the BGG area and some other subbasins, and relatively high variance prohibited formal statistical assessments. Instead, comparison was based on ranges exhibited by water quality variables in the several data sets, presented by Table 1. With this method it cannot be said authoritatively if one versus another case represents higher or lower levels, but the assessment does provide an indication of relative magnitudes of the variables in different circumstances.

It should be kept in mind in evaluating the BGG and NW 107$^{th}$ Cascade performance that the water quality results were affected by a stream that enters the sampling manhole downstream of the cascade, and thus does not receive the treatment given the remainder of the flow by the natural drainage system. However, the subcatchment generating that side flow is only about 1.5 percent of the total contributing area and should have little influence.

Table 1 presents water quality variable concentration ranges for three types of cases: treatment by a natural drainage system (lightest shading), flow through a ditch-and-culvert street drainage system (medium shading), and flow at the entrance of a drainage system (darkest shading). Performance of the two natural drainage system treatments, BGG/NW 107$^{th}$ Cascade and the NW 110$^{th}$ Cascade, was generally comparable, with neither clearly superior to the other. Of the 10 water quality variables, BGG/107$^{th}$ had slightly higher minimums in six and maximums in five instances. Working with more samples, Chapman (2006) and Horner and Chapman (2007) showed that the concentrations of all water quality variables were statistically significantly lower in the NW 110$^{th}$ Cascade outlet compared to the inlet, except for dissolved zinc (lower but not statistically significantly) and soluble reactive phosphorus (higher in the discharge, apparently because of net release from vegetation).

In comparing performance of the two NDS installations with flow through a ditch-and-culvert system, it can be seen that all maximum values were very substantially lower in the NDS effluents. Minimums were generally but not always lower; and when they were, the differences were more marginal. The same statements apply to a comparison between flow from the natural drainage systems and runoff entering local drainage systems at the high point near the commercial arterial Greenwood Avenue. The treatment systems can thus reliably reduce sometimes quite elevated pollutant concentrations to certain levels, but they cannot greatly or reliably decrease concentrations in the least contaminated urban runoff flows. These phenomena have been respectively described as the "reliable maximum" and "irreducible minimum" concentrations (Horner and Chapman 2007).

The ability of natural drainage systems to reduce contaminant concentrations is coupled with the substantial decreases in discharge volumes resulting from infiltration and evapotranspiration. These dual reductions, in turn, produce considerable declines in pollutant loadings to receiving waters.

Table 1. Comparison of Ranges of Water Quality Variables in Several Pipers Creek Subbasins[a]

| CASE: | After flow through Green Grid/Cascade | | After flow through ditch-and-culvert drainage | | After flow through ditch-and-culvert drainage | | Flow entering drainage system near Greenwood | | Flow entering drainage system near Greenwood | | After flow through cascade | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LOCATION: | BGG/NW 107th and 4th NW[b] | | BGG/NW 107th Pre-construction[c] | | NW 120th and 5th NW[d] | | NW 122nd and Ridgewood N[c] | | NW 110th west of Greenwood N[e] | | NW 110th and 3rd NW[e] | |
| VARIABLE | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. |
| TSS (mg/L) | 11 | 80 | 18 | 236 | 4 | 215 | 13 | 204 | 34 | 324 | 9 | 42 |
| TN (mg/L) | 0.769 | 2.52 | 0.907 | 4.34 | 0.480 | 5.51 | 0.591 | 4.87 | 0.500 | 3.49 | 0.600 | 1.600 |
| TP (µg/L) | 97 | 192 | 128 | 305 | 65 | 495 | 102 | 429 | 70 | 590 | 75 | 240 |
| SRP (µg/L) | 15 | 88 | 3 | 125 | 8 | 247 | 3 | 113 | 3 | 49 | 21 | 110 |
| Motor oil (mg/L) | 0.23 | 0.44 | 0.35 | 2.10 | 0.15 | 2.69 | 2.20 | 5.40 | 0.08 | 3.51 | < 0.11 | 0.33 |
| Total Cu (µg/L) | 2.1 | 11 | 9.9 | 43 | 4.8 | 45 | 9.7 | 42 | 6.9 | 42 | 3.9 | 8.0 |
| Dissolved Cu (µg/L) | 2.0 | 6.9 | 5.1 | 24 | 1.0 | 18 | 1.8 | 28 | 1.2 | 13 | 1.4 | 7.2 |
| Total Zn (µg/L) | 22 | 57 | 22 | 75 | 30 | 298 | 65 | 314 | 47 | 465 | 39 | 110 |
| Dissolved Zn (µg/L) | 14 | 24 | 5.0 | 31 | 6.0 | 231 | 9.0 | 252 | 15 | 348 | 12 | 67 |
| Total Pb (µg/L) | < 1 | 12 | 5.6 | 36 | 3.9 | 51 | 3.1 | 59 | 9 | 65 | 1.6 | 8.0 |

[a] See Water Quality Analyses, *General Analyses and Methods*, above for abbreviations of water quality variables. BGG—Broadview Green Grid; Min.—minimum; Max.—maximum

[b] From this study

[c] From Engstrom (2004)

[d] From Engstrom (2004) and Chapman (2006)

[e] From Chapman (2006)

## SUMMARY AND CONCLUSIONS

This study sought to characterize the ability of a combined SEA-Streets and stepped-pool cascade system to adjust discharge volumes and peak flow rates and treat stormwater runoff in an urban setting. The hydrologic data were sufficient to arrive at firm conclusions regarding runoff quantity management. Despite a dearth of water quality data, those available give indications supportive of previous conclusions drawn from monitoring other nearby drainage systems. Specifically:

- Instances of discharge from the drainage system at NW 107th Street and 4th Avenue NW decreased from 76.2 percent of all events monitored before the system was upgraded to 60.6 percent after construction of the Broadview Green Grid and NW 107th Cascade.

- With the new drainage network, both the overall basin runoff coefficient (dropping from 0.07 to 0.02) and the volume of discharge per unit of precipitation decreased to about 29 percent of the quantities measured with the preceding system.

- Occurrences of the largest discharges (> 1000 $ft^3$, or 28.3 $m^3$) went from 30.5 percent pre-construction to 16.4 percent of all events after the new system went into operation.

- The volume discharged per unit of precipitation deviated more between the old and new drainage systems when antecedent conditions went from relatively wet (0.5-1.5 inch [13-38 mm] of rain in the preceding 7 days) to very wet (< 1.5 inch [38 mm] in the antecedent week).

- The two previous conclusions demonstrate that the BGG and NW 107th Cascade system is acting especially to protect Pipers Creek from elevated discharges in the largest storms and wettest conditions, when the risks to the channel and its habitats are the greatest.

- Indications from the limited water quality analysis are that the BGG/NW 107th and NW 110th natural drainage systems discharge runoff of comparable quality, with neither clearly out-performing the other.

- Discharges from both natural drainage systems exhibited maximums of 10 water quality variables very substantially lower than flows entering neighborhood drainage systems at the high point near Greenwood Avenue and flows passing through ditch-and-culvert street networks. Minimums differed much less among the drainage system cases, being slightly lower at the outlets of the NDS installations in most instances but slightly higher sometimes. These observations indicate that NDS treatment is capable of reliably producing effluent concentrations no higher than certain levels (the "reliable maximum" values) but cannot greatly or reliably reduce pollutants in the least contaminated urban runoff below certain "irreducible minimums".

- The advantages of natural drainage systems over conventional ones in runoff quantity reduction and quality improvement are compounded in producing much lower pollutant loadings to receiving waters.

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# APPENDIX A

## ADDITIONAL BROADVIEW GREEN GRID (BGG)/NW 107$^{TH}$ CASCADE ANALYSIS

The question examined was: What are the differences in total discharge volume, peak flow rate, and time to reach peak discharge for comparable storms at the Broadview Green Grid (BGG)/NW 107$^{th}$ Cascade discharge point before and after construction of the system? Initially, the greatest interest was in comparing performance during events occurring with approximately 1- to2-year frequencies and having approximately 24 hour durations, representing common design bases. While storms meeting this description occurred in the post-construction period, representing 1.2- and 2.3-year frequencies (both 24-hour durations), there were no events anywhere close to these before construction.

Events in the frequency range 4.1-4.5 years occurred in both periods, but representing differing durations (2- and 6-hour). As the disparate durations suggest, investigation of their hyetographs showed substantially varying characteristics. The post-construction event produced approximately 50 percent more rain in 24 hours. Therefore, these storms would provide a poor basis for comparisons and were dropped for this purpose.

Other events in the pre- and post-construction precipitation data sets were assessed in an attempt to identify at least one pair of storms similar in pattern. The storms of 9/16/03 and 6/22/05 matched relatively well, as shown by the table, and were the only close match.

| RAINFALL | 9/16/03 | 6/22/05 |
|---|---|---|
| 5-minute | 0.07 | 0.06 |
| 10-minute | 0.11 | 0.10 |
| 15-minute | 0.13 | 0.14 |
| 20-minute | 0.16 | 0.18 |
| 30-minute | 0.23 | 0.22 |
| 45-minute | 0.35 | 0.27 |
| 1-hour | 0.39 | 0.30 |
| 2-hour | 0.68 | 0.45 |
| 3-hour | 0.83 | 0.67 |
| 6-hour | 0.88 | 0.89 |

Small amounts of additional rain fell in both cases, but there was no discharge in either case after about 5.5 hours of continuous rain. The BGG/Cascade system performed as follows during these events.

| QUANTITY | 9/16/03 | 6/22/05 | Difference (%) |
|---|---|---|---|
| Discharge volume ($ft^3$) | 3011 | 2818 | 6.4 |
| Discharge production ($ft^3$/inch rainfall) | 3422 | 3166 | 7.5 |
| Peak flow rate (cfs) | 0.45 | 0.34 | 24.4 |
| Time to peak (hours:minutes) | 4:30 | 4:05 | 9.3 |

The results do not show dramatic differences before and after the presence of the natural drainage system (NDS) for this storm pair. However, the assessment recounted in the main text of the report more dramatically showed discharge production dropping from 8324 to 2471 $ft^3$/inch of rainfall overall, a change of 70 percent. Storms in the pair compared were relatively intense for Seattle (0.16 inch/hour average), a condition when the NDS did not yield a great advantage.

The considerable volume reduction overall appears to be mainly a function of preventing discharge at all in the relatively small and less intense storms, which represent the norm for Seattle. Also, even more marginal reductions on a percentage basis in the larger storms add up over time to substantial urban runoff prevented from entering the receiving water, a benefit in cutting pollutant mass loadings as well as decreasing stress on stream channels associated with conveying more volume. The pre-construction period had two very large storms, and it is unfortunate that the post-project era had no storms anywhere close to those in size to provide a means of directly comparing benefits in such conditions.