NW 110TH STREET NATURAL DRAINAGE SYSTEM

PERFORMANCE MONITORING

With Summary of Viewlands and 2nd Avenue NW SEA Streets Monitoring

Prepared for

Seattle Public Utilities

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SEATTLE PUBLIC UTILITIES' NATURAL DRAINAGE SYSTEM INITIATIVE

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 treat 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 forested conditions (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 4-6 years. The Broadview Green Grid was completed in stages over the past two years. Additional systems are being considered for the NW 120th Street area. Outside the Pipers Creek watershed, SPU is installing similar natural drainage systems in the redeveloped High Point Seattle Housing Authority project 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, and also 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. 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. It drains to another cascade designed similarly to the NW 110th cascade and installed along NW 107th in 2005. The work outlined in this plan covers flow and water quality monitoring at the discharge end of the NW 107th Street Cascade. This station represents the output of the combined Broadview Green Grid and NW 107th Cascade system.

PERFORMANCE MONITORING

History

The University of Washington (UW) began flow monitoring at 2nd Avenue NW and Viewlands in 2000. The initial 2nd 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 continues to the present day.

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 are being monitored, 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 107th, NW 120th, and NW 122nd Streets. This work provided baselines for the natural drainage systems subsequently constructed upstream from the NW 107th Street monitoring point and planned, but not yet built in the vicinity of NW 120th and NW 122nd Streets. The NW 107th and NW 120th 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 122nd 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 120th 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 110th Street Cascade during the years 2004 to 2006. This report focuses on the findings of that work and is drawn from Chapman (2006), the source for complete details and the full database.

In the fall of 2006 the UW returned to work at NW 107th Street to monitor the performance of the Broadview Green Grid over the succeeding two years. This study will be the subject of a future report.

Summary of Previous Results

Viewlands Cascade

Flow was monitored at the Viewlands Cascade natural drainage system inlet and outlet during 128 precipitation events from October 1, 2000 through April 30, 2002. According to the best estimates, the Viewlands Cascade cut the average peak flow rate of entering runoff by about 60 percent and the total influent volume over a period of time by over half. However, little or no reduction of either peak flow rate or volume occurred during relatively large storms. There was no discharge from the end of the channel in 27 percent of the events monitored. It can completely infiltrate the catchment response to about 0.13 inch (3.3 mm) of precipitation and 1750 ft^3 (50 m^3) of influent regardless of the season or conditions (Horner, Lim, and Burges 2004).

Based on estimates for the ditch that preceded the Viewlands Cascade project, the new channel reduces runoff discharged to Pipers Creek in the wet months by a factor of three relative to the old ditch and cuts flow velocities by approximately 20 percent, both under identical conditions. Reducing velocities and associated erosiveness was a major goal of the project.

During the monitoring period the new Viewlands channel retained roughly 1.5 million ft^3 (43000 m^3) of runoff that entered it, preventing its direct release to Pipers Creek and the elevation of erosive flows there. This quantity is about three times the amount of retention estimated were the preceding narrow, partially concreted ditch still been in place.

2nd Avenue NW SEA Streets Project

Prior to construction of the SEA Streets project baseline flow monitoring from the original street was performed at the discharge point of the project area at the northwest corner of 2nd Avenue NW and NW 117th Street. This monitoring occurred during the period March 19-June 18, 2000 and embraced 35 events totaling 6.32 inches (161 mm) of precipitation. The catchment discharged in all events, delivering a total of 8601 ft^3 (244 m^3) of runoff to the downstream drainage system leading to Pipers Creek (Miller, Burges, and Horner 2001). As a crude measure of yield, the street generated 1361 ft^3 of runoff per inch of rain (1.52 m^3 per mm).

Monitoring of the completed SEA Streets project began on January 20, 2001. Over the next approximately two years (through March 31, 2003) the system experienced 162 events producing 76.9 inches (1954 mm) of precipitation. The new street discharged runoff during only 11 storms (6.8 percent), yielding 1948 ft^3 (55 m^3) of runoff, or 25.3 ft^3 of runoff per inch of rain (0.028 m^3 per mm). This yield is just 1.9 percent of the amount before the project's construction.

Flow monitoring continued through June 30, 2007. The last recorded discharge was on December 14, 2002. Rainfall totals at Seattle-Tacoma International Airport for the intervening years were:

> 2003—41.78 inches (1061 mm);
> 2004—31.10 inches (790 mm);

2005—35.44 inches (900 mm);
2006—48.82 inches (1240 mm); and
2007 through June 30—17.51 inches (445 mm).

The long-term averages at the airport are 37.99 inches (965 mm) annually and 18.92 inches (481 mm) for the first six months of the year. Thus, the period since 2nd Avenue NW natural drainage system last discharged represent times from somewhat below to much above average. On and about October 20, 2003 the airport gauge registered its highest ever 24-hour rainfall total. The Viewlands rain station in the 2nd Avenue NW neighborhood recorded 4.22 inches (107 mm) of rain from late on October 19, 2003 to the morning of October 21 (a period of 32.5 hours). The next month a quantity of 3.86 inches (98 mm) fell at Viewlands over a 51.25-hour period from November 17 to 19, 2003. Then, in November 2006 Seattle experienced its largest ever monthly rainfall, 15.63 inches (397 mm) at the airport. Therefore, the SEA Streets drainage system has ceased discharging runoff even with exposure to large short- and long-term precipitation quantities.

The 2nd Avenue NW SEA Streets site thus demonstrated a clear tendency to store and prevent surface runoff from even more rainfall than during its early years. The reason for this development can only be speculation. However, it is likely that the vegetation, as it matures, more effectively intercepts rainfall, after which it can evaporate; assimilates more water into its tissues, for storage and possible transpiration; and assists percolation through the soil by piping water along the root structures.

NW 110TH STREET MONITORING OBJECTIVES

The NW 110th Street monitoring program was structured to determine:

- The effectiveness of the Cascade system at reducing the volumes and peak flow rates of both wet-season and dry-season storms;
- The effectiveness of the system at reducing pollutant mass discharges, and how its performance compares to the ability of conventional stormwater best management practices (BMPs) in this regard;
- Pollutants concentrations in the flow discharged from the Cascade in relation to levels known to be toxic to aquatic organisms; and
- Factors governing the Cascade's hydrologic and water quality performance.

This report presents the results associated with the first three objectives. Readers interested in findings pertaining to the fourth objective should consult Chapman (2006).

MONITORING LOCATIONS AND METHODS

DESCRIPTION OF THE NW 110TH STREET CASCADE AND ITS DRAINAGE CATCHMENT

The NW 110th Street Cascade was built primarily to manage stormwater runoff coming from Greenwood Avenue N and the relatively flat ridge top between NW 110th and NW 112th Streets. Pre-project assessment indicated that water is collected by a number of catch basins on Greenwood Avenue and transported to NW 110th Street and then westward to the Cascade inlet. It was thought that a small amount of flow also comes from just east of Greenwood via another catch basin. These areas total about 10 acres (4.1 ha) and were estimated by SPU (2002, 2004) to be 40 to 45 percent impervious, mostly roofs and streets.

During the course of the study it was noted that a small amount of flow was being measured at the 110th Cascade inlet relative to the precipitation quantity falling on a 10-acre catchment. Careful observation revealed that water from much of the supposed catchment was not actually reaching the cascade, because many rooftops discharge to unconnected surface or subsurface areas or the sanitary sewer and water does not easily reach some of the Greenwood and NW 110th catch basins. All in all, the impervious area actually contributing to the measured flow was estimated to be 0.8-1.0 acre (0.32-0.41 ha, Chapman 2006). Additional area may contribute during the largest storms and during very wet conditions.

Additional runoff flows into the Cascade all along its length as sheet flow from NW 110th Street and intersecting streets. These flows are termed the “lateral inflows” in this report. Being widely distributed, they could not be measured. The subcatchment generating these flows was determined through field reconnaissance and outlined on a map from SPU’s GIS. Then, the total and impervious areas within the subcatchment were estimated in two ways: by hand measuring on the map and using the measuring tool in King County’s IMAP system. Results of the two methods agreed within 2 percent. The total subcatchment area was estimated at 8.1 acres (3.3 ha) and the impervious portion at 1.1 acre (0.45 ha). Therefore, the impervious areas within the subcatchments contributing above and below the cascade inlet are approximately equal. Since the land uses in the two subcatchments are similar, a reasonable assumption to quantify the cascade system’s performance was to double the measured inflow to get the total runoff input. This method of combining field reconnaissance and observation of flows with map analysis can be applied in future monitoring programs in similar circumstances, when only a portion of the inflow can be collected and measured directly.

The NW 110th Street Cascade consists of a series of 12 bioretention cells, separated by concrete V-notch weirs, in a stepped-pool configuration along the north side of the street. The total length is approximately 900 horizontal ft (274 m) between the inlet and the outlet at 3rd Avenue NW. The vertical drop is 53 ft (16 m), for an average slope of nearly 6 percent.

The cells are rectangular, though slightly irregular in plan form, and are excavated to well below the road grade. In sum, the cell beds have roughly 4500 ft^2 (418 m^2) of surface area. Cell depths measured from the weir inverts to the ground surface range from 3 to 5 inches (7.6-12.7 cm), giving a total above-ground storage volume of 1400-1500 ft^3 (39.7-42.5 m^3). The cell bottoms consist of river rock to a depth of about 1 ft (30 cm).

Monitoring stations were placed to collect influent and effluent runoff. Being located in the first cell, the inlet station received the flow originating on and around Greenwood Avenue N but not the runoff generated at lower elevations along NW 110th Street. For logistical reasons the outlet station was at the downstream end of the eleventh of the twelve cells.

DESCRIPTION OF THE VENEMA DRAINAGE CATCHMENT

Venema Creek is the largest tributary to Piper's Creek. It flows into the mainstem only 1500 ft (457 m) before discharge to Puget Sound. Its headwaters are in a ravine located near the corner of 4th Avenue NW and NW 120th Street. In the dry season, Venema Creek is fed by the numerous springs and seeps located in the ravine. In the wet season, the creek is the recipient of large volumes of storm water runoff discharged via the engineered street-drainage system. The area contributing to storm flows in the headwaters of Venema Creek is at least 70 acres (28.4 ha) in extent (the precise boundaries of the basin are in question).

It was originally estimated that impervious surfaces, including roads and rooftops, cover 44 percent of the basin. The upper reaches of the drainage system are located on the top of the Broadview ridge, from NW 120th St to NW 130th St. As this area is flat and has no other source areas, many of the residential streets have no constructed drainage systems. Water collects at the edge of the road, if there is a great deal of runoff, and eventually might find its way to a ditch. The ditches here, where they occur, are grass-lined and of a very low gradient. This water eventually is piped underneath Greenwood Avenue to the west. Greenwood and its right-of-way comprise the largest contiguous piece of impervious surface in the basin. Water here is collected in catch basins and discharged down the slope to the west in open ditches or pipes.

The east-west streets from NW 120th to NW 143rd all slope to the west at 6-9 percent. Most east-west streets have concrete-lined open ditches to convey storm water runoff, but occasionally pipes or grass ditches carry the water down the hill. Water flows in these ditches westward until the great majority of it is collected along the eastern edge of 3rd Avenue NW. Some of the water, however, continues west. The water that is collected along 3rd flows south and then turns west at 120th, where it discharges to Venema Creek.

The water-quality sampling station in the Venema Creek basin was located at the southwest corner of NW 120th Street and 4th Avenue NW. This is essentially the final point in the engineered drainage system before discharge to Venema Creek. At this point, all of the water from the contributing basin is flowing through an 18-inch (45.7 cm) concrete pipe located in a 10-ft (3 m) deep manhole.

MONITORING EQUIPMENT AND PROCEDURES

Flow-Weighted Composite Water Sampling

Monitoring equipment consisted of ISCO Model 6700 automatic samplers equipped with ISCO Model 730 bubbler flow modules at the Cascade inlet and outlet and the Venema station. 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) [Note: As Chapman (2006) reported, rainfall less than 0.30 inch was very unlikely to produce an effluent.];

- Antecedent dry period—12 hours with less than 0.04 inch (1 mm) of rain [Note: This criterion was relaxed at first to ensure collection of sufficient samples but was activated later as sample numbers increased.]; 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 goal of the monitoring program was to capture at least 10 storm events during the October–April period of each year (2004-2005 and 2005-2006), as well as some dry-season events as opportunities allowed. Generally, storm flow sampling events were spaced at least one week apart to allow time for pollutants to accumulate on paved surfaces between washoff periods. However, this criterion was relaxed to take advantage of opportunities and increase representativeness.

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 1998 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).

Composites samples cannot be utilized for bacteria analyses. To get some data on this category of water quality variable, grab samples were collected for analysis of fecal coliform bacteria and *Escherichia coli* (*E. coli*).

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 (2004) Sampling and Analysis/Quality Assurance Project Plan. Chapman (2006) also details the plan. The major quantitative components were analyses of field and laboratory duplicates, laboratory spike samples, and equipment rinsate blanks.

Particle Size Distribution

Particle size distribution (PSD) was analyzed using a Laser In-Situ Scattering and Transmissometry (LISST) instrument manufactured by Sequoia Scientific, Inc. PSD is am important measurement to understand potential solids settleability and transport of other pollutants in the particulate state. The relatively small particles, particularly those in the fine silt and clay fractions, have proportionately slow settling velocities and, in their generally large numbers compared to the larger particles, also represent a large share of the surface area available to retain metal ions and organic compounds.

Unfortunately, there are no standardized protocols or instrumentation for PSD recognized by U.S. Environmental Protection Agency, the Washington Department of Ecology, or *Standard Methods for the Examination of Water and Wastewater*. This monitoring program suffered from an inability to generate representative, repeatable results, despite a great effort to do so. Chapman's (2006) Appendix R describes the problems and various attempts to solve them. Obstacles included equipment limitations, especially ability to maintain a well mixed sample and reproducibility; variability and bias introduced in aliquot acquisition by the ISCO sampler and sub-sampling from the composite sample; and processing samples soon enough to avoid particle flocculation and consequent change in the distribution. Various exploratory tests were performed to investigate the dimensions of these problems and attempt to solve them. They included replication of analyses from the same aliquot and from aliquots sub-sampled from the same container, measurements with standard particles, and assessment of the degree of particle flocculation over time and the consequent effect of holding time on results.

Special Considerations for Flow Measurement

While ISCO flow meters were used to control the ISCO samplers for flow-weighted composite water sampling, the data records from the ISCO probes were not used in the final analysis of the hydrologic record at the 110th Cascade. This final analysis utilized Druck pressure transducer data recorded by Campbell Scientific data loggers (model CR10x at the inlet station and model CR510 at the outlet site).

At the sampling site in the Venema Creek basin, the flow measurements used to run the ISCO sampler were also used in the final hydrologic analysis. This site posed many challenges in terms of flow measurement and sample acquisition. The equipment was located in the street right of way above a 10-foot deep, 4-ft diameter manhole. The sampling line was lowered into the manhole, and for the majority of the sampling effort, the sampling line was not fixed in place. Near the end of the program the sample line was fixed in place by means of steel re-bar.

Runoff from the Venema contributing basin entered the manhole via an 18-inch concrete pipe. An ISCO 750 area-velocity flow module was placed in this pipe about 2 ft upstream from the entry into the manhole. This equipment measured flow level in the pipe and, when the flow depth exceeded 1 inch, it also measured the velocity of the flow. Therefore, both Manning's equation and the area-velocity equation were used to calculate flow rates at this station. Near the end of the sampling program an ISCO 4150 series flow meter was installed at the Venema station, this time in the 18-inch concrete pipe downstream of the manhole, because of difficulties in calibrating the equipment at this station. Chapman (2006) gives detail on how the measurements from these various pieces of equipment were used.

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.

DATA ANALYSIS

Analysis of Pollutant Concentrations

Summary Statistics

Analysis of a flow-weighted composite sample provides a measure of the event-mean concentration (EMC) of the analyte. Using EMCs in multiple-event data analysis requires expressing the central tendency (e.g., median, arithmetic mean, geometric mean) of EMC data set. The best expression of central tendency depends on the statistical distribution of the data. The probability plot correlation coefficient (PPCC) was used to assess whether the data could be considered normally distributed (Zar (1984) and Helsel and Hirsch (1991) are references for all statistical procedures employed in this study). If so, then the arithmetic mean was preferred as the measure of central tendency. If the distribution was not normal, then the data were log-transformed and the PPCC again calculated. If the data were log-normal, the geometric mean was preferred as a measure of the center of data. If the log-transformation failed to achieve normality, then the fully non-parametric median was used to estimate the central tendency. Uncertainties in the estimates of central tendency were expressed in terms of the parametric and nonparametric 90 percent confidence limits.

An additional estimate of central tendency of the data was the flow-weighted average concentration. This estimate takes into account that the larger storms are more influential than small storms in determining annual pollutant mass loadings. The flow-weighted average concentration was calculated as $C_{avg,flow-wt} = \Sigma C_i V_i / \Sigma V_i$, where $C_{avg,flow-wt}$ is the flow-weighted average concentration, C_i is the EMC for storm I, and V_i is the *sampled* runoff volume from storm i (*not* the total flow volume for the storm).

Comparisons Among Monitoring Sites

The treatment capabilities of the 110th Cascade system were assessed by comparing pollutant concentrations and mass loadings entering and leaving. The discharge quantities were also compared with those in the Venema drainage, which received no treatment.

When evaluating whether one data set tended to contain higher EMCs than another, the choice of statistical test depended on whether the EMCs are paired or unpaired. In the unpaired case, there was no natural structure in the order of observations across groups. The EMCs were not necessarily from the same storm, and the number of observations at the two stations may have differed. In the paired comparison, there were EMC observations at each site for the same storm. This approach eliminated noise that might have been present when the unordered data were analyzed.

The test preferred for comparing data sets with unpaired observations is the t-test. However, the parametric t-test is invalid if either of the data sets is not normally distributed. The t-test also assumes an additive difference between the two groups. Box plots and quantile-quantile (Q-Q) plots were generated to evaluate if the difference between the groups indeed is additive, or if a multiplicative relationship exists. If the relationship between the groups appeared to be multiplicative in nature, and the distributions were normal when log-transformed, then a t-test was used on the transformed data. If normality could not be achieved even with a log-transformation, then the fully non-parametric Wilcoxon rank-sum test was used. The magnitude of the difference between the groups was estimated by the difference between means (if the t-test was used) or by the Hodges-Lehman estimator (if the rank-sum test was used).

When comparative tests were carried out on paired data, the data themselves were not used.

Instead, the tests were carried out on the differences between the pairs. In other words, if data set A had observations $\{X_1, X_2, \ldots X_n\}$ and data set B had observations $\{Y_1, Y_2, \ldots Y_n\}$, then the paired test was carried out on the values $\{(X_1-Y_1), (X_2-Y_2), \ldots (X_n-Y_n)\}$. If the differences were normally distributed and the relationship between the groups appeared to be additive (according to scatter plots of the data), then the t-test was used on the differences. If the differences were not normal but were symmetric, then the Wilcoxon signed-ranks test was used to determine if the EMCs in one group were significantly larger than in the other. If neither of these tests could legitimately be used, then the fully non-parametric sign-test was employed. The magnitude of the difference between the groups was estimated by the difference between the means (t-test), the Hodges-Lehman estimator (signed-ranks test), or the difference between the medians (sign test).

The ideal means of comparing water quality data sets is according to the paired watershed procedure of U.S. Environmental Protection Agency (1993). However, timing did not allow setting up this study to conform to the design of such an investigation regarding simultaneous sampling of two watersheds before and then after imposition of some change in conditions. However, there were eight samples from the same storms at both the 110th Cascade outlet and Venema stations, permitting a comparison of catchments with and without natural drainage systems. Chapman (2006) presents additional detail on the statistical analyses comparing pollutant concentrations at the various stations.

Analysis of Pollutant Mass Loadings

In this study, the preferred metric for characterizing system performance was the percentage reduction in pollutant mass loading. The reduction was calculated in a conservative manner, with no assumptions needed regarding the lateral inflows to 110th Cascade. This metric takes into account the large amounts of water detained by the system. As described by Chapman (2006), several methods were used to determine mass loadings by combining runoff volumes and pollutant concentrations, the central tendencies of which were established as described above. These methods gave similar results when computing efficiencies of loading reductions.

MONITORING RESULTS

STORM RUNOFF QUANTITY

Runoff Production in Relation to Precipitation

Figure 1 plots runoff volume registered by the Campbell Scientific instrument versus rainfall depth for all 239 storms that occurred during the period of monitoring at the 110th Cascade inlet. Several statistical regression techniques were applied to these data, the best-fit lines for two of which Figure 1 shows. SPU estimated the catchment area contributing to the 110th Cascade inlet at approximately 10 acres (4.1 ha). If the flow volumes are converted to water depth across the catchment, then the slope of the fitted line becomes the runoff coefficient; i.e., the ratio of runoff produced to rainfall. All regression methods considered indicate a runoff coefficient of 0.10-0.11, which is equivalent to about 1 acre (0.41 ha) of directly connected impervious surface with a runoff coefficient of 1.0. That situation, in fact, is what was observed and described above, and this regression analysis lends support to its conclusions.

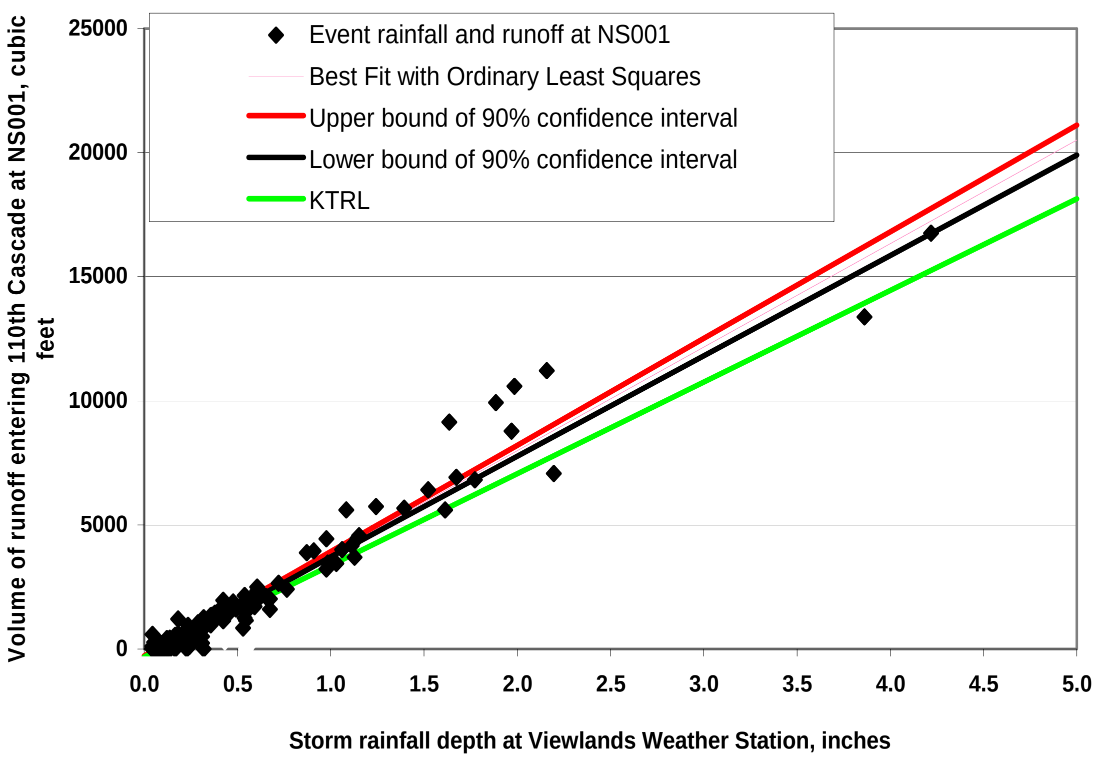

Figure 1. Scatter Plot of Runoff Volume at 110th Cascade Inlet Versus Rainfall Depth for All Storms in the Period October 11, 2003-March 31, 2006 (NS001 is inlet station; KTRL is the Kendall-Theil-Robust Line.)

Another view of runoff production can be gained by considering the largest storm of record at the inlet station, which occurred on October 19-21, 2003. This storm registered 4.22 inches (107 mm) of rain in 32 hours, and 16,755 ft^3 (475 m^3) of runoff discharged over the weir. This volume of runoff is equivalent to 0.46 inch (11.7 mm) spread over the presumed 10-acre (4.1-ha) basin. This is equivalent to saying that the apparent runoff coefficient was 0.11, or alternatively that the area effectively draining to the station with a runoff coefficient of 1.0 was only 1.1 acre (0.45 ha); i.e., 4.22 inches of rain over 1.1 acres is 16,755 ft^3. It is clear from these two different ways of assessing runoff production entering the 110th Cascade that much less runoff consistently results than would be expected in a highly developed urban catchment. It is hence apparent that much of the basin is not connected to the drainage system leading into the 110th Cascade.

Importance of Antecedent Conditions

The Antecedent Precipitation Index (API) is defined as $API_t = R_{t-1} + k*API_{t-1}$, where API_t is the index for day t, API_{t-1} is the index for the previous day, R_{t-1} is the rainfall depth for the previous day in inches, and k is a coefficient reflecting the relative rate of soil drying (Linsley, Kohler and Paulhus 1982). The value of k can range from approximately 0.85 (sand) to 0.98 (clay). In this study, a k of 0.85 was chosen due to the somewhat sandy nature of the weathered till present at the site. Over the full period of monitoring the median API for all storms was about 0.6. If there was any discharge at all, on average, the amount of runoff produced at the cascade outlet in the wet (API > 0.6) condition was about 2400 ft^3 per inch of rain (2.67 m^3 per mm), while the amount in the dry condition was about 780 ft^3 per inch of rain (0.87 m^3 per mm).

In the dry condition (117 storms), the 93 storms less than 0.48 inch (12.2 mm) did not produce outflow from the 110th Cascade system. Of the 24 storms greater than 0.48 inch, only 14 generated runoff at the outlet. The largest storm completely infiltrated in this dryer condition was a 0.98-inch (24.9 mm), 12-hour storm on August 6, 2004.

In the wet condition (118 storms), the 66 storms having less than 0.29 inch (7.4 mm) of rain were completely infiltrated. Of the 52 remaining events, 35 produced a discharge. The largest storms that were completely infiltrated in this wetter condition were a 0.83-inch (21.1 mm), 51-hour storm on May 17-19, 2005, and a 0.58-inch (14.7 mm), 14.25-hour storm on February 27, 2006.

Another method of categorizing storms relative to preceding conditions utilizes the seven-day-antecedent rainfall. Four antecedent states were defined, dry, medium dry, medium wet, and wet, corresponding to 7-day antecedent rainfall depths of < 0.1, 0.1– 0.25, 0.25 – 0.5, and > 0.5 inch (< 2.5, 2.5-6.4, 6.4-12.7, and > 12.7 mm), respectively. In the dry condition, only storms greater than 1 inch (25.4 mm) in 24 hours caused the system to discharge. In the wettest condition, only storms greater than 0.3 inch (7.6 mm) produced an outflow. Some storms up to 0.5 or 0.6 inch (12.7 of 15.2 mm) were completely absorbed by the 110th Cascade system in this condition. Figure 2 graphically represents the storm rainfall quantities required for discharge from the 110th Cascade system.

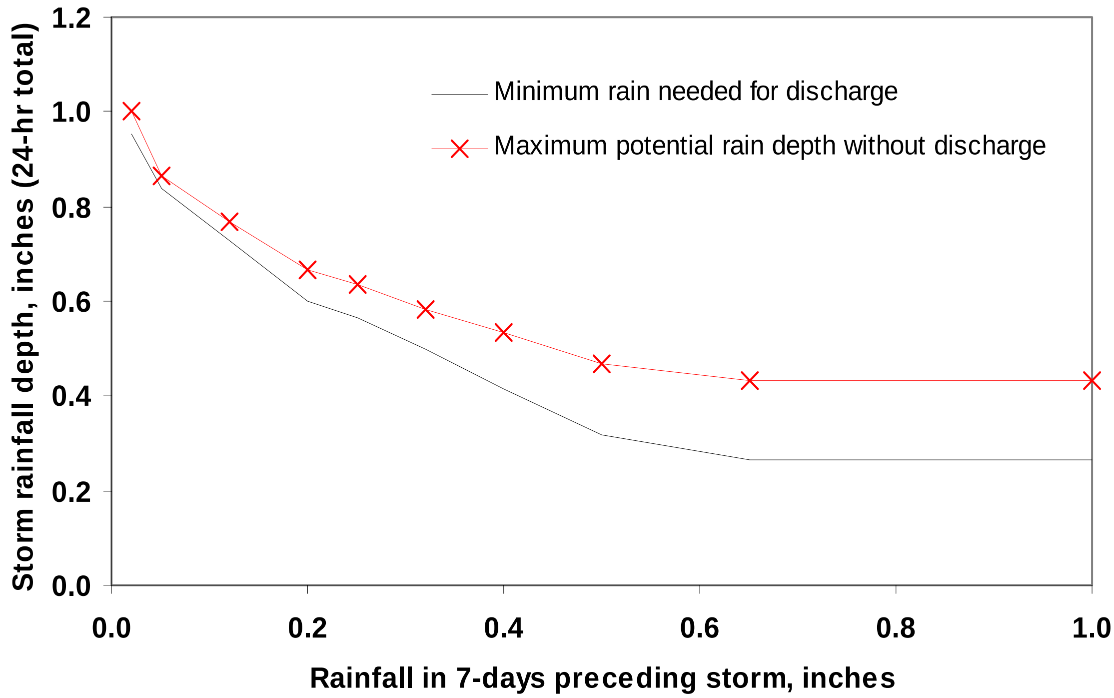

Figure 2. Rainfall Thresholds for Discharge of 110th Cascade Based on Antecedent Rainfall

Runoff Volume and Peak Flow Rate Reduction

Volume Reduction

In 186 of 235 storms, no flow left the 110th Cascade system, and hence the volumes and peak flow rates were reduced 100 percent. As noted above, storms of less than 0.3 inches (7.6 mm) never resulted in an overflow, even in very wet conditions. In very dry conditions, storms up to one inch in 24 hours could be completely retained by the system.

From October 22, 2003 to the end of the monitoring period 87.8 inches (2230 mm) of rain fell at the Viewlands rain station, producing 269,637 ft^3 (7641 m^3) of runoff at the inlet station (Figure 3). The total outflow from 110th Cascade for this period was 140,641 ft^3 (3440 m^3). The difference, amounting to 48 percent of the inflow, was lost through infiltration and evapotranspiration. However, the channel received much more flow, via the lateral inflows, than measured. Assuming equal effective areas of contribution and equal flows generated above and below the inlet, as reasoned above, leads to an estimate that approximately 74 percent of all water influent to 110th Cascade was actually retained, and eventually either infiltrated or evaporated from the system.

It is quite possible that the cascade reduced the flow volumes and peak rates in every one of the remaining 49 rain events. In all but eight storms occurring between October 2003 and March 2006, the flow volume registered at the inlet was larger than at the outlet. For these eight storms, estimating the runoff volume detained depended on the assumption stated above regarding the lateral inflows. It appeared that in very large, wet-season storms, the system probably detained some water, but potentially only 20 percent or less of the inflow volume.

The amount and proportion of water infiltrated or evaporated varied from storm to storm, but only during eight storms did the amount discharging surpass that measured at the inlet. In six of these eight storms the exiting volume was only slightly greater than the registered influent volume. Both storms when the effluent volume was much greater than that entering were large events that came when soils were very wet, on November 17-19, 2003 and January 29-30, 2006.

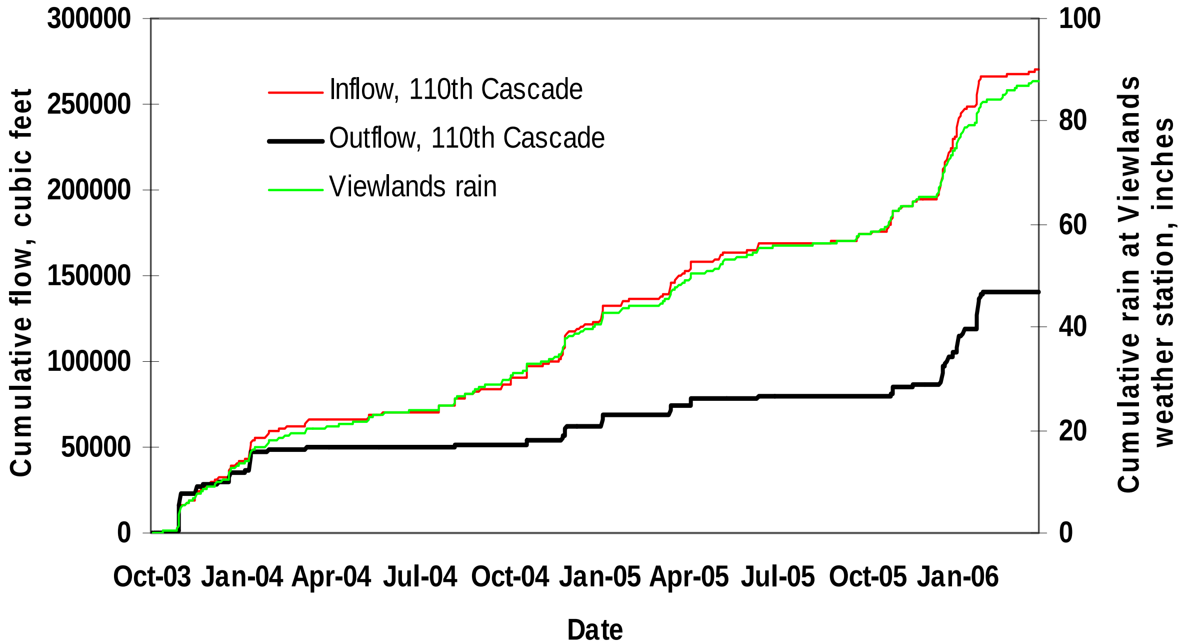

Figure 3. Rainfall and Comparison of Inflow and Outflow Volume, October 2003-March 2006

Peak Flow Rate Reduction

Only 13 of 235 storms had an outflow peak flow rate higher than that at the inlet, and the increase was small in every case. Based on the estimate that the true inflow to 110th Cascade was twice that entering at the inlet station, it appears that the true peak flow rate reduction in these 13 storms was at least 20 and often close to 50 percent. Thus, it is likely that the system reduced peak flow rates in every storm.

Infiltration Rates

The cascade system hence was highly successful in decreasing runoff, in terms of both rates and overall volumes discharged, converting surface flow to infiltration and evapotranspiration. It was beyond the scope and impossible with the measurements made in this study to separate those two components of the hydrologic balance. Infiltration most likely predominated overall, and certainly in the wet season; but evapotranspiration is thought still to be important and even contributing to surface flow reduction in the winter.

To provide insights for future designs there was a desire to quantify, at least approximately, what minimum infiltration rate to expect. Rates estimated through analysis of rain and runoff data, as well as with the aid of a simple model (Chapman 2006), demonstrated considerable variability dependent on storm characteristics and soil wetness. To get an idea of the limiting condition, the rate in relatively large, extended storms falling on comparatively wet soils, Table 1 presents examples of rainfall events producing at least 0.9 inch of rain over extended periods and having API in the "wet" range (≥ 0.6). These storms were all in the cooler months and thus represent infiltration, largely, and probably not much evapotranspiration. Infiltration rates were 0.3 or 0.5 inch/hour (7.6 or 12.7 mm/hour) in all but one of these events, one having two to four times as much rainfall as any other example. Thus, it appears that a rate of 0.3-0.5 inch/hour (7.6-12.7 mm/hour) would be a reasonable, relatively conservative design value.

Table 1. Estimated Infiltration Rates in Relatively Large, Extended Storms on Comparatively Wet Soils

Examples	Storm Characteristics				Volumes					Estimated Infiltration Rates	
	Rainfall	Duration	Antecedent conditions		Outflow	Inflow	Estimated True Inflow	Estimated Infiltration	Estimated Infiltration	Volume Rate[c]	Water Depth Rate[d]
Date(s) of Storm	(inches)	(hours)	API[a]	7-day rain[b]	(ft^3)	(ft^3)	(ft^3)	(ft^3)	(%)	(ft^3/hour)	(inch/hour)
November 17-19, 2003	3.86	51	0.8	0.71	23008	13388	26776	3768	14	45	0.1
January 28-30, 2004	1.64	33	0.6	0.86	10035.8	9134	15070	5034	33	109	0.3
December 9-11, 2004	1.89	37	1.5	1.75	5387	9929	13400	8000	60	177	0.5
April 15, 2005	1.15	23	0.7	0.50	4092	4058	8116	4024	50	175	0.5
November 5, 2005	0.91	14	1.8	2.25	4113	3949	7248	3135	43	115	0.3
January 12-14, 2006	0.98	39	2.7	3.10	855	3460	6800	6000	88	116	0.3
January 29-30, 2006	2.16	26	1.2	0.77	17921	14924	22758	4837	21	188	0.5

[a] Antecedent Precipitation Index

[b] Rainfall (inches) in the 7 days preceding the storm

[c] Estimated infiltrated volume, minus 1500 ft^3 (42.5 m^3) estimated amount of above-ground storage) divided by the storm duration

[d] Volume infiltration rate (preceding column) spread out over 4500 ft^2 (418 m^2) of channel surface area

STORM RUNOFF WATER QUALITY

Storm Characteristics

The principal monitoring objective was the establish the performance of the 110th Cascade by comparing its discharge water quality with runoff quality at the inlet and at the Venema (untreated station). Sampling yielded 14 paired EMC values (11 for total metals) for the first comparison and eight (six for total metals) for the second. Overall, the 110th inlet was represented by 26 EMCs, the outlet by 14, and Venema by 17.

A check was made on whether or not the sampled storms were representative of the larger storm population. If anything, the samples were biased towards larger, more intense rain events, an artifact of the decision to sample runoff only from storms greater than 0.15 inches in depth. The median storm depth was 0.18 inches; hence, the majority of samples were taken in events larger than the median. This sampling distribution was not a concern, since larger and more intense storms were more important when considering the total annual mass loading of pollutants to Piper's Creek.

The flow volume associated with each composite sample was also determined. Then, these flow volumes were summed in order to calculate the percentage of the total flow that was sampled at each station during the 16-month sampling period. At the inlet and outlet to the 110th Cascade system, the composite samples represented about 40% of all flow. In the Venema basin, the composites represented about 25% of all flow. Hence the composite samples together represented a fairly significant fraction of all flow at the respective stations. These calculations only take into account the portions of the storms that were actually sampled. If it is assumed that the composite samples represent entirely the storms during which they were acquired, the percentages would b higher.

Data Quality

Field and laboratory QA/QC measures indicated that the data largely met the standards set forth in the Sampling and Analysis/Quality Assurance Project Plan (City of Seattle 2004). Laboratory duplicates, used as an indicator of repeatability, violated the terms of the SAP only 1.4 percent of the time. Laboratory spikes, meant to test for biases associated with laboratory measurements, were in violation in just 1.6 percent of samples. No pollutants were detected in equipment rinsate blanks. This result indicates that equipment washing and field handling methods did not contaminate samples. Finally, six field duplicates were acquired to test for biases associated with subsampling. The data from these duplicates violated the SAP 11% of the time. Most of the violations were associated with metals measurements. In the large majority of cases, though, pollutant levels differed very little from duplicate to duplicate.

Data Distributions

Table 2 summarizes the population values for all water quality variables at all sites. Typically, the geometric mean was preferred as the estimate of the EMC central tendencies, as the data sets were often log-normally distributed. In some instances the log transformation did not achieve normality of all data sets; in these cases Table 2 gives the median. The flow-weighted average concentrations computed using the flow and concentration values from all storms were comparable to the EMC geometric means (or medians) in most cases. The flow-weighted average was most strongly influenced by the largest sampled events. These storms tended to exhibited moderate concentration levels, and as such the flow-weighted averages tended to approximate the average EMC. Consult Chapman's (2006) Appendix K for measures of dispersion of the data from these central locations.

Table 3 highlights the extremes of the data for each quantity at the 110th Cascade outlet. As an example, the range of TSS EMCs seen in 14 storms was 9 to 42 mg/L. If the highest and lowest values are eliminated, the new range would be 10 to 40 mg/L. In general, the effluent EMCs probably rarely go below the smaller value or above the larger value. This statement can be made with substantial confidence, since the sampled storms included some of the largest and most intense events seen over the past several years. The higher value in each pair can be regarded as the reliable effluent concentration; i.e., the highest concentration that the cascade is likely to discharge. The lower value is an expression of the "irreducible minimum," the lowest concentration that can be achieved with this practice.

Table 2. Event Mean Concentration Central Tendencies and Flow-Weighted Average Concentrations for Water Quality Variables

	Water Quality Variable[a]	Estimator Used for EMC Central Tendency	EMC Central Tendency			Flow-Weighted Average		
			110th In	110th Out	Venema	110th In	110th Out	Venema
	Total suspended solids	Median	94	29	41	120	30	85
Nutrients	Total Nitrogen	Geometric mean	1.200	0.882	1.094	1.146	0.807	1.125
	Total Phosphorus	Geometric mean	0.190	0.139	0.160	0.210	0.133	0.200
	Soluble Reactive Phosphorus	Geometric mean	0.014	0.041	0.024	0.013	0.036	0.017
Metals	Total copper	Geometric mean	0.0162	0.0055	0.0076	0.0165	0.0063	0.0073
	Total zinc	Median	0.094	0.045	0.042	0.120	0.047	0.041
	Total lead	Geometric mean	0.0186	0.0037	0.0100	0.0174	0.0045	0.0097
	Dissolved copper	Geometric mean	0.0043	0.0029	0.0031	0.0036	0.0029	0.0022
	Dissolved zinc	Median	0.033	0.030	0.022	0.049	0.026	0.020
	Dissolved lead	NA[b]	NA[b]	NA[b]	NA[b]	NA[b]	NA[b]	NA[b]
	Total hardness	Geometric mean	9.5	12.3	8.6	8.3	10.1	8.3
TPH	Motor oil	Median	1.17	0.19	0.56	1.41	0.22	0.68
	Diesel	NA[b]	NA[b]	NA[b]	NA[b]	NA[b]	NA[b]	NA[b]
Bact.	Fecal coliforms	Median	1220	820	1620	NA[b]	NA[b]	NA[b]
	Escherichia coli	Median	605	680	860	NA[b]	NA[b]	NA[b]

[a] All values in mg/L, except bacteria in number/100 mL

[b] NA—not available because the variable was detected in no or few samples, making calculation of summary statistics impossible or not meaningful (dissolved lead and Diesel), or because flow weighting was impossible with grab sampling not associated with flow measurement (bacteria)

Table 3. Event Mean Concentration Ranges Measured in 110th Cascade Discharge Samples and Truncated to Omit Largest and Smallest Values

Water Quality Variable[a]	Number Observed	True Minimum	True Maximum	Truncated Minimum[b]	Truncated Maximum[b]
Total suspended solids	14	9	42	10	40
Total nitrogen	14	0.600	1.600	0.600	1.400
Total phosphorus	14	0.075	0.240	0.089	0.230
Soluble reactive phosphorus	13	0.021	0.110	0.023	0.099
Total copper	11	0.0039	0.0080	0.0039	0.0076
Total zinc	11	0.039	0.11	0.039	0.11
Total lead	11	0.0016	0.0080	0.0018	0.0067
Dissolved copper	14	0.0014	0.0072	0.0017	0.0049
Dissolved zinc	14	0.012	0.067	0.018	0.057
Dissolved lead	14	<0.0010	0.0020	<0.0010	<0.0010
Total hardness	14	6.3	25	7.8	17
Motor oil	14	<0.11	0.33	<0.15	0.33
Diesel	14	<0.05	<0.13	<0.05	<0.11

[a] All values in mg/L

[b] Truncated values are the second lowest and second highest measured.

Paired Station Pollutant Concentration Comparisons

Comparison of 110th Cascade Inflow and Outflow Water Quality

On average (Table 2), concentrations were lower at the 110th Cascade outlet than at the inlet, except for SRP, total hardness, and *E. coli*. SRP in the discharge was about three times as high as in the inflow. Venema average concentrations fell between the 110th influent and effluent, except for total and dissolved zinc, total hardness, bacteria. The zinc values were lower than found in the 110th discharge, while bacteria were higher. However, a simple comparison of the central tendencies of data sets is not always a robust analysis. A more meaningful assessment in this setting is to consider variance, the pairing of observations, and the lateral inflows between the monitored inlet and outlet at 110th.

Table 4 reports the results of the statistical tests carried out to compare the data sets from the inlet and outlet of the 110th Cascade system. For nearly all water quality variables, the null hypothesis (that the data sets were the same) was rejected at high confidence levels (low p-values); i.e., the runoff at discharge was significantly cleaner than when entering. The results were the same regardless of whether paired or unpaired tests were used. For most pollutants, establishing significant differences between the inlet and outlet required only a few observations, because in all storms one station had substantially more of the pollutant than the other station. The relatively few samples required to establish the significance of differences for almost all water quality variables is a strong indication that the monitoring program completed is sufficient to define well the 110th Cascade system's performance.

The pollutants exhibiting the biggest differences in concentration between the cascade's inlet and outlet were TSS, motor oil, and total metals. The only contaminants not reduced in concentration were dissolved zinc, for which there was no discernable difference between the inlet and outlet with the 14 samples available, and soluble reactive phosphorus, which was present at significantly higher concentrations at the discharge. Outflow was also slightly harder than the inflow.

Table 4. Comparison of Pollutant Concentrations at 110th Cascade Inlet and Outlet

	Unpaired Comparisons		Paired Comparisons		# Paired Samples	# Needed[b]	Site with Higher Concentrations
Water Quality Variable[a]	Different?	p-value	Different?	p-value			
Total suspended solids	Yes	<0.001	Yes	0.001	14	< 4	110th Cascade inlet
Total nitrogen	Yes	0.015	Yes	0.014	14	9	110th Cascade inlet
Total phosphorus	Yes	0.054	Yes	0.012	14	7	110th Cascade inlet
Soluble reactive phosphorus	Yes	<0.001	Yes	<0.001	13	< 4	110th Cascade outlet
Total copper	Yes	<0.001	Yes	0.002	11	< 4	110th Cascade inlet
Total zinc	Yes	0.001	Yes	0.006	11	5	110th Cascade inlet
Total lead	Yes	<0.001	Yes	0.001	11	< 4	110th Cascade inlet
Dissolved copper	Yes	0.037	Yes	0.051	14	12	110th Cascade inlet
Dissolved zinc	No	0.186	No	0.367	14	24	Neither
Dissolved lead	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]
Total hardness	Yes	0.057	Yes	0.002	14	< 4	110th Cascade outlet
Motor oil	Yes	<0.001	Yes	<0.001	14	4	110th Cascade inlet
Diesel	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]

[a] All values in mg/L
[b] Number of paired observations required to detect a significant difference between the two sites at a 90 percent confidence level based on the variance in the data
[c] NA—not available because the variable was detected in no or few samples, making calculation of statistics impossible or not meaningful

It is important to view the above comments in the context of the lateral inflows between the inlet and outlet. Because of these unmeasured flows, the differences in pollutant concentrations at the two stations are not necessarily attributable to treatment by the cascade system. It is possible that the water sampled at the outlet was not at all the same water sampled at the inlet, or that the flow was diluted.

Table 2 presents summary statistics using the entire data sets at the 110th Cascade inlet and outlet. Another way of looking at the data is to use only the inflow paired with outflow values when there was a discharge (the values underlying the Paired Comparisons columns in Table 4). Taking TSS as an example, the range of inflow concentrations in that data subset was 34-644 mg/L. As already pointed out, the range of outflow concentrations was 9-42 mg/L, or 10-40 mg/L truncating the range to remove the largest and smallest values. In the data subsets being considered here, the mean and median inflow concentrations were 150 and 98 mg/L, respectively. The mean and median outflow concentrations were 27 and 26 mg/L, respectively. The average concentration difference between inflow and outflow was 86 mg/L (57-139 mg/L lower and upper 90 percent confidence limits). The best estimate of TSS concentration reduction was 76 percent (68-82 percent lower and upper 90 percent confidence limits).

Comparison of 110th Cascade Outflow and Venema Water Quality

Table 5 shows that results of the comparison between runoff quality at the cascade outlet and untreated Venema catchment. The paired tests were preferred because they eliminated the noise attributable to hydrologic variability. These tests showed with a high degree of certainty that the water leaving the 110th Cascade basin was cleaner than that leaving the Venema basin in most respects. For instance, the Venema flow had three-to-four times higher TSS and total lead than that leaving the 110th Cascade basin. Of course, this comparison pertains only when the latter discharged; in most storms there was no flow from the 110th Cascade system. Dissolved zinc, soluble reactive phosphorus, total zinc and dissolved copper are exceptions to the general trend. In the latter two cases, there was no detectable statistical difference between the concentrations at the two sites with the number of samples available. For dissolved Zn and SRP, the concentrations at the cascade discharge were significantly higher than those in the Venema catchment.

As with the comparison between the 110th inlet and outlet water quality, relatively few samples were required to establish the significance of differences for most quantities. The exceptions were total zinc and dissolved copper, mostly because of high variance in the Venema samples. Still, the monitoring at both 110th and Venema was adequate in most respects to understand well the performance of the natural versus conventional drainage systems.

Table 5. Comparison of Pollutant Concentrations at 110th Cascade Outlet and Untreated Venema Catchment

Water Quality Variable[a]	Unpaired Comparisons		Paired Comparisons		# Paired Samples	# Needed[b]	Site with Higher Concentrations
	Different?	p-value	Different?	p-value			
Total suspended solids	Yes	0.004	Yes	0.010	8	< 4	Venema basin outlet
Total nitrogen	Yes	0.072	Yes	0.027	8	5	Venema basin outlet
Total phosphorus	No	0.313	Yes	0.014	8	< 4	Venema basin outlet
Soluble reactive phosphorus	Yes	0.037	Yes	0.005	6	< 4	110th Cascade outlet
Total copper	Yes	0.028	Yes	0.056	6	5	Venema basin outlet
Total zinc	Yes	0.044	No	0.714	6	111	Neither
Total lead	Yes	0.002	Yes	0.004	6	< 4	Venema basin outlet
Dissolved copper	No	0.568	No	0.601	8	74	Neither
Dissolved zinc	Yes	0.042	Yes	0.008	8	< 4	110th Cascade outlet
Dissolved lead	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]
Total hardness	Yes	0.014	Yes	0.068	8	7	110th Cascade outlet
Motor oil	Yes	0	Yes	0.008	8	< 4	Venema basin outlet
Diesel	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]

[a] All values in mg/L
[b] Number of paired observations required to detect a significant difference between the two sites at a 90 percent confidence level based on the variance in the data
[c] NA—not available because the variable was detected in no or few samples, making calculation of statistics impossible or not meaningful

Dissolved Metals Levels Relative to State Water Quality Criteria

Metals were a particular concern among the pollutants measured here, because of their toxicity to aquatic biota. The metal concentration considered acutely or chronically toxic to biota is a function of the hardness of the water and the duration of exposure. The dissolved species, the basis for state water quality criteria, were of most concern, because of their mobility and availability to organisms.

Figures 4 and 5 plot dissolved copper and zinc EMCs, respectively, versus total hardness EMCs at all stations. The lines on the graph indicate the acute and chronic toxicity criteria according to Washington State water quality standards. Data plotting above these lines indicate that the average condition of the runoff during the storm was above the criterion. The only composite sample that was below both the acute and chronic criteria for copper and zinc was the November 3, 2005 sample at the cascade inlet. These figures also demonstrate that the magnitudes of exceedance of the toxicity criteria were less at the 110th Cascade outlet than at the inlet, and less than at Venema for copper but not zinc. Despite the difference, the water leaving the 110th Cascade system was still consistently above the dissolved metals criteria.

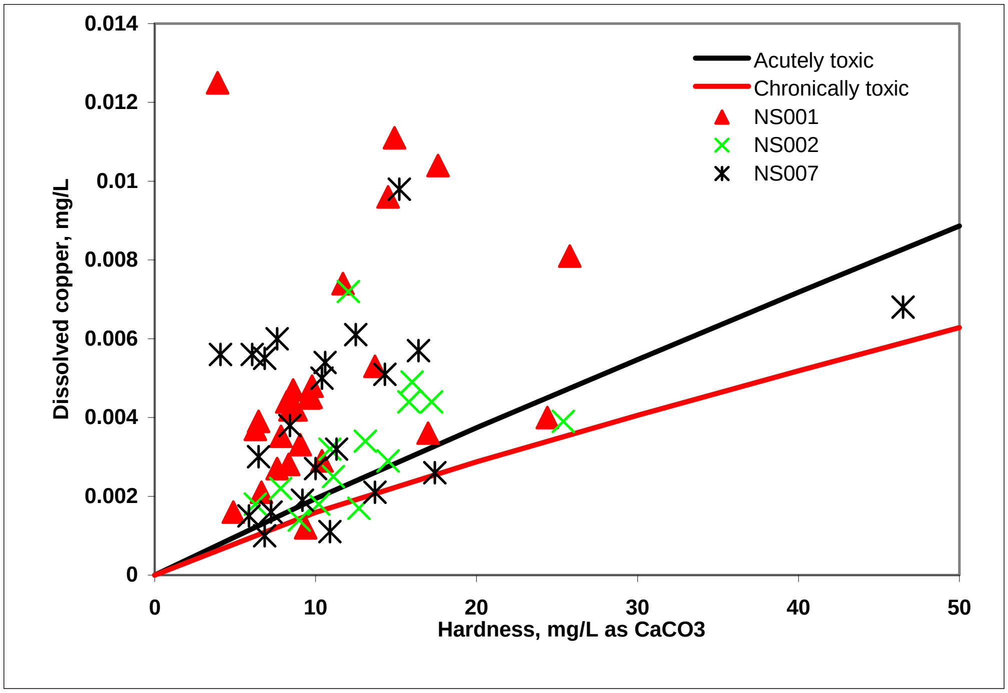

Figure 4. Dissolved Copper Concentrations in 110th Cascade Inlet (NS001), Outlet (NS002), and Venema (NS007) Stations Relative to State Water Quality Criteria

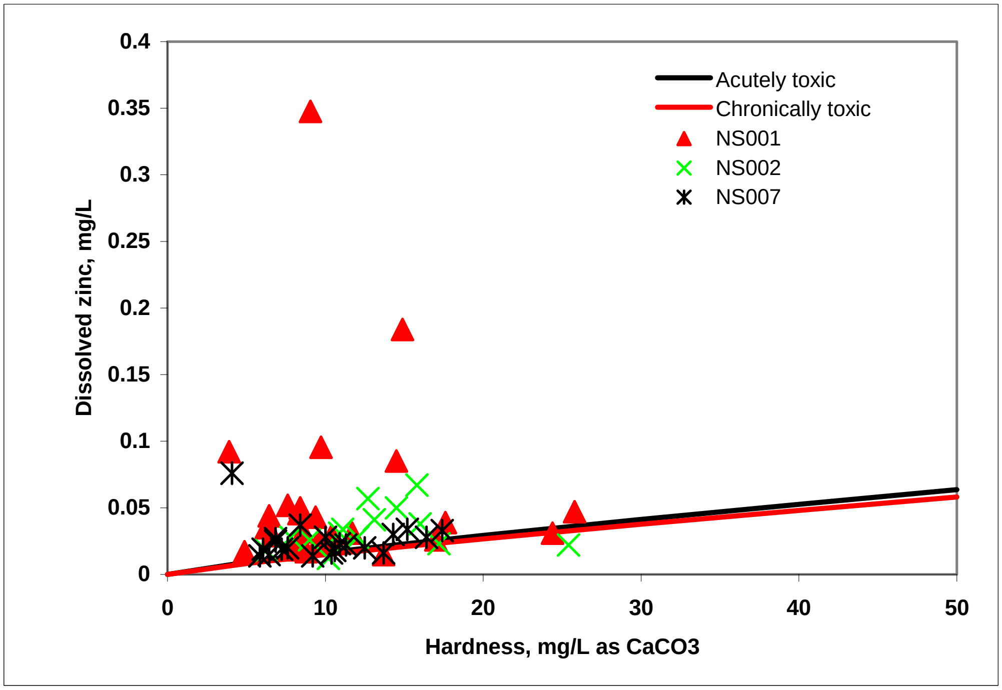

Figure 5. Dissolved Zinc Concentrations in 110th Cascade Inlet (NS001), Outlet (NS002), and Venema (NS007) Stations Relative to State Water Quality Criteria

The dissolved lead detection limit of 0.001 mg/L was only exceeded during four storms (twice at the inlet to 110th Cascade, once at the outlet to 110th Cascade, and once at the outlet to the Venema basin). None of these four observations were greater than the state's acute toxicity standard, but they all were greater than the chronic toxicity criterion. The lead chronic toxicity criterion (0.0002 – 0.0004 mg/L for total hardness of 10 – 20 mg/L as $CaCO_3$) is below the detection limit. Therefore, it can be said that the chronic criterion was exceeded in all storms when dissolved lead was detected.

Reduction of Pollutant Mass Loadings

Table 6 presents the results of conservatively estimating mass loading reductions by ignoring the unmeasured lateral inflows to the 110th Cascade. It is apparent that the system removed the majority of the influent pollutants. The best estimates suggest that the mass of TSS at the outlet was 84-88 percent less than that at the monitored inlet. Given the uncertainties in the median TSS at the two sites, it can only be said with 90 percent certainty that the TSS removal was greater than 72 percent. This is a very conservative estimate, because it uses the lowest possible median value for the inlet concentration and the highest value for the outlet concentration. Again, it also ignores removal of pollutants from the lateral inflows.

Mass loading data are frequently normalized on the basis of per unit contributing area over an annual period. Using only paired inflow and outflow data when there was a discharge and assuming no lateral inflow, with TSS as an example, the best estimate of mass loading reduction was 86 percent. From Chapman's (2006) Table N.5, the mass inflow was 754-995 lbs TSS/acre EIA-year (847-1118 kg TSS/ha EIA-year), depending on how concentrations were averaged (EIA is effective impervious area of the contributing catchment). With 86 percent reduction the outflow then would be 106-139 lbs TSS/acre EIA-year (118-157 kg TSS/ha EIA-year).

Table 6. Estimated Reductions in Pollutant Mass Loadings Over the Full Sampling Program at the 110th Cascade

Water Quality Variable[a]	% Reduction Method 1[b]	% Reduction Method 2[b]	% Reduction Method 3[b]	90% confidence interval
Total suspended solids	84	88	86	72 - 91
Total nitrogen	63	65	57	53 - 74
Total phosphorus	63	69	65	49 - 74
Soluble reactive phosphorus	No significant decrease			
Total copper	83	81	78	77 - 88
Total zinc	76	80	79	48 - 85
Total lead	90	87	86	84 - 94
Dissolved copper	67	60	45	50 - 78
Dissolved zinc	55	74	72	21 - 70
Dissolved lead	NA[c]	NA[c]	NA[c]	NA[c]
Total hardness	38	40	26	15 - 55
Motor oil	92	92	92	86 - 97
Diesel	NA[c]	NA[c]	NA[c]	NA[c]

[a] All values in mg/L
[b] Methods 1, 2, and 3 compute mass loadings using the central tendency of concentrations and total volumes, flow-weighted average concentrations and total volumes, and paired storm concentrations and volumes, respectively. Refer to Chapman's (2006) Appendix N for details.

[c] NA—not available because the variable was detected in no or few samples, making calculation of statistics impossible or not meaningful

It appears that the load of total nitrogen was reduced 57-65 percent and total phosphorus by 63-69 percent. The most conservative estimates, using the extremes of the confidence intervals, show that the TP and TN removals were no less than 50 percent.

Metals were also removed well by the system. The estimates shown in Table 6 indicate that 86-90 percent of the total lead mass was captured, with the most conservative estimate being 84 percent. The total loadings of copper and zinc were reduced by 78-83 and 76-80 percent, respectively. It should be noted, though, that the low estimate of total zinc removal is 48%. This number must be viewed in context. The total zinc observations at the inlet and outlet stations are not normally distributed, and only the inlet observations are log-normally distributed. As such, the median was used to estimate and compare the central values, and this estimator has a wide confidence interval. The confidence interval gives a low estimate of system performance, resulting from the variability seen in the data. This observation highlights differences that can and do result depending on the statistical techniques and assumptions employed.

In several storms, motor oil was not detected at the outlet; in these cases one-half the reporting limit was used in the calculations of loading reduction. All three methods show that 92% of the motor oil was removed by the system.

<u>Comparisons with other BMPS</u>

Pollutant concentrations in the effluent of 110th Cascade were compared to concentrations in the outflow from other BMPs documented in an international data base of stormwater studies (GeoSyntec Consultants, Inc. 2006). The effluent of 110th Cascade was significantly lower in total and dissolved copper, dissolved lead, and dissolved phosphorus than the discharge from a number of stormwater treatment systems, including biofilters, detention basins, media filters, and wetland basins. The only pollutant that was significantly higher in the effluent of 110th Cascade than in other observed BMPs was zinc.

The data base of studies just mentioned did not provide information on mass loading reductions by the various types of BMPs. Barrett (2005) examined a large California Department of Transportation (Caltrans) BMP data base reporting influent and effluent concentrations for TSS, SRP, nitrate-nitrogen, dissolved copper and dissolved zinc. He observed, as in this study, that effluent concentrations in the outflow from some BMPs were a function of influent concentrations for some pollutants, while in other cases effluent concentrations varied randomly, regardless of influent quality. He established “design storm” influent concentrations representative of the Caltrans highway system where the monitoring occurred. For the BMPs where outlet concentration appeared to be a function of inlet concentration, he used a parametric regression equation to calculate the representative outlet quality, given the representative influent quality. For each BMP, he also estimated the extent to which the BMP retained storm flows. Taking into account this reduction in flow volume, along with the representative inlet and outlet pollutant concentrations, he calculated (with confidence intervals) the percent loading reductions typical of wet basins, multi-chamber treatment trains, sand filters, extended detention basins, swales, and filter strips.

The 110th Cascade system was evaluated in a similar manner. In terms of TSS loading reduction, the 110th Cascade appeared to perform more effectively than swales, filter strips and extended detention basins, and was not significantly different from the other BMPs considered by Barrett. Dissolved copper was removed less effectively than by filter strips (in terms of mass), but was not significantly different from the other BMPs in this respect. Regarding dissolved zinc, it appeared (per the procedures of Barrett) that 110th Cascade was significantly better than all other BMPs except the Delaware sand filter. However, the procedure of Barrett depended on an inlet concentration of dissolved zinc of 0.122 mg/L, typical of the Caltrans system. This value is higher than almost all of the observations at the inlet to 110th Cascade, and its use as a representative inlet concentration leads to the estimate that the 110th Cascade system removes between 83% and 92% of the mass of dissolved zinc in the design storm. The best estimates in this study (see Table 6) suggest that 110th Cascade did not reduce the mass of dissolved zinc by this amount. These findings underscore the difficulties in making meaningful comparisons between studies, or generalizing about classes of BMPs. There are many ways to quantify the performance of a stormwater treatment system and differing technical and analytical methods differ from study to study.

Particle Size Distribution

A general conclusion from replicate sample and standard particle testing was that the LISST instrument could accurately report the median diameter of particles in a relatively narrow size range but not a broader range, such as occurs in environmental samples. However, observed size-distribution curves did not correspond well to the published actual plots. Comparatively large particles (approximately 40 μm and larger) produced the greatest variability. In addition to the variability from aliquot to aliquot as sensed by the instrument, sub-sampling introduced further variability. Among the many different procedures attempted, no one method or combination of methods consistently yielded similar distribution curves. All of the dispersion of measurements made it impossible to assess flocculation and the maximum holding time that should be observed. Overall, then, the instrumentation and methodology available for this study is not adequate for the task of accurately and precisely establishing PSD for purposes of assessing treatability of stormwater runoff.

Though TSS has been monitored in water quality studies for decades, efforts are still being made today to find repeatable, representative, and inexpensive ways of measuring the amount of solids in water. There are many opportunities for bias to be introduced, from the method of acquisition of the sample, to the method of sub-sampling, to the method of measurement (James 2005). Suspended sediment concentration (SSC) is an alternative to TSS and has been documented by U.S. Geological Survey (USGS, Gray et al. 2000) to have advantages stemming largely from its basis in measuring the dry weight of all the sediment from a known volume of a water-sediment mixture, instead of subsampling as in TSS determination. In An evaluation of 3,235 paired SSC and TSS data USGS found that as sand-size material in samples exceeded about a quarter of the sediment dry weight, SSC values tended to exceed their corresponding paired TSS values. TSS analyses of three sets of quality-control samples (35 samples) showed unexpectedly small sediment recoveries and relatively large variances. In contrast, the method for determining SSC produces relatively reliable results for samples of natural water, regardless of the amount or percentage of sand-size material in the samples.

Still, even if SSC would replace TSS, information on the particle composition is still necessary for a thorough understanding of settling behavior and overall pollutant transport, meaning a reliable and standardized means of measuring PSD. That means does not appear to be available at this time. James (2005), quoting URS Greiner/Woodward Clyde (1999), observed that PSD) data show conflicting results which vary from study to study and may be due to sampling and analytical methods or watershed characteristics. LISST technology is not the only means available to determine PSD. Sieving is a low-technology alternative but is burdensome and subject to its own difficulties in getting accurate and precise data. Another instrumental technique is the Coulter counter, long used in phytoplankton and bacterial studies and, to a much lesser extent and more recently, for PSD determination. An online search in scientific data bases and Google found no record of investigation of the quality of Coulter counter PSD results such as performed for the LISST instrument in this work. The subject of solids measurement is prominent in the stormwater field now, and breakthroughs are possible within the next several years. SPU should keep abreast of developments and make every attempt to bring reliable PSD monitoring into its program.

CONCLUSIONS AND RECOMMENDATIONS

This study sought to characterize the ability of a second-generation stepped-pool cascade system to treat stormwater runoff in an urban setting. Despite some information gaps and sources of uncertainty, the data collected in this study were enough to draw strong conclusions regarding the characteristics of the 110th Cascade treatment system, and urban runoff in general.

Conclusions from Earlier Natural Drainage System Monitoring

- Earlier monitoring of the first-generation Viewlands Cascade found it to cut the total influent volume over a period of time by over half and the average peak flow rate of entering runoff by about 60 percent. However, little or no reduction of either peak flow rate or volume occurred during relatively large storms. There was no discharge from the end of the channel in 27 percent of the events monitored. It can completely infiltrate the catchment response to about 0.13 inch (3.3 mm) of precipitation and 1750 ft^3 (50 m^3) of influent.

- Another natural drainage system preceding the 110th Cascade, the 2nd Avenue NW SEA Streets project in its first two years discharged runoff during only 6.8 percent of the rainfall events, contrasting with the street it replaced, which discharged in all events monitored. The SEA Streets drainage system's yield (runoff volume per unit rainfall depth) was just 1.9 percent of the amount before the project's construction. Since passing about 2 years of age, it has not discharged at all, despite the occurrence of the largest 24-hour rainfall and the wettest month in Seattle's history. It is likely that the maturing vegetation more effectively intercepts rainfall, assimilates more water into its tissues, and assists percolation through the soil by piping water along the root structures.

Conclusions Regarding 110th Cascade Monitoring and Performance

- Analyzing the 110th Cascade faced being able to estimate unmeasurable sheet flows entering the system downstream of the inlet flow gauge. Combining field reconnaissance and observation of flows with map analysis was successful in estimating the effective contributing catchment area and flow volume. The method was independently verified by regressing flow volume per unit total contributing area versus rainfall depth. These methods can be applied in future monitoring programs in similar circumstances, when only a portion of the inflow can be collected and measured directly.

- The flow record comprises 235 precipitation events, during or after which no flow discharged from the cascade in 186 (79 percent). In 117 storms during dry conditions (defined by an antecedent precipitation index), the 93 events less than 0.48 inch (12.2 mm) produced no outflow. Of the 24 larger storms, only 14 generated runoff at the outlet. In the wet condition (118 storms), the 66 storms having less than 0.29 inch (7.4 mm) of rain were completely infiltrated. Hence, the system is capable of completely attenuating surface runoff from about 0.3 inch (7.6 mm) of rain under any condition. Of the 52 remaining events in wet conditions, 35 produced a discharge. The second-generation 110th Cascade, constructed in amended soils, improved upon the performance of the earlier Viewlands Cascade in increasing the number of events with no outflow from 27 to 79 percent and the fully absorbable rainfall quantity from 0.13 to 0.3 inch (3.3 to 7.6 mm).

- At least 48 percent of all water entering the system was detained, and either infiltrated, evaporated or transpired. The true number was probably closer to 74 percent, on the basis of the reasonable and demonstrated assumption that the contributing basin below the inlet has the same effective contributing area and generates the same flow volume as that above the inlet.

- Of the 49 events with any discharge at all, the outlet peak flow rate was above the rate at the inlet in only 13. Based again on the estimate that the true inflow to 110th Cascade was twice that entering at the inlet station, though, it appears that the system reduced peak flow rates in every storm, and usually by over half.

- Considering only relatively large, extended storms falling on comparatively wet soils, it appears that an infiltration rate of 0.3-0.5 inch/hour (7.6-12.7 mm/hour) is a reasonable, relatively conservative value for design of a cascade in a hydrogeologic environment similar to the 110th Cascade.

- Water quality monitoring established the reliable effluent concentration (the highest concentration that the cascade is likely to discharge and the irreducible minimum (the lowest concentration that can be achieved with this practice) for solids, nutrients, metals, and petroleum hydrocarbons (Table 3).

- In the minority of events for which there was any discharge, the only contaminants not reduced in concentration between the inlet and outlet of the cascade were dissolved zinc, for which there was no significant difference between the inlet and outlet, and soluble reactive phosphorus, which was present at significantly higher concentrations at the discharge.

- Using only the inflow paired with outflow values when there was a discharge, the best estimate of TSS concentration reduction was 76 percent (68-82 percent lower and upper 90 percent confidence limits).

- In comparing the 110th Cascade and untreated Venema systems, it must be kept in mind that the former discharged rather rarely. When it did, all pollutant concentrations were significantly less at the cascade outlet than at Venema, except for dissolved zinc, soluble reactive phosphorus, total zinc and dissolved copper. In the latter two cases, there was no detectable statistical difference between the concentrations at the two sites. For dissolved Zn and SRP, the concentrations at the cascade discharge were significantly higher than those in the Venema catchment.

- For most water quality variables, establishing significant differences between the cascade inlet and outlet and between the cascade and Venema discharges required fewer observations than the 14 or eight data pairs produced by the monitoring program. The relatively few samples needed is a strong indication that the monitoring program completed is sufficient to define well the 110th Cascade system's performance.

- Most dissolved copper and zinc samples from all sites exceeded the state of Washington toxicity criteria. The magnitudes of exceedance were less at the 110th Cascade outlet than at the inlet but still consistently above the criteria.

- The best estimates of conservatively estimating pollutant mass loading reductions over the full monitoring program (Table 6) indicate reductions of no less than 85-90 percent for total suspended solids, lead and motor oil; 60 percent for total nitrogen and total phosphorus; 80 percent for total copper and total zinc; 50 percent for dissolved copper and zinc. There was no significant decrease of soluble reactive phosphorus loading.

- Using only paired inflow and outflow data when there was a discharge and assuming no lateral inflow, the best estimate of TSS mass loading reduction was 86 percent. At that level of reduction, the cascade was estimated to decrease mass inflow from 754-995 lbs TSS/acre EIA-year (847-1118 kg TSS/ha EIA-year) to 106-139 lbs TSS/acre EIA-year (118-157 kg TSS/ha EIA-year).

- The monitoring program experienced great difficulty in obtaining reliable analyses of particle size distribution and expended considerable effort to find ways of doing so. It was possible to measure accurately the median diameter of particles in a relatively narrow size range but not a broader range, such as occurs in environmental samples. Also, observed size-distribution curves did not correspond well to published actual plots for standard samples. Comparatively large particles (approximately 40 µm and larger) produced the greatest variability. There is no convenient and well documented and standardized way of analyzing stormwater PSD at this time.

Recommendations

- The results of this study should be used to plan and design future cascade drainage systems and project their performance and benefits. The data offer means of quantifying expected runoff quantity and quality control, often with measures of uncertainty. For design in similar settings, the conservative infiltration rate of 0.3-0.5 inch/hour (7.6-12.7 mm/hour) is a starting point but should be confirmed by percolation testing at the proposed project site.

- Since the cascade did not reduce levels of metals to below toxic criteria, preventive source controls should be part of any watershed strategy incorporating natural drainage systems, preferably; or other BMPs must be developed that address this type of pollution.

- While the monitoring program completed is sufficient to define well the 110th Cascade system's performance, its operation could change over the years. The extensive database from its early years is available for convenient comparison of its effectiveness later. Restarting the monitoring program should be considered after 5-10 more years of service. In addition to the pollutants already monitored, emerging water quality concerns, such as commercial, industrial, and automotively generated chemical compounds, should be considered for inclusion. Monitoring at that time should also incorporate analysis of metal contents of channel bottom soils, in relation to areas not regularly channeling urban runoff, to determine if potentially toxic elements are beginning to build up.

- When carrying out stormwater investigations, planners should thoroughly investigate basin drainage conditions prior to study design. Analyses of flow and water quality data at a site (and comparisons of data between sites) depend on well defined contributing area boundaries. The determination of the treatment performance of a system requires data from a representative inlet and an outlet.

- In future monitoring it would be best if all entering flow can be concentrated at one inflow point. If that is impossible, as it was at the 110^{th} site, the methods developed during this project using field observations, map assessment, and statistical procedures together should be used to obtain estimates of unmeasured inflows with relative confidence.

- To check for trends over time, especially when comparing the pre- and post-construction conditions in a treatment basin versus a control basin, the paired watershed procedures presented by the U.S. Environmental Protection Agency (1993) should be followed. Generally but dependent on specific objectives, observations should be made for both periods in both basins at inlet and outlet stations.

- The comparison of water quality data from two sites must take into account hydrologic factors and basin conditions. Typically, comparisons of water quality data sets treat the individual observations as log-normally distributed, random values that vary about some average. However, observations of pollutant levels are heavily influenced by rain patterns and pollutant-supply dynamics. This noise could potentially be eliminated by making many observations over longer periods of time and during many types of storms, but such extensive monitoring is probably unaffordable. Comparisons of data sets from different sites and different time periods can only be justified if hydrologic conditions are quantified and shown to be reasonably similar.

- The cascade studied here was effective in many ways, but it is still not certain that further application of natural drainage systems can truly be restorative for streams over time. Receiving water biological and habitat monitoring should be coupled with treatment system hydrologic and water quality studies to determine their ultimate effectiveness in improving ecosystems.

- Although particle size analysis was not successful in this project, the subject of solids measurement is prominent in the stormwater field now; and breakthroughs are possible within the next several years. SPU should keep abreast of developments and make every attempt to bring reliable PSD monitoring into its program.

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