SEATTLE STREET SWEEPING PILOT STUDY

Monitoring Report

Prepared by

Seattle Public Utilities

and

Herrera Environmental Consultants

February 12, 2009

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Prepared by

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Executive Summary

This report summarizes the results of a 1-year study sponsored in 2006 by Seattle Public Utilities (SPU) to evaluate whether street sweeping can significantly reduce the mass of pollutants discharged to area receiving water bodies while reducing the frequency of catch basin cleaning by removing sediment/debris from the street before it is transported in stormwater runoff. The investigation was jointly conducted by SPU and the Seattle Department of Transportation (SDOT).

Background

SPU is responsible for managing the quality and quantity of stormwater discharged from the public storm drain system, which serves an estimated area of 40,800 acres in the Seattle metropolitan area. SPU undertook this investigation in part to respond to the requirements of its National Pollutant Discharge Elimination System (NPDES) municipal stormwater permit, which requires the City to implement a variety of projects and programs to improve stormwater quality. Additionally, this study investigates whether street sweeping can be effective in reducing the effect of City outfalls on sediment quantity and quality in the offshore receiving environment.

Because Seattle is largely built-out, there is little undeveloped land available to site large regional stormwater treatment facilities. Therefore, source control is an important component of the City's stormwater program. Street sweeping has the potential to be an effective source control strategy by preventing a significant amount of sediment and associated contaminants from being discharged to receiving waters, which not only impacts water/sediment quality but also impairs substrate quality. Other benefits may include reduced flooding, better aesthetics due to less trash on roadways, and improved air quality due to reductions in street dirt.

Under its NPDES permit, Seattle is required to annually inspect each of the estimated 35,000 to 40,000 catch basins in the City and to clean these when the sediment depth exceeds 60 percent of the sump depth, or where the minimum clearance between the sediment surface and the invert of the lowest pipe is less than 6 inches (Ecology 2005, 2007). Catch basin inspection and cleaning constitutes nearly 60 percent of SPU's $3.7 million drainage-related maintenance budget. If street sweeping can reduce the frequency at which catch basins require cleaning, SPU could realize a significant savings in its maintenance budget for catch basin cleaning.

Seattle is also involved in a number of state and federal cleanup projects involving contaminated sediment in several of the large water bodies offshore of the City (e.g., Duwamish Waterway, Lake Union, and East Waterway). Ongoing discharges from City storm drains have been identified as a potential source of pollutants to these water bodies. Reducing the amount of pollutants discharged by expanding or improving street sweeping practices could minimize the potential for sediments to become recontaminated following cleanup and reduce the City's overall liability should contamination reoccur in the future.

SDOT is responsible for maintaining City roadways and has an annual budget of approximately $1.2 million for street sweeping and leaf pickup operations. The sweeping program is primarily conducted for road maintenance and aesthetic purposes, and historically has not been designed or funded to provide water/sediment quality benefits. Figure ES1 shows the existing routes and frequencies for the SDOT street sweeping program. Sweeping activities generally focus on commercial roadways in downtown Seattle, the Ballard and University mixed-use neighborhoods, and select arterials throughout the City. Sweeping frequency varies from monthly or less on select arterials, to 6 nights per week in the commercial areas. Although SDOT has recently upgraded its fleet to include regenerative air sweepers, it is anticipated that mechanical-type sweepers will continue to be needed because the age, condition, and road surface material in many areas of the City are not suitable for the newer high efficiency sweepers, which require relatively smooth surfaces to be effective.

Pilot Study Design

The SPU project team elected to use a mass balance approach, which focuses on measuring the amount of sediment and associated pollutants present on the street, removed by sweeping, and accumulated in catch basins between test (swept) and control (unswept) sites, rather than measuring stormwater quality to quantify the effects of street sweeping. This decision was based, in part, on previous sweeping studies that often had difficulty showing statistically significant improvements in stormwater quality due to high temporal and spatial variability of stormwater flows and pollutant concentrations, and consequent difficulty in detecting measurable differences between the control and test sites (Martinelli et al. 2002; USGS 2007; Center for Watershed Protection 2008).

In addition, SPU conducted a baseline stormwater quality investigation in 2005 to determine if it was feasible to collect the numbers of samples needed to obtain statistically significant results for the pilot study (Herrera 2006) within the project funding constraints, which assumed a two and half year study collecting 12 samples per year for a total of 30 samples per site. Six grab samples were collected in each of two paired catchments, which are typical of residential sites in Seattle, and selected water quality parameters were analyzed.

A power analysis showed that the number of samples required would be cost prohibitive due to the variability of stormwater quality and low pollutant concentrations in the samples. At the target level of sampling (30 samples), stormwater sampling would be able to detect a difference (relative to the mean) of approximately 190 to 370 percent for total suspended solids; 40 to 70 percent for total phosphorus; 10 to 220 percent for motor oil; and 40 percent for dissolved copper. Because this level of uncertainty was unacceptable, a mass balance approach on stormwater solids (i.e., street dirt, sweeper waste, and catch basin sediment) was employed in this study.

Test sites (Figure ES2) were selected in two residential areas (West Seattle and Southeast Seattle) and one industrial area (Duwamish Diagonal). At each test site, two 4-15 block areas were identified, one control (i.e., unswept) and one test site (i.e., swept).

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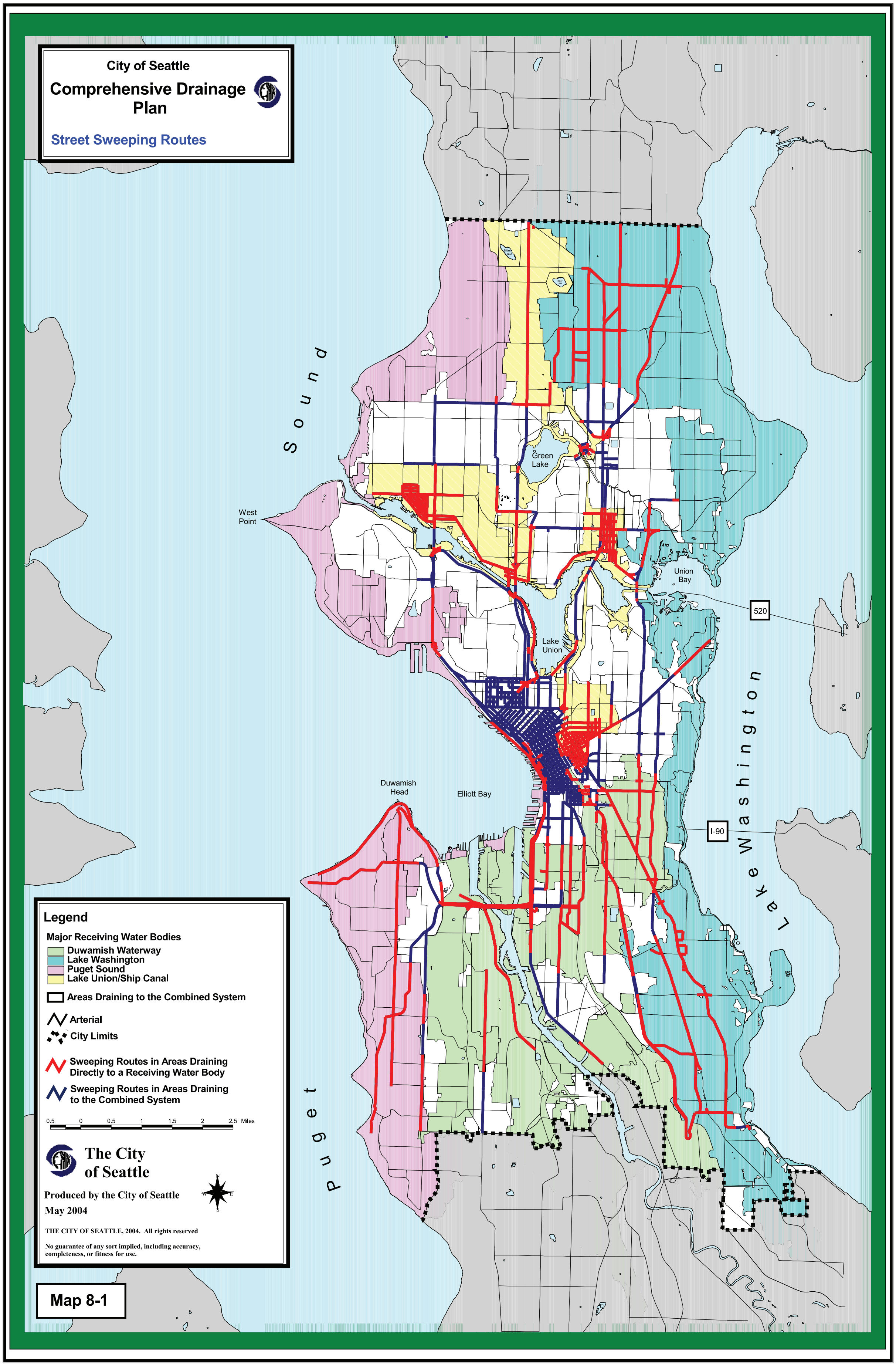

Figure ES1. Seattle street sweeping routes.

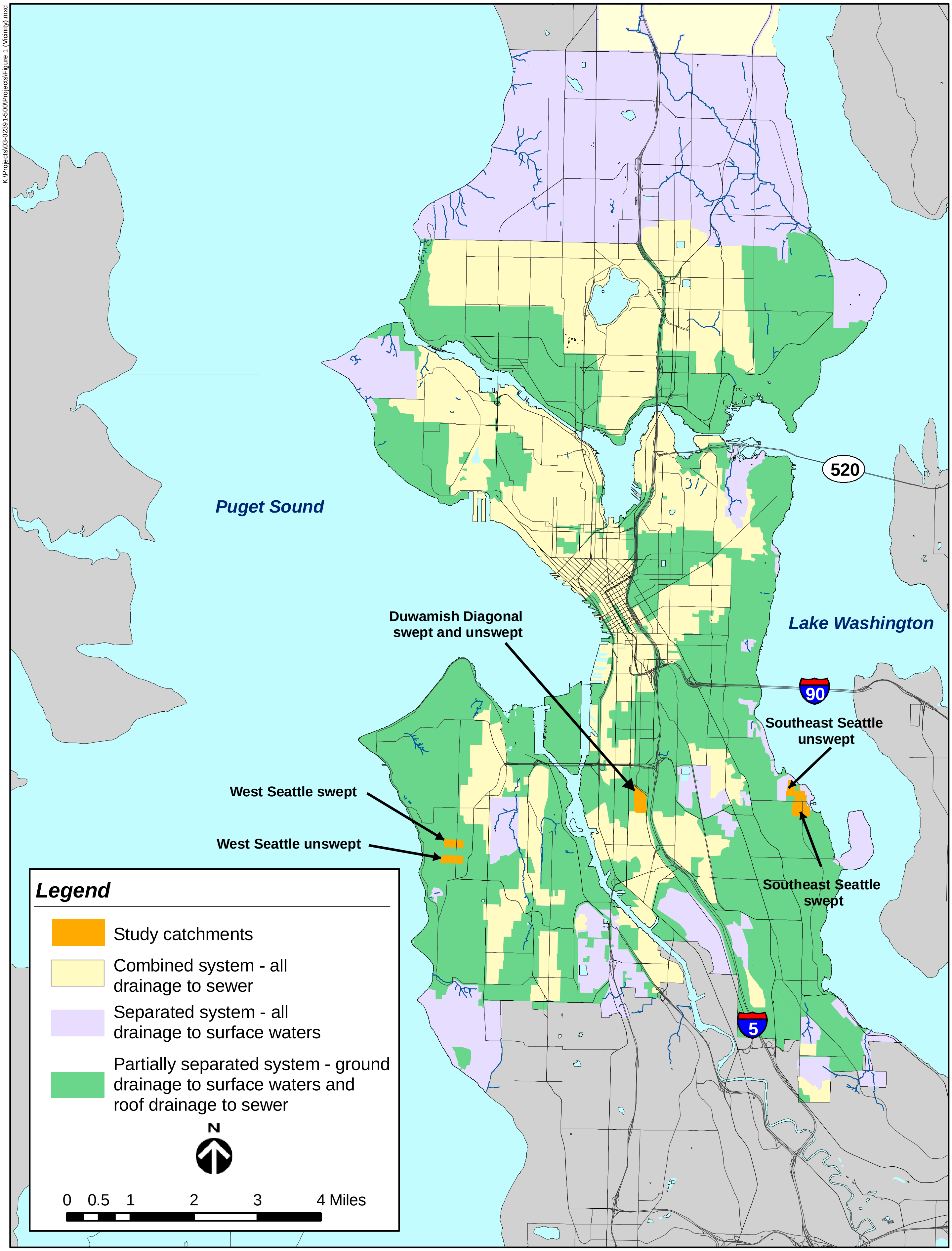

Figure ES2. Study area locations and drainage areas for the Seattle Street Sweeping Pilot Study.

Criteria used to select test sites included:

- Located in separated or partially separated service areas to evaluate sites that drain directly to a receiving water body. Note that Seattle is served by a combination of separated storm drain/sewer systems, combined sewer systems, and partially separated systems. Runoff from combined sewer areas is collected and conveyed to a regional wastewater treatment facility.
- Located in mostly or fully curbed areas, where street sweeping is most effective.
- Test and control areas are similar in size, and have similar land use, topography, and vegetative characteristics.
- Parking restrictions for area residents and businesses would not be unreasonable.
- No physical restrictions for sweeping such as large tree branches that would require pruning to allow sweepers to access the curb lane.
- Have existing flooding potential that could be relieved by street sweeping (e.g., streets lined with deciduous trees that will shed leaves, potentially clogging storm drain inlets).

The pilot test was conducted from June 20, 2006, through June 19, 2007 at the two residential study areas, and from November 24, 2006 through June 15, 2007 at the Duwamish Diagonal industrial area. The industrial area test began later because of the difficulty in locating suitable test (swept) and control (unswept) sites.

In the swept test sites, each side of the street was swept on alternating weeks, for an overall sweeping frequency of once every two weeks. Sweeping was conducted on alternating sides of the street to minimize impacts on residents/businesses by allowing them to move their vehicles to the opposite side of the street during scheduled sweeping events. The residential sites were swept on Tuesday mornings when most residents were at work and the industrial site was swept on Friday evenings when most businesses were closed.

SDOT crews swept the streets using a Schwarze Industries Model A8000 regenerative air sweeper. Each side of the street was swept from the curb to a width equal to the street sweeper (i.e., a single pass is 11.5 feet wide). A single pass covered nearly all of a traffic lane in the two residential areas, and approximately 50 percent of a traffic lane on the industrial streets in the Duwamish Diagonal study area. While some streets within the unswept sites may have been swept in the recent past as part of the City's existing street sweeping program, streets in the unswept site were not scheduled for sweeping at any time during the study. The street sweeper was operated at a rate of approximately 5 to 7 miles per hour, but slowed to make turns and maneuver around parked cars.

The pilot study was designed to calculate a mass balance for the following components of street dirt/sediment:

- Dirt remaining on street (i.e., street dirt)
- Dirt removed by street sweeper (i.e., sweeper waste)
- Dirt that accumulates in catch basins (i.e., catch basin sediment)
- Dirt exported from the site in urban runoff (estimated via mass balance).

The mass of street dirt, sweeper waste, and catch basin sediment was measured approximately every four weeks. Street dirt samples were collected using an industrial vacuum and weighed from both the swept and unswept sites on one to two days prior to sweeping. Samples were collected from alternate sides of the street on each consecutive sampling event to coincide with street sweeping events. Sweeper waste was stored in separate dumpsters assigned to each test site. Each dumpster was weighed on an industrial scale after excess water was removed with a trash pump. Material greater than 2 centimeters in diameter was removed by hand and weighed separately to determine the proportion of debris in the waste material. Sediment accumulation in the catch basins was determined by measuring down from the rim of the maintenance hole to the surface of the sediment. A total of 12 catch basins were sampled at each test/control site.

Street dirt, sweeper waste, and catch basin sediment samples were collected for chemical analysis every four weeks and archived. At the end of each quarter, a single composite sample of each media type was prepared from the archived samples and submitted to the laboratory for analysis. Samples were analyzed for total suspended solids, metals, organic content (total volatile solids and total organic carbon), semi-volatile organic compounds, and PCBs.

Test Results and Conclusions

Sediment and Pollutant Removal

Study results summarized in Figure ES3 clearly show that sweeping each side of the street every other week is very effective in reducing the amount of sediment and associated pollutants discharged from city streets. Sweeping reduced the amount of dirt per unit area of street (referred to in this report as street dirt yield) in all three study areas. The median monthly street dirt yield at the swept sites was 48, 74, and 90 percent less than the control (unswept) sites in Duwamish Diagonal, West Seattle, and Southeast Seattle, respectively. On an annual basis, sweeping removed approximately 2,200 to 3,100 pounds of material per acre of street swept (referred to as sweeper waste yield) and the amount was similar at each of the three test areas.

Sweeping can also reduce the amount of pollutants discharged from City streets to area receiving water bodies. Contaminants found in street dirt, sweeper waste, and catch basin samples included metals, petroleum hydrocarbons, and phthalates. Of these chemicals in the 55 samples analyzed, zinc (18 percent), chromium (15 percent), motor oil (82 percent), carcinogenic PAHs (78 percent), di-n-octylphthalate (65 percent), bis(2-ethylhexyl)phthalate (60 percent), butylbenzylphthalate (35 percent), and di-n-butylphthalate (29 percent) concentrations were above the Washington state sediment/soil standards and guidelines.

Effect on Catch Basin Cleaning

At the start of the pilot study, it was anticipated that street sweeping would reduce the amount of sediment that accumulated in area catch basins and, thus, would reduce the frequency at which catch basins needed to be cleaned. However, test results did not show that street sweeping affected the amount or rate of sediment accumulation in the test area catch basins. Differences in the amount of sediment that accumulated in the catch basins between the swept and unswept sites at the end of the study period were not statistically significant, either on the basis of total mass or mass per unit area of street draining to the catch basin. Swept versus unswept sediment accumulations in the 12 monitored catch basins at each site were 580 kilograms versus 610 kilograms in West Seattle (57 versus 60 g/m^2/year or 510 versus 540 lb/acre/year), 630 versus 260 kilograms in Southeast Seattle (70 versus 36 g/m^2/year or 620 versus 320 lb/acre/year), and 200 versus 140 kilogram in Diagonal Duwamish (34 versus 24 g/m^2/year or 300 versus 220 lb/acre/year).

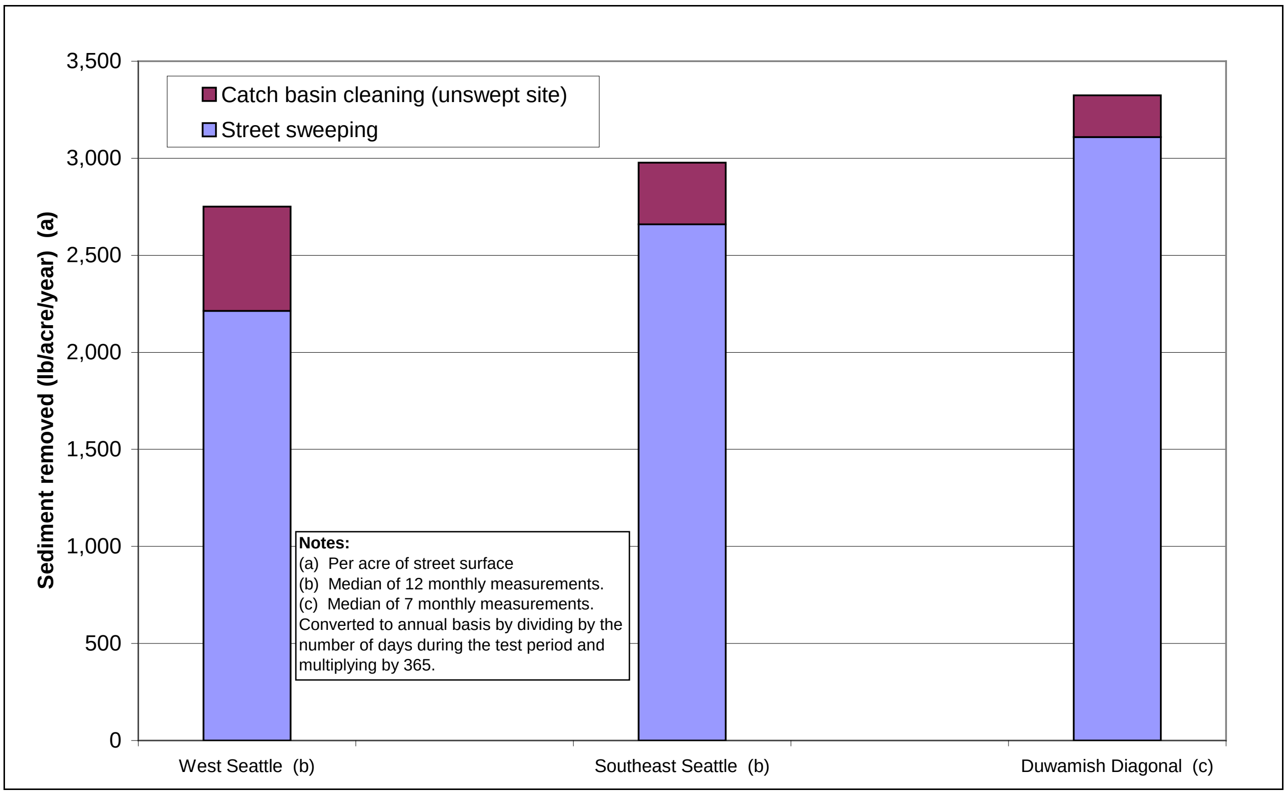

Figure ES3. Comparison of street sweeping and catch basin cleaning effectiveness.

This result indicates that street sweeping may not help to reduce SPU's catch basin maintenance costs and since the City is required to regularly clean catch basins under its NPDES municipal stormwater permit, this finding was a serious disappointment. One key qualifying factor is the fact that most of catch basins in the study sites were less than 10 percent full of sediment at the end of the study period, which is well below the 60 percent cleaning threshold established by the state. In addition, because of the difficulty in accurately measuring sediment accumulation in the pilot study catch basins and the limited duration/geographic coverage of the pilot study, it is unclear whether this finding is a consistent finding throughout the City. Further investigation of the effect of street sweeping on catch basin sediment accumulation and required cleaning frequency is warranted.

Cost Effectiveness

Street sweeping has the potential to be a cost effective strategy for removing sediment and associated pollutants from roadways in the City of Seattle and is likely to be more cost-effective than annual catch basin cleaning or stormwater treatment. Costs for a full-scale sweeping program were estimated based on SDOT's 2006 unit costs ($35 per curb mile) using a 3 percent inflation factor and a 15 percent contingency to convert to 2008 dollars, for a total of $43 per curb mile. Solids handling and transportation costs were estimated at $34/wet ton and solids disposal was approximately $43.50/wet ton.

The estimated life cycle costs for a full-scale sweeping program in Seattle ($0.34 per wet kilogram of material removed) are estimated to be approximately 90 percent of catch basin cleaning costs ($0.38 per wet kilogram of material removed). For comparison with catch basin cleaning operations, costs are presented on a wet weight basis because SPU is charged on a wet weight basis to dispose of its catch basin wastes and does not routinely measure the moisture content of this material.

The difference in cost between street sweeping and catch basin cleaning would be even larger if calculated on a dry weight basis because sweeper waste is fairly dry compared to catch basin sediment. For comparison purposes, dry weight costs were estimated based on a moisture content of 41 to 49 percent in sweeper waste measured during the pilot study and assuming a moisture content of 75 to 85 percent in catch basin solids. Using these values, the life cycle costs for a full-scale sweeping program are about 20 to 40 percent of catch basin cleaning costs ($0.51 to $0.77 per kilogram dry sweeper waste with an average of $0.62 per kilogram dry sweeper waste solids versus $1.50 to $2.50 for catch basin cleaning).

Street sweeping is also cost effective compared to treating stormwater prior to discharge. A rough comparison was made by converting the total mass removed by sweeping to a comparable stormwater TSS load. This adjustment was necessary because stormwater treatment facilities are typically evaluated based on their ability to remove TSS, which does not include larger particles associated with the bedload fraction that is included in street sweeper and street dirt measurements. SPU estimates stormwater treatment costs for capital projects based on dollars per kilogram dry TSS removed. Life cycle costs for recent estimated regional-scale stormwater treatment projects in Seattle have ranged from $10 to $30 per dry kilogram TSS removed. In Seattle, regional projects typically involve project areas of 200 to 300 acres. In comparison, life cycle costs for street sweeping are estimated at approximately $5 per kilogram dry TSS removed or approximately 15 to 50 percent of regional stormwater treatment costs.

Parking Management

The project team worked closely with local residents and businesses to ensure that parking issues did not affect the study results. Sweeping schedules were designed to minimize impacts to the neighborhoods and signs were installed throughout the test areas advising residents of parking restrictions. In addition, a sweeping schedule was sent to residents and businesses that explained the purpose of the pilot study, and described when each side of the street was not available for parking during the study period. SPU also monitored the numbers of cars that were not moved on designated sweeping days in the two residential test areas throughout the study, but violators were not ticketed. Initially, compliance with the parking restrictions was good, but the number of violations increased each month (from 52 to 197 violations per month), reaching a peak in January 2007. In February 2007, the Seattle Police Department began issuing tickets. As a result, compliance improved, with the number of violations ranging from 34 to 59 for the rest of the study.

Although compliance with parking restrictions varied throughout the study period, parked vehicles did not appear to affect the ability of the sweeper to access the curb lane. During the worst month (January 2007), only about 10 percent of the curb lane was blocked in the West Seattle study area, which experienced the most violations. SPU put a good deal of effort into managing parking during the study. It is not clear whether parking problems would have been more severe if SPU had not implemented a parking management effort, but parking will need to be considered to ensure the effectiveness of any future large scale street sweeping program.

Recommendations

Based on the results of the pilot study, it is recommended that the City begin pursuing an expanded street sweeping program to reduce the amount of pollutants discharged to area receiving water bodies from City streets. The program should start by prioritizing areas within the City where water/sediment quality improvements are most needed and where street sweeping has the greatest potential to improve water and sediment quality (e.g., arterials and curbed roads in separated or partially separated areas). Because the pilot study showed that a sweeping frequency of once every two weeks was effective in reducing sediment loading, it is recommended that this frequency be established for any new areas. In addition, the sweeping frequency should be increased to once every two weeks in existing areas that are currently swept less frequently. A sweeping frequency of once every two weeks can be achieved by sweeping alternate sides of the street on the same day each week, which would be relatively straightforward to implement from an operations, parking management, and public relations perspective. Given the magnitude of parking related issues in Seattle, the City will need to develop a parking management public relations plan as well as continue to work closely with the Seattle Police Department’s Parking Enforcement Division regarding the implementation of any future ticketing efforts.

The pilot study did not answer a number of questions related to street sweeping that are important for the City of Seattle. Further investigation is recommended in the following areas:

- Evaluate whether street sweeping can also be cost effective in areas without curbs. Many of the streets in the industrial sections of Seattle are not curbed. Because industrial streets have the potential to contribute a significant pollutant load to Seattle area water bodies, it is important for the City to develop a cost-effective strategy for dealing with these roadways.

- Continue to evaluate street sweeping performance by monitoring the mass of sweeper waste removed and tracking how mass removal rates vary with the type of streets swept (e.g., land use, traffic volume, number of parked cars, and the absence of curbs).

- Continue to evaluate the effectiveness of street sweeping at reducing drainage system maintenance costs. While this study showed that sweeping had a negligible effect on reducing catch basin sediment buildup, this result is counterintuitive and should continue to be studied as it has the potential to save the City considerable money if justified by further analysis.

Introduction

Seattle Public Utilities (SPU) is responsible for managing stormwater runoff (quantity and quality) within the city service area. Street runoff is of particular concern to the City because the public right-of-way makes up approximately 26 percent of Seattle's total land area. SPU has a number of tools for improving stormwater quality from new and redevelopment projects, including codes and manuals that prescribe non-structural (e.g., source control) and structural best management practices (BMPs) such as stormwater wet ponds, vaults, filters, and natural drainage systems, but improving stormwater quality from existing development is much more difficult. Because most existing development and roadways in the City were constructed long before stormwater controls were implemented, runoff typically discharges directly to area receiving water bodies without treatment. Retrofitting these existing systems to improve stormwater quality is often difficult, and in many cases, retrofitting is not feasible due to physical site constraints (e.g., utility conflicts, grade restrictions, and tidal influence). Consequently, nonstructural measures for improving the quality of runoff have become increasingly important. One nonstructural measure being considered by the City of Seattle to reduce stormwater pollution is street sweeping.

This report documents the results of a pilot study conducted by SPU to evaluate whether street sweeping can significantly reduce the mass of pollutants discharged to area receiving water bodies and reduce the frequency of catch basin cleaning by removing sediment/debris from the street before it can be picked up and transported in stormwater runoff. Although the City currently sweeps most major arterials on a regular basis, the sweeping program is designed primarily for aesthetic purposes (e.g., trash/debris removal). If street sweeping can be shown to yield cost-effective benefits, the City may consider modifying its street sweeping practices to realize benefits other than simple aesthetic improvements.

This pilot study was conducted to answer the following two questions:

- Does street sweeping reduce the rate of sediment accumulation in catch basins and thus reduce the frequency of catch basin cleaning?
- Does street sweeping increase the total amount of sediment and associated pollutants removed from a catchment compared to the amount removed by catch basin cleaning alone?

This report begins with background information regarding Seattle's street sweeping program, drainage system, permit compliance drivers, and the pilot study approach. In addition, this report describes the study areas and methods, presents results for each study component, and provides parking management information, cost estimates, conclusions, and recommendations.

Background

Traditionally, streets have been swept for aesthetic reasons, and this service is typically housed within the transportation or street maintenance department of city governments. Apart from transporting vehicles, streets can also convey pollutants, leaves, and debris that can impact the functionality of a drainage system, contribute to the impairment of water/sediment quality, and result in maintenance problems.

The varied benefits of street sweeping have generated increased attention for its use as a stormwater management BMP. In addition to reducing litter, street sweeping:

- Protects water and sediment quality by removing dirt and other pollutants before they enter the drainage system and receiving water bodies
- May reduce maintenance costs by reducing the amount of sediment/debris conveyed to the storm drain or combined sewer system
- May reduce flooding in some areas by removing street debris (e.g., leaves) that may otherwise clog the stormwater collection system.

Seattle's Existing Street Sweeping Program

The Seattle Department of Transportation (SDOT) currently performs all municipal street sweeping in Seattle. In general, SDOT sweeps streets for road maintenance and aesthetic purposes rather than drainage system maintenance, flood prevention, or water quality. SDOT's street sweeping and leaf pickup operations have an approximate annual budget of $1.2 million and a fleet of eight sweepers (four Schwarze A8000 regenerative air sweepers and four Schwarze M6000 mechanical sweepers).

A recent telephone survey performed by SPU staff found Seattle's municipal street sweeping program to be proportionally smaller in both size and scope than many other local and national sweeping programs, including Bellevue, Kirkland, Everett, Olympia, and Tacoma; Portland and Beaverton in Oregon; San Diego, Sacramento, Sacramento County, Alameda, Long Beach, Santa Monica, Los Angeles, San Francisco, and San Jose in California; San Antonio, Texas; Baltimore, Maryland; Tampa, Florida; and Minneapolis, Minnesota.

Since 2005, SDOT has steadily transitioned from using solely mechanical broom sweeping technology to the current mixed fleet containing half regenerative air sweepers. Regenerative air sweepers, which are relatively new to the industry, are especially effective at collecting small particles (<60 microns in diameter). Because many pollutants present in urban runoff tend to sorb onto particulates, particularly the smaller size particles (e.g., medium sand to silt and clay), street sweeping is expected to also reduce the pollutant loading to area receiving water bodies. Although regenerative air sweepers have been found to be more effective in removing solids, these sweepers cannot be used on all streets in the City (e.g., cobblestone streets). Therefore, SDOT will continue to operate a mixed fleet of street sweepers.

Figure 1 shows the current routes and frequencies of routes for Seattle's municipal street sweeping program. As the map illustrates, the majority of existing sweeping activities are concentrated in commercial portions of the city, including downtown Seattle and the Ballard and University District neighborhood commercial zones. The Central Business District, for example, is swept six nights per week. Selected city arterials are swept monthly or less frequently. Many other arterials, as well as all residential streets, are currently not swept. This is a significantly different strategy than most cities contacted by SPU; most cities sweep all land use areas with a majority of curb and gutter (industrial, commercial, and residential). However, sweeping frequencies do vary widely.

In August 2005, SPU conducted an informal but structured telephone survey targeted at various municipalities, located both within the Pacific Northwest and around the country, regarding their street sweeping activities. Results of the survey indicate that street sweeping occurs most often in central business areas, less often on main arterial streets and industrial areas, and least often on residential streets. In larger cities, sweeping is typically performed in the central business district (CBD) nightly, and sweeping on main arterial streets and in industrial areas occurs as often as several nights a week to once a month. The frequency of residential street sweeping varies greatly from city to city. Some cities sweep residential streets as often as once per week while others sweep only a few times a year or not at all. Examples of the information obtained from those municipalities contacted are noted below:

- San Jose, California: CBD is frequently swept at night by city crews, main arterials and industrial areas are swept twice a month, and residential areas are swept monthly
- Santa Barbara, California: Residential areas are swept weekly during the daytime, and more often for busy areas and the business district
- Virginia Beach, Virginia: Entire city is swept on a 60- to 90-day cycle
- Ventura, California: Residential areas are swept once a month, and arterials and the business district are swept once or twice a week
- El Paso, Texas: Residential areas are swept quarterly, main streets are swept twice a month, and the CBD is swept nightly
- Gresham, Oregon: Each street is swept nine times per year
- Norfolk, Virginia: CBD is swept nightly, main roads are swept monthly, and residential areas are swept every two months
- Bellevue, Washington: Arterials are swept monthly, bike lanes are swept twice monthly, and residential neighborhoods are swept quarterly

- Kirkland, Washington: Entire city is swept monthly
- Everett, Washington: CBD is swept three days/week, bike lanes are swept quarterly, and residential streets and arterials are swept every three weeks
- Tacoma, Washington: CBD and arterials are swept every three weeks, and residential areas are swept quarterly
- Portland, Oregon: Downtown is swept 6 nights per week and other areas are swept 6 to 8 times per year
- Sacramento County, California: Arterials are swept monthly and residential areas are swept twice per year
- Washington County, Oregon: All streets are swept 12 times per year
- Olympia, Washington: Downtown is swept nightly and residential areas are swept monthly if time allows
- Santa Monica, California: Residential areas are swept weekly and commercial areas are swept nightly
- Los Angeles, California: Commercial areas are swept daily, industrial areas are swept weekly, and residential areas are swept monthly
- Arcadia, California: Each street is swept weekly
- Ventura, Florida: Business area is swept daily and residential areas are swept weekly
- Milpitas, California: Commercial areas are swept weekly and residential areas are swept twice per month
- Milwaukee, Wisconsin: Each side of street is swept at least once per month with increased sweeping frequency during leaf-fall season.

Seattle Drainage System

The goals and approaches for this study were developed based, in part, upon Seattle storm drain system functions. Seattle has three types of drainage and wastewater systems, including:

- Separated storm drain and sanitary sewer system
- Combined storm drain and sanitary sewer system
- Partially separated storm drain system and sanitary sewer system.

In general, the north and south ends of the city are served by a separated system while the central and north-central areas of the City have a combined storm and sanitary sewer system. Figure 2 shows the locations of each of these service areas in Seattle.

In areas with separated systems, stormwater runoff and sanitary sewage (i.e., municipal and industrial wastewater) are collected and conveyed in separate pipes. The drainage system collects stormwater runoff from streets and adjacent properties, and discharges directly to the nearest receiving water body. In most cases, runoff is not treated prior to discharge. Sanitary sewage is conveyed to King County's West Point Treatment Plant and treated effluent is discharged to Puget Sound via a deep water outfall off of West Point.

In areas with a combined system, stormwater and sanitary sewage are conveyed in a single pipe. In general, older areas of the city are served by the combined system. Under normal conditions, both stormwater and sanitary sewage are conveyed to the West Point Treatment Plant. However, during large storm events, the volume of runoff can exceed the capacity of the pipe system. To prevent sewer backups, the combined system is equipped with emergency overflows that release excess flow to the nearest receiving water body. This combined sewer overflow (CSO) contains a mixture of untreated sanitary sewage and stormwater. King County reports that stormwater makes up between 80 and 90 percent of CSO discharges (EVS 2000).

Partially separated areas in Seattle are served by both separated storm drains and combined sewer systems. In these areas, runoff from the streets is usually, but not always, collected by storm drains and discharged directly to nearby receiving water bodies. However, areas outside the public right-of-way often continue to drain to the combined system.

Both the separated and combined systems are equipped with inlets and/or catch basins to collect stormwater runoff. Inlets are grated structures that collect and route runoff to a nearby catch basin before discharging the runoff to a conveyance system. Catch basins contain a small sump and are usually equipped with a small downturned elbow or tee to trap sediment and floatable debris. Some catch basins are designed with a grated cover and function as both a stormwater inlet and sediment/debris trap. All runoff is supposed to pass through a catch basin before entering the conveyance system to prevent the downstream pipes from becoming clogged with debris.

Street Sweeping and Stormwater Management

Street sweeping is increasingly becoming an integral part of stormwater management programs nationwide. In fact, in many municipalities, street sweeping is now specifically noted and required in individual National Pollutant Discharge Elimination System (NPDES) permits. For example, California municipalities are increasingly required to conduct street sweeping for their NPDES permit (e.g., Sacramento County, the City of Ventura, the City of San Jose, City of Malibu, and the City of Arcadia). In addition, a street sweeping requirement is included in the NPDES permit for the City of Venice, Florida. Many utilities, particularly in California but also in a growing number of other municipalities, place great emphasis on the pollution prevention aspects of street sweeping as the primary best management practice (BMP) to control and improve water and air quality.

The City of Seattle is subject to two NPDES permits:

- The municipal stormwater permit covers stormwater discharges from those portions of the city served by separated or partially separated drainage systems.
- The combined sewer overflow (CSO) permit covers discharges from the city-owned combined sewer system.

Street sweeping is not required under either permit. However, the City recognizes that street sweeping may be an effective tool to reduce pollutant loading from city streets and could benefit both water and sediment quality in area receiving water bodies. In fact, SPU's Comprehensive Drainage Plan (SPU 2004) recommended that this pilot study be conducted and identified street sweeping as a potential BMP. The City is also currently party to cleanup efforts involving contaminated sediment in several area waterways. Discharges from storm drains and combined sewer overflows may contribute to waterway contamination. Therefore, street sweeping may also be an effective source control measure to reduce future cleanup costs.

Pilot Study Approach

Herrera (2005a) reviewed the available literature on street sweeping and catch basin effectiveness pertinent to the study goals identified above. Generally, previous studies have either monitored water quality to directly measure the benefits of street sweeping by quantifying pollutant concentrations/loads in treated (swept) and untreated (unswept) areas, or have modeled the effects of street sweeping using a model that simulates water quality in relation to sediment accumulation and transport. With the modeling approach, a limited number of stormwater samples are collected to calibrate the model.

The initial study approach used here was based on conclusions of a literature review of street sweeping studies (Herrera 2005a) and evaluation of potential monitoring approaches (Herrera 2005b). This research was then used to develop a baseline water quality monitoring study to select sites and refine the monitoring approach for the Street Sweeping Pilot Study (Herrera 2005c). Based on a statistical analysis of the baseline water quality data and the objectives of the pilot study, the project team elected to focus the pilot study on monitoring sediment quantity and quality rather than stormwater quality. Because many previous studies have had difficulty demonstrating a significant difference in stormwater quality between swept and unswept sites (Martinelli et al. 2002, Center for Watershed Protection 2008, USGS 2007), focusing on sediment mass/chemistry was considered to be the most cost-effective way to evaluate street sweeping performance. It also provides the information necessary to estimate a sediment mass balance between swept and unswept study areas by measuring the mass of sediment that is removed by the sweeper and catch basins versus what remains on the street.

Pilot Basin Area Selection

As noted earlier, there were two primary objectives for the pilot study: measuring the potential reduction in the amount of sediment and associated pollutants discharged from city streets, and potential reductions in catch basin maintenance costs. Site-specific conditions can have a significant effect on the success of accomplishing these tasks. For instance, industry research suggests that street sweeping is not particularly effective on streets that do not have curbs and gutters, because curbs typically retain sediment and associated pollutants in the gutter line where it can be effectively removed by street sweepers. On uncurbed streets, dirt and associated pollutants can migrate outside the reach of street sweepers and onto road shoulders and adjacent unpaved areas. A recent study in Wisconsin showed that, during most of the year, 75 percent of the sediment (and pollutants) captured through sweeping is found within 3 feet of the curb-face (USGS 2007), and Pitt and Amy (1973) found that 90 percent of the total street dirt mass is found within the first foot of the curb. The site selection process took this research into account, along with a knowledge and understanding of Seattle's storm drain system and area receiving water bodies.

Figure 3 divides the City of Seattle into one of three geographically defined categories:

1. Areas containing less than 50 percent curb and gutter that would show little or no benefit (with the exception of arterials located within these basins, which are generally curbed) from sweeping due to a poor ability for sediments to accumulate on the roadway surface.

2. Areas containing a majority of curb and gutter, but that are located in the combined sewer system service area and therefore discharge to a regional wastewater treatment plant.

3. Areas containing more than 50 percent curb and gutter that are located in the separated or partially separated storm drain service areas and drain directly to receiving water bodies.

Category 1 and 2 areas were not considered for the pilot study. Category 2 areas show promise because of the ability of sweeping to reduce catch basin cleaning and to reduce grit and pollutant loading at the region's wastewater treatment plants, but not for reducing the amount of pollution discharged to area receiving water bodies. Sites within the Category 3 areas were further explored and were considered as the most promising regarding any future street sweeping pilot or program focusing on both receiving water body pollution prevention and possible drainage system maintenance savings.

Ultimately, test sites were chosen in West Seattle, Southeast Seattle, and Duwamish Diagonal because they have the following features:

- Located in separated or partially separated service areas, and thus street runoff drains to a receiving water body.

- Located in mostly or fully curbed areas.
- Contain areas that can be paired for comparison (i.e., swept area and unswept control area of appropriate size, similar land use, topography, and vegetative characteristics).
- Parking restrictions for neighborhood residents (moving cars from one side of the street to the other each week) will not be unreasonable.
- Located in an area that is fairly “ordinary” in nature (i.e., site generally contains characteristics not unique to the rest of the city) such that results can be expected to reasonably represent the rest of the city.
- No physical restrictions for sweeping (e.g., no exceptionally large amount of tree branch pruning would be required to allow sweepers to access the curb lane).
- Existing flooding potential could be relieved by street sweeping (e.g., streets lined with deciduous trees that will shed leaves, potentially clogging storm drain inlets).

Baseline Water Quality Monitoring

Because the quality of stormwater runoff is highly variable, previous street sweeping studies have had difficulty showing statistically significant improvements in water quality (see Herrera 2005a and recent examples below). Therefore, prior to designing the pilot test, a baseline stormwater quality monitoring effort was implemented in December 2005 at four test areas (one in Southeast Seattle, one in Ballard, and two in West Seattle) to assess the following issues and concerns associated with monitoring stormwater quality to assess sweeper performance:

- Determine the variance of selected water quality parameters to establish the sample size required to obtain statistically significant results for the pilot study
- Determine whether stormwater quality is comparable between the paired catchments
- Verify that stormwater pollutant concentrations are similar to those reported for other residential areas in Seattle.

A power (statistical) analysis of the baseline water quality data indicated that similar difficulties would likely be encountered in pursuing such a study in Seattle’s residential areas (Herrera 2006). Based on the variance in the baseline data set, power analysis calculates the minimum difference in a parameter concentration that would be statistically significantly different from a second set of data, and this minimum detectable difference is divided by the mean of the baseline data set to determine the minimum detectable difference expressed as a percentage of the mean.

The power analysis showed that the number of samples required would be cost prohibitive due to the variability of stormwater quality and low pollutant concentrations in the samples. At the target level of sampling (30 samples), stormwater sampling would be able to detect a difference (relative to the mean) of approximately 190 to 370 percent for total suspended solids, 40 to 70 percent for total phosphorus, 10 to 220 percent for motor oil, and 40 percent for dissolved copper. A statistically significant decrease in parameter concentration cannot be detected if the minimum detectable difference exceeds 100 percent. This level of uncertainty was unacceptable so a mass balance approach on stormwater solids (i.e., street dirt, sweeper waste, and catch basin sediment) was employed in this study.

A street sweeping study recently completed in Madison, Wisconsin compared the effects of three kinds of sweepers on stormwater quality in residential drainage basins. In that study, a power analysis on the 40 paired stormwater samples collected showed that it would have taken 200 paired stormwater samples to detect a 25 percent difference between the calibration and treatment tests (USGS 2007).

In a study of the effects of street sweeping on highway runoff in Wisconsin (Martinelli et al. 2002), 80 composite stormwater samples (20 samples before sweeping and 20 samples after sweeping at test and control sites) were collected to determine event mean concentrations (EMCs) of suspended sediment, and only weak conclusions could be made. Analysis of replicate samples for the study showed that high variability of suspended sediment concentrations in samples (an average difference of 46 percent with a standard error of 50 percent) made all but the highest changes in runoff concentration difficult to detect.

A recent study in Baltimore (Center for Watershed Protection 2008) measured EMCs in runoff from two catchments for a series of storms with and without street sweeping. For one catchment, 17 storms were sampled before sweeping and 11 storms were sampled during the sweeping test. In the other catchment, 15 storms were monitored before sweeping and 7 storms were monitored during sweeping. Overall, no significantly positive changes in stormwater quality were observed in this study, and the only statistically significant change observed was an increase in TSS and hardness with sweeping in one of the catchments.

The project team concluded that monitoring stormwater quality alone is not likely to produce results useful for decision making. Therefore, it was decided that the study should focus on sediment mass and quality. Sediment contamination is one of Seattle's primary water quality concerns. In addition, SPU uses total suspended solids (TSS) removal as a water quality indicator and on a life cycle cost basis (e.g., dollars per kg of TSS removed) to evaluate the performance of stormwater treatment options for capital improvement projects.

Contaminants of Concern

Studies have found that street dirt contains a variety of pollutants including heavy metals (e.g., cadmium, chromium, copper, lead, and zinc), as well as petroleum hydrocarbons and other organic contaminants (Galvin and Moore 1982, Sartor and Gaboury 1984, HDR 1993, Gadd and Kennedy 2003, Breault et al. 2005). These contaminants can wash off streets during storm events and be transported to receiving water bodies via municipal storm drain systems. Roadway pollutants are transported in both dissolved and solid forms, and thus can affect both water and sediment quality in areas offshore of storm drain outfalls. By removing street dirt before it reaches the stormwater collection/conveyance system, street sweeping has the potential to reduce the amount of pollution discharged to the environment.

The City of Seattle is currently involved in several cleanup projects related to contaminated sediment present in urban waterways throughout the City. Municipal storm drains have been identified as a potential contributor to sediment contamination. As part of ongoing source control efforts in the Lower Duwamish Waterway, the City has been investigating contaminants present in stormwater solids by collecting sediment samples (inline grabs, inline sediment traps, and catch basin grabs) from various locations throughout its storm drain system (SPU and King County 2005). As of December 2007, SPU has collected over 60 sediment samples from catch basins located in the public right-of-way (ROW). Most of the samples were collected from industrial roadways, but approximately 20 percent of the samples represent residential/commercial streets and arterials. The following contaminants were frequently detected in sediment samples collected from ROW catch basins:

- Arsenic (38 percent)
- Copper (100 percent)
- Mercury (44 percent)
- Lead (100 percent)
- Zinc (100 percent)
- Motor oil (100 percent)
- Bis(2-ethylhexyl)phthalate (98 percent)
- Butylbenzylphthalate (75 percent)
- PCBs (72 percent)
- Polycyclic aromatic hydrocarbons (94 percent).

Of these chemicals in 55 samples analyzed, zinc (18 percent), chromium (15 percent), motor oil (82 percent), carcinogenic PAHs (78 percent), di-n-octylphthalate (65 percent), bis(2-ethylhexyl)phthalate (60 percent), butylbenzylphthalate (35 percent), and di-n-butylphthalate (29 percent) concentrations were above the Washington state sediment/soil standards and guidelines.

Study Sites

The pilot study was conducted in the following locations (Figure 4):

- West Seattle (residential)
- Southeast Seattle (residential)
- Duwamish Diagonal (light industrial).

Residential areas were selected for pilot testing because residential land use makes up approximately 41 percent of the total land area in Seattle. In areas served by separate or partially separate storm drain systems (i.e., the municipal separate storm sewer system or MS4 which is covered by the City's NPDES permit), land use distribution is 42, 25, 13, 13, and 7 percent for residential, right-of-way, commercial, open space, and industrial land use categories, respectively. Land use is estimated from the King County parcel database where residential includes single and multi-family; commercial includes commercial, government, public facilities, schools, and other; and open space includes open space/parks and vacant. The Duwamish Diagonal industrial area was included in the pilot study to support source control activities being conducted as part of the Lower Duwamish Waterway Superfund investigation, as well as to evaluate whether street dirt accumulation in industrial areas is significantly higher than in residential areas and would therefore result in even greater benefits from street sweeping.

Because of the large amount of residential land area and the generally uniform nature of the older residential developments in Seattle, it was relatively easy to select study sites in these areas. However, because of the wide variability in industrial activities (e.g., a variety of manufacturing facilities, equipment and vehicle repair, construction contractors, and warehouse and terminal facilities), it was very difficult to select comparable areas for swept and unswept pairs for the industrial area. Numerous industrial streets in the City were evaluated, but few were suitable for testing due either to lack of curbs, heterogeneity of industrial activities, or interference with ongoing SDOT street sweeping operations.

Each study area was divided into a swept site and an unswept site. Swept and unswept site pairs contained similar land use, topography, and numbers of catch basins. An unswept site was included in each of the three study areas for the purposes of calculating a mass balance between the amounts of sediment removed via street sweeping and catch basin cleaning versus catch basin cleaning alone.

The streets in all three study areas are primarily paved concrete with curbs. The roadways are moderately weathered (e.g., the application of a stiff brush can loosen the top few millimeters of road surface releasing cement dust and small components of aggregate from the concrete). The age of these concrete streets is unknown, as the city does not track the age of non-arterial streets in its database (Hansen 2007). Field observations of pitting and patching generally indicate that the streets are oldest in the Southeast Seattle study area and newest in the Duwamish Diagonal study area. Roadway characteristics of each test site are summarized in Table 1.

Southeast Seattle

The Southeast Seattle study area is primarily residential and drains to Lake Washington. The northernmost of the two study sites was designated as the unswept site (Figure 5). The southern site was designated as the swept site (Figure 6). Most of the streets in the test sites are local residential streets. However, major arterials comprised approximately 23 percent of the unswept site (approximately 850 feet of 50th Ave S and 1,200 feet of S Genesee St) and approximately 14 percent of the swept site (approximately 1,300 feet of 50th Ave S). Each site drains to a distinct point that can be sampled for water quality.

West Seattle

The West Seattle study area (Figure 7) is primarily residential and drains to Puget Sound. The northernmost of the two sites was designated as the swept site. The southern site was designated as the unswept site. A majority of the streets in these study sites are local residential streets. However, the approximately 650-foot section of California Ave SW in both the swept and unswept sites is a major arterial, representing 14 percent of the swept site and 13 percent of the unswept site. Each site drains to a distinct point that can be sampled for water quality.

Duwamish Diagonal

The Duwamish Diagonal study area (Figure 8) is primarily light industrial and drains to the Lower Duwamish Waterway via the City's Diagonal Ave S combined sewer overflow/storm drain. Most of the businesses in this area provide warehouse and product delivery services for food products, clothing, welding supplies, trucks and automobile parts, packages, and internet security equipment. Other businesses operating in the area include a bank, an auto repair shop, printing shops, a painting contractor, and a barrel cleaning/restoration facility. Traffic is comprised primarily of heavy trucks and employee vehicles. All streets in the study area are local industrial streets. There are no major arterials in either the swept or unswept sites.

The swept sites and the unswept sites are not distinct catchments because portions of each site drain to the same storm drain; neither site drains to one distinct point that can be sampled for water quality. A majority of the stormwater from both sites drains south to a common storm drain located at S Snoqualmie St, and the northernmost portion of both sites drains north to a common storm drain at S Dakota St.

Study Design and Monitoring Procedures

As explained earlier, the pilot study was conducted to evaluate the effectiveness of street sweeping in reducing the amount of pollutants discharged to area receiving water bodies and to determine whether sweeping can reduce the frequency with which catch basins need to be cleaned. The study was designed to quantify these effects by comparing the amount of street dirt and associated pollutants removed via street sweeping and catch basin cleaning versus catch basin cleaning alone, using swept and unswept sites within Seattle as tests and controls

Three different study areas were selected to evaluate potential differences in street and adjacent land use activities on both the amount of dirt/pollutant accumulation within the roadway, as well as on sweeping practices (e.g., vehicle parking and scheduling issues in residential versus industrial areas). With the exception of the industrial area, where sampling was delayed due to difficulties in locating an appropriate test site, sampling was conducted over a 12-month period to assess whether there were seasonal differences in street dirt accumulation and the physical/chemical characteristics of street dirt. Testing was conducted for a 7-month period at the Duwamish Diagonal industrial test site. Because the focus of this study was on sweeping effectiveness, the sampling program focused on collecting measurements within the public right-of-way. Although it was not possible to entirely eliminate offsite inputs (e.g., runoff entering the roadway from adjacent driveways and lot areas), care was taken in selecting test/control sites to minimize inputs from areas outside the right-of-way. For example, the catch basins selected for sampling were not plumbed to stormwater collection systems located outside the roadway.

Street Sweeping Procedures

The pilot test was conducted from June 20, 2006, through June 19, 2007 at the two residential sites, and from November 24, 2006 through June 15, 2007 at the Duwamish Diagonal site. The industrial area test began later because of the difficulty in locating a suitable test site.

In the swept test areas, each side of the street was swept on alternating weeks, for an overall sweeping frequency of once every two weeks. Sweeping was conducted on alternating sides of the street to minimize impacts on residents by allowing them to move their vehicles to the opposite side of the street during scheduled sweeping events. The West Seattle and Southeast Seattle sites were swept on Tuesdays in the morning hours between 8 a.m. and 12 p.m., and the Duwamish Diagonal site was swept on Friday evenings after 10 p.m.

The sweeping schedule was maintained throughout the test period, with very few missed sweeping events. Table 2 shows the number of possible and actual sweeping events during the study period.

Missed sweeping events are summarized below:

- July 4, 2006 holiday: West Seattle and Southeast Seattle
- November 28, 2006 snow storm: West Seattle

- January 13, 2007 snow storm: Duwamish Diagonal
- January 16, 2007 snow storm: West Seattle and Southeast Seattle.

The street sweeper used in this study was a Schwarze Industries Model A8000 regenerative air sweeper (Figure 9). SDOT currently uses both regenerative air and mechanical sweepers. Although studies have shown that regenerative air sweepers are more effective in removing smaller diameter particles (Sutherland 1997), mechanical sweepers will continue to be used in those areas of the city where street conditions are not suitable for regenerative air sweepers (e.g., cobblestone streets, pavement in poor condition, rough-textured pavement). In a test conducted under ideal conditions, Pacific Water Resources, Inc. (2004) reported that regenerative air sweepers can achieve pick-up efficiencies of 96 to 99 percent or more, compared to about 86 to 98 percent for mechanical sweepers. However, because this test was conducted under ideal conditions (i.e., loose, dry street dirt deposited on a smooth rubber-coated concrete floor in an airplane hangar, with no time limit, and sweepers operating at approximately half the speed used in normal street sweeping), sweeper efficiencies are expected to be somewhat lower during normal field operations.

Each side of the street was swept from the curb to a width equal to the street sweeper (i.e., a single pass is 11.5 feet wide). A single pass covers nearly all of a traffic lane in the two residential areas, and approximately 50 percent of a traffic lane on the industrial streets in the Duwamish Diagonal study area. While some streets within the unswept sites may have been swept in the recent past as part of the City’s existing street sweeping program, streets in the unswept site were not scheduled for sweeping at any time during the study. The street sweeper was operated at a rate of approximately 5 to 7 miles per hour and slowed to make turns and maneuver around parked cars. Sweeper waste was collected from each test area and stored in separate dumpsters for weighing and sampling.

The pilot study involved measuring the mass of sediment and chemical characteristics in the following three media:

- Street dirt
- Street sweeper waste
- Catch basin sediment.

Sampling and analysis methods are described in the project sampling and analysis plan (Herrera 2006). The Street Sweeping Pilot Study was designed to calculate a mass balance for the following components of street dirt/sediment:

- Dirt remaining on street (i.e., street dirt)
- Dirt that accumulates in catch basins (i.e., catch basin sediment)
- Dirt removed by street sweeper (i.e., sweeper waste)
- Dirt exported from the site in urban runoff (i.e., total suspended solids).

Within a swept site, the sediment mass collected by the street sweeper plus the mass captured by catch basins is equivalent to the total mass of sediment removed from the streets and thus, is not exported to receiving waters. The amount of mass removed translates directly into a reduction in the sediment and associated particulate-bound pollutant loading to nearby receiving water bodies.

Table 3 summarizes the measurement and sampling frequency, as well as the chemical analyses conducted on each sample. The proposed sampling schedule involved monthly monitoring of sediment mass and the quarterly analysis of sediment chemistry in all three media. Street dirt and sweeper waste samples were collected every month and composited each quarter, while catch basin sediment samples (composites from one grab sample per catch basin) were collected each quarter.

Deviations from the proposed sampling schedule are summarized below:

- Catch basin sampling was delayed for a period of four weeks at the two residential study areas because of insufficient accumulation of sediment due to a lack of rainfall during the first three months of the study (July to September). As a result, the first composite sample was prepared after the sixteenth week, while the second, third, and fourth composite samples each comprised an accumulation period of 12 weeks. This change resulted in the study being extended from 48 to 52 weeks.

- The first street dirt samples were collected two weeks later than originally scheduled because of difficulties with the sampling equipment (discussed below in the description of the methods used for street dirt collection).

- Street dirt samples were not collected in November 2006, due to an extended period of wet weather. Approximately 13.04 inches of rain fell in November at the City of Seattle rain gauge station and 15.63 inches at the Sea-Tac Airport station. As a result, the streets never dried out enough to allow samples to be collected.

- Only two street dirt samples (instead of three) were collected in the residential study areas during the second quarter in December 2006 (two weeks apart in West Seattle and three weeks apart in Southeast Seattle). The second samples were collected only 13 days after the first samples in West Seattle and 24 days after the first samples in Southeast Seattle because rainfall was predicted for the rest of the sampling period. Sample collection returned to roughly a monthly schedule in the third and fourth quarters of the study.

- Extra sweeper waste measurements were made and extra samples were collected when the capacity of the storage dumpster was reached before the end of the planned one-month period. The extra samples were added in volumetric proportion to the quarterly composite samples based on the time period of collection that they represented (e.g., multiple samples collected during a month were combined into one 16-ounce monthly sample using 4 ounces of material per week of sweeping, and the three monthly samples were combined in equal proportion for the quarterly composite sample.) One extra dumpster measurement was made for each swept site during November 2006. Measurements were made at the planned monthly intervals at the two residential swept sites for the remainder of the study. At the Duwamish Diagonal swept site, two extra measurements were also made in December 2006, and from January through June 2007 the schedule was altered slightly due to scheduling problems with the company that empties the dumpsters. For example, the sample collected in March represented a 5-week accumulation period because the dumpster was not emptied on time. The two sampling periods that followed were each delayed by one week to yield four-week sampling periods, and the final sampling period in June was then extended by 1 week to coordinate with the event scheduled for the residential swept sites.

Despite all of these changes, the pilot study successfully collected all the samples identified in the sampling plan (i.e., 12 per test site in West Seattle and Southeast Seattle, and 9 per test site in the Duwamish Diagonal study area).

Street Dirt Sampling

Street dirt samples were collected and weighed once every four weeks from both the swept and unswept sites. Sample collection was scheduled to occur one or two days before sweeping. Samples were collected from alternate sides of the street on each consecutive sampling event to coincide with street sweeping events. When street dirt sampling was delayed due to weather, the field crew sampled the side of the street that was scheduled to be swept the following day. Individual samples were then composited prior to weighing and archiving for chemical analysis.

Samples were collected using an industrial vacuum cleaner (Shop-Vac™). A stainless steel spatula and tongs were used when necessary to dislodge compacted material, particularly along the curb line. The Shop-Vac™ was equipped with a 2.5 horsepower motor that creates 90 inches of sealed suction pressure and can move 100 cubic feet per minute of air. The Shop-Vac™ came equipped with corrugated black plastic vacuum tubing, a stainless steel hopper, and a 14-inch by 0.5-inch aluminum nozzle. During pre-project testing, phthalates were detected in a blank sample collected using the factory-supplied plastic tubing (280 μg/kg). Therefore, before project sampling began, the vacuum tube was replaced with Teflon tubing. Phthalates were not detected in blank samples collected using the Teflon vacuum tubing.

The street dirt sampling method was altered during the course of the study. During the first sampling event, field crews noted that a relatively large amount of dirt had accumulated in the seams between the concrete panels, as well as in cracks in the concrete; in some cases plants were observed growing in the seams. Therefore, during the following two sample events, dirt was dislodged from the seams and cracks, and plant roots were shaken to remove the dirt. However, because this material was not dislodged by the sweeper and did not appear to be available for transport by stormwater runoff, the project team decided to discontinue this practice, and during all subsequent events, only the dirt present on the street surface was removed. As described in the results section, approximately twice as much street dirt was collected from the unswept sites during events 2 and 3, when material was removed from cracks/seams, compared to the other sampling events. However, the removal of this material did not substantially increase street dirt mass in the swept sites.

The sampling methods used in this study differed in one important aspect from other street sweeping studies. Organic matter, such as leaves and pine needles, was specifically included in pilot study samples, whereas most other studies have focused primarily on the inorganic sediment fractions. Organic material was included because this study utilizes a mass balance approach and therefore a measure of the total mass of material was needed. In addition, because organic material is also present in the catch basin sediment and cannot be easily removed when sampling, it was necessary to include the organic component when sampling street dirt and sweeper waste. The inclusion of this organic material may have increased the mass and organic matter content of our samples compared to samples collected for other studies reported in the literature.

Sample Collection Procedures

Street dirt samples were collected from two transects located in eight randomly selected blocks (i.e., 16 sample locations per swept/unswept site). Samples were then combined into a single composite sample for the analysis of chemical and physical parameters. Inorganic particles greater than 2 cm in diameter (e.g., rocks and trash) were removed and weighed separately. The remaining street dirt was homogenized using a stainless steel spoon and transferred into three 16-ounce jars for storage until the end of a 12-week period (or 16 weeks in the case of the first sampling period). One 16-ounce jar was refrigerated at 4ºC for physical analyses and two 16-ounce jars were frozen at -18ºC for chemical analyses. A portion of each sample (approximately 1 ounce) was retained prior to compositing for the analysis of total solids by the laboratory.

Sections between intersecting streets were used to define blocks at the residential sites. In the Duwamish Diagonal study area, blocks were defined as the area between catch basins. Street dirt samples were always collected from blocks draining to the catch basins sampled for the study. The sampling locations included most blocks in the West Seattle study area, approximately one-third of the blocks in the Southeast Seattle study area (which contained a total of 25 blocks in each swept/unswept site), and all of the blocks in the Duwamish Diagonal study area (see Figures 5, 6, 7, and 8). If a transect was obstructed by a parked vehicle (as was often the case), the transect was moved to the nearest adjacent location that was free of obstruction.

Each transect extended from the centerline of the street to the curb, and covered between two and four widths of the 14-inch-wide vacuum nozzle, spaced 14 inches apart. Because a minimum of approximately three pints of material was required for chemical analyses, the number of transects sometimes needed to be increased in order to collect sufficient material. The actual area sampled varied depending on the amount of material that was anticipated to be collected, which was based on visual observations by the sampling staff immediately prior to sampling.

For the first four months of the study, when street dirt was very dry and leaves had not yet fallen, the street sample was collected using only the vacuum apparatus because the vacuum could easily pick up all the organic material present on the street. Any leaves that were present were easily broken-up by the vacuum nozzle. However, by the fifth sampling event in December, the vacuum was not able to pick up all of the material because a large proportion of the street dirt contained freshly fallen leaves. At this point, and for the remaining sampling events, leaves and large debris were picked up with the stainless steel tongs, stored in a separate container, and combined with vacuum materials at the end of the sampling event.

The vacuum cleaner components were cleaned and decontaminated between sites by removing visible debris with a stiff brush, scrubbing with a phosphate free detergent, and rinsing with deionized water.

Street Sweeper Waste Sampling

Material collected by the sweeper was stored in separate dumpsters assigned to each test site. Each dumpster was weighed approximately once every four weeks over the study period. Excess water that separated from the sweeper waste was removed from each dumpster using a trash pump prior to weighing, and this water was discharged to a nearby sanitary sewer. The dumpsters were weighed on an industrial scale that had a capacity of 5,000 pounds and an accuracy of ±1 pound. The scale was calibrated once at the beginning of the study and once midway through the study when the scale needed repair. Samples were collected immediately after weighing and the dumpsters were then emptied.

Dumpsters were covered and locked when not in use. However, on a number of occasions a dumpster was inadvertently left unlocked, and on few occasions, small amounts of garbage or even large pieces of furniture had been deposited in the dumpsters. In each instance, the garbage and debris was removed (as it was easily discernable from sweeper waste) and it appeared that sweeper waste samples were not visibly contaminated by the garbage.

Sample Collection Procedures

Samples were collected once every 4 weeks or more often when necessary. Grab samples were collected from multiple locations in the dumpster using a stainless steel shovel. Individual grabs were placed in a stainless steel mixing bowl and particles greater than 2 cm in diameter were removed by hand and weighed separately to determine the proportion of debris in the waste material. The remaining material was homogenized using a stainless steel spoon, transferred into two or three 16-ounce jars, and stored until the end of the 12- or 16-week sampling period. One 16-ounce jar was refrigerated at 4ºC for physical analyses and one or two jars, (depending upon the organic matter content of the sample), were frozen at -18ºC for chemical analyses.

At the end of each 12- or 16-week period, sweeper waste samples collected during the period were composited into one sample for each of the three basins. Equal portions of each sample were placed in a bowl, homogenized using a stainless steel spoon, and transferred into appropriate sample jars for the physical and chemical analyses. In addition, a portion of each sample (approximately one ounce) was retained prior to compositing for the laboratory analysis of total solids.

Catch Basin Sediment Sampling

Catch basin sampling locations are shown on Figures 5, 6, 7, and 8. A total of 12 catch basins were sampled in each site, representing most of the catch basins in the swept and unswept sites in the West Seattle study area (16 and 18 total catch basins, respectively) and the Duwamish Diagonal study area (16 and 17 total catch basins, respectively), and representing approximately one-third of the catch basins in the swept and unswept sites in the Southeast Seattle study area (38 and 36 total catch basins, respectively).

Sediment accumulation was measured and samples were collected every 4 weeks from both swept and unswept sites starting in September in the two residential study areas (12 monitoring events) and in December in the Duwamish Diagonal study area (9 monitoring events). Measurements were not made in August because it was assumed that no sediment would have accumulated, since there had been no rainfall, and a spot check of a few catch basins confirmed this assumption. At the start of the study the depth to the bottom of each catch basin sump was measured along with the depth to the outlet invert elevation. The median sump depth was 2.6 feet in the West Seattle study area, 2.7 feet in the Southeast Seattle study area, and 2.2 feet in the Duwamish Diagonal study area. The catch basin capacity was determined based on the average sump depth multiplied by the catch basin area. Sump storage capacities ranged from 2 to 31 cubic feet with a median capacity of 21 cubic feet.

All catch basins and inlets in the study areas were cleaned before the beginning of the study, but two catch basins in the Southeast Seattle unswept site were missed during the initial cleaning. Catch basin CCN-5 was cleaned soon after the project began, but catch basin CCN-9 was never cleaned. Sediment accumulation in CCN-9 was determined by subtracting the initial sediment depth from subsequent measurements. SPU collected sediment samples from each study area prior to cleaning to characterize baseline conditions.

There were a few minor deviations from the sampling plan in the Duwamish Diagonal study area:

- Initially, catch basins DDW-11 and DDW-12 in the unswept site were not cleaned. DDW-11 was cleaned within 1 week of the beginning of the study, but DDW-12 was not cleaned until it was accidentally cleaned in April 2007. Catch basin DDW-12 is located at the driveway of the Federal Express facility and may have been cleaned by private contractors.

- All of the catch basins in both the swept and unswept sites were accidentally cleaned sometime between April 24, and May 14, 2007, approximately 5 weeks before the end of the study. As a result, sampling at those sites was delayed until July 6, after a several rainfall events had mobilized enough sediment into the catch basins to continue sampling.

Sediment Volume Measurement Procedures

The depth of sediment accumulation within each catch basin was determined by measuring down from the rim of the maintenance hole to the surface of the sediment, using a 1-inch-diameter PVC pole. The pole was then pushed through the sediment to the bottom of the catch basin to measure the sediment depth. The overlying water in the catch basins was not removed prior to measuring the sediment depth. Consequently, measurements were made with approximately 2 feet of standing water in the sump.

Five depth measurements were made within each sampled catch basin, four along the perimeter of the maintenance hole, and one in the center. The first perimeter measurement was recorded at the northern edge of the hole, and the other three edge measurements were made at successive 90-degree increments. In the event that an inlet or outlet pipe blocked measurement in a particular direction, the measurement was made immediately clockwise of the obstruction. The average sediment depth was multiplied by the catch basin area (determined from field measurements) to calculate the volume of accumulated sediment.

Sediment Sample Collection Procedures

Sediment sampling procedures for catch basin sediments generally followed *Recommended Protocols for Measuring Selected Environmental Variables in Puget Sound* (PSEP 1996). Catch basin sediment and debris samples were collected to the maximum depth possible using a stainless steel scoop attached to an extension pole. Given the small amount of sediment accumulation (1 to 2 inches over the study period), it was not feasible to sample only the material that accumulated between sampling dates. Therefore, the sample represented the sediment that accumulated over the entire study period rather than the sediment accumulated between each sampling event. Between three and 20 scoops (depending upon the volume recovered) of sediment were collected from within each catch basin, emptied into a large stainless steel bowl, and homogenized using a stainless steel spoon. Particles greater than approximately 2 centimeters (cm) in size (which were rare) were removed from the sample, placed in a separate container, and weighed to determine the proportion of debris. Leaves and leaf particles were not removed from the samples. Free standing liquid was decanted from the scoop and the mixing bowl prior to sample homogenization. A pint jar was then filled with the homogenized material.

The pint jars containing samples from each individual catch basin were refrigerated and allowed to settle for a minimum of 24 hours and as much as 72 hours, depending upon the water content. Any additional free standing water was then decanted. An 8-ounce jar was then packed with the settled material from each catch basin and weighed to determine the bulk density of the sediment. Sediment remaining in the pint jars from each individual catch basin was then analyzed for total solids.

The material used to measure bulk density in each catch basin was then transferred into one large, clean stainless steel bowl for compositing. The 12 individual catch basin samples from each swept/unswept area were combined into a single composite sample, which yielded six samples for analysis (one for each swept/unswept study area). The composite samples were homogenized using a stainless spoon and placed into the appropriate sampling containers.

A photograph was taken of each sample in the bowl, and of the debris that was removed and placed in a separate bowl. Samples to be analyzed for total solids and grain size analyses were stored at 4ºC. Samples to be analyzed for chemical parameters were stored at -18ºC. Sample compositing and archiving was conducted at the Herrera laboratory. A field duplicate composite sample was collected from one study site during two of the four sampling events. The field duplicate was a laboratory blind (i.e., given a unique number) and was created by alternately filling sample containers from a single homogenized sample.

Analytical Procedures

The catch basin sediment samples were analyzed for bulk density at the Herrera laboratory as described above for conversion of volume measurements to wet weight (i.e., wet weight = volume x bulk density). All other physical and chemical parameters were analyzed by Analytical Resources, Inc. according to the methods specified in Table 4.

Grain size was analyzed using sieve sizes ranging from 75mm (cobbles) down to 75 µm (very fine sand). Total volatile solids and total organic carbon were analyzed as measures of organic content, and for normalizing organic chemical concentrations to organic carbon for comparison to Washington State Sediment Management Standards (SMS) (WAC 173-204).

Results and Discussion

The pilot study was conducted to answer the following two questions:

- Does street sweeping reduce the rate of sediment accumulation in catch basins and thus reduce the frequency of catch basin cleaning?

- Does street sweeping increase the total amount of sediment removed from a site compared to the amount removed by catch basin cleaning alone?

Results are presented in the following order:

- Rainfall
- Sediment mass measurements
- Sediment physical and chemical properties.

Rainfall

Local precipitation data were compiled to evaluate potential washoff conditions for road surfaces and washout conditions for catch basins. Table 5 and Figure 10 present data obtained from the following rain gauges:

- Seattle rain gauge RG16 located in southeast Seattle at the geographic center of the project basins at E Marginal Way S and 13th Avenue SW (N47.5350° and W122.3139).

- Seattle rain gauge RG18 located in southeast Seattle at Rainier Avenue S and S Kenny Street (N47.5481° and W122.2750).

- National Weather Service gauge at Seattle-Tacoma International Airport (Sea-Tac gauge).

Rain gauge station RG16 was selected as a representative gauge for all three basins. However, this station was taken out of service on March 12, 2007 to accommodate construction activities at the nearby King County pump station. Data from station RG18 was used for the period March 12, 2007 through the end of the study. Data from Sea-Tac were included in order to compare monthly precipitation during the study period to long-term rainfall records (1970 to 2007).

The total annual precipitation measured at City rain gauge stations RG16 and RG18 during the 12-month study period (July 2006 through June 2007) was 37.42 inches, approximately 13 percent (4.32 inches) wetter than the estimated historical average of 33.1 inches. The historical average is estimated using the mean annual precipitation from 1978 to 2002 for station RG16 (32.6 inches) and station RG18 (34.8 inches) (MGS 2003), and weighting by the number of days each station was used during the study period.

The Sea-Tac Airport total annual precipitation during the pilot study (July 2006 through June 2007) was 43.4 inches, approximately 17 percent (6.3 inches) wetter than normal (average annual rainfall from 1970 through 2000 at Sea-Tac is approximately 37.1 inches). November 2006, was the wettest month on record, with 15.6 inches of rain compared to the historical average for November (5.9 inches). Precipitation in December 2006 was also approximately 2 inches greater than normal, and in January and March 2007 was about one-inch greater than normal. Precipitation totals in the remaining months were lower than normal, with April 2007 being an exceptionally dry month at 0.6 inches compared to the historical average of 2.6 inches.

Sediment Measurements

Because the test sites were not all the same size, the pilot test results were evaluated based on the amount of material collected (i.e., street dirt, catch basin sediment, or sweeper waste) per area of street surface and per curb mile. For the purposes of this report, quantities reported in units of grams per square meter of street surface (g/m^2) or pounds per acre of street surface per year (lb/acre/year) are referred to as "areal" values, and those reported in units of pounds per curb mile (lb/curb mile) or pounds per curb mile per year (lb/curb mile/year) are referred to as "lineal" values. All sediment mass measurements are presented based on dry weight. The following naming conventions have been used to describe the three media that were tracked during the pilot study:

- Street dirt yield: Mass of material collected per unit area or length on a dry weight basis by vacuuming randomly selected transects in the swept and unswept test sites. Estimated using samples collected and weighed every four weeks within two days prior to a scheduled sweeping event, and converted to dry mass from total solids measurements.

- Catch basin accumulation: Quantity of sediment that accumulated in the catch basins per unit area on a dry weight basis. Estimated using catch basin sediment depth measured every four weeks and converted to dry mass based on sump area, sediment bulk density, and total solids measurements.

- Sweeper waste yield: Mass of material removed by street sweeper per unit area or length on a dry weight basis. Estimated using the total mass of sweeper waste in dumpsters measured approximately every four weeks and converted to dry mass from total solids measurements of samples collected at each dumpster weighing.

As is the case with most environmental data, the distribution of the data is asymmetrical. Therefore, where applicable, results are described using the median to indicate the central tendency.

Comparisons between the three study sites were complicated by the fact that the Duwamish Diagonal test site was only sampled for 7 months and the residential test sites were sampled for 12 months. In addition, an SPU contractor inadvertently cleaned catch basins in the Duwamish Diagonal study area in May 2007, which affected the last three months of catch basin measurements in this study area. For the purposes of this study, annual yields were estimated based on daily rates, which were determined by dividing the measured yield by the sampling period, and multiplying by 365 days per year.

Summary of Results

This section provides an overview of the quantity measures recorded during the pilot study in relation to the two primary study objectives. Detailed information and analysis of the test results are provided in subsequent sections.

Objective 1: Determine whether there is a statistically significant difference in street dirt yield and catch basin accumulation between the control (unswept) and treatment (swept) sites, and in street dirt yield, sweeper waste yield, and catch basin accumulation between the three study areas. Key conclusions from the pilot test are listed below:

- Monthly street dirt yields *were significantly different* between the control (unswept) and treatment (swept) test sites for the two residential study areas, but the daily street dirt yield and catch basin accumulations *were not significantly different* for all three study areas.

    - Although street sweeping reduced the street dirt yield in all three study areas, differences in the monthly street dirt yield between swept and unswept sites *were significant* for West Seattle ($p = 0.007$) and Southeast Seattle ($p = 0.002$), but *were not significant* for Duwamish Diagonal ($p = 0.086$) due to the low yield observed in the unswept site.

    - The estimated daily street dirt yields were highly variable (-2.8 to +4.1 g/m^2/day) and *were not significantly different* ($p > 0.05$) between the swept and unswept sites. These yields were also *not significantly different* from zero in any site over the study period.

    - Although quantities varied between test sites, catch basin accumulation *was not significantly different* between swept and unswept sites in any of the three study areas (p values ranged from 0.132 to 0.958).

- With one exception, there *were no significant differences* in street dirt, sweeper waste, or catch basin accumulation between the three study areas:

    - The street dirt yield *was not significantly different* between the three study areas at the swept sites ($p = 0.099$ and median monthly values ranged from 9 to 19 g/m^2. However, the street dirt yield *was* *significantly different* at the unswept sites ($p = 0.001$ and the median monthly value for the Duwamish Diagonal unswept site [0.34 g/m^2] was lower than those for the residential unwept sites [74 and 75 g/m^2]).

- The sweeper waste yield was *not significantly different* between the three study areas ($p = 0.654$ and median monthly values ranged from 16 to 20 g/m^2).

- The catch basin sediment accumulation rate over the entire study period *was not significantly different* between the three study areas ($p = 0.747$ and median values ranged from 0.08 to 0.11 g/m^2/day at the swept sites, and $p = 0.501$ and median values ranged from 0.06 to 0.11 g/m^2/day at the unswept sites).

Objective 2: Answer the two major study questions regarding the effectiveness of street sweeping in reducing catch basin cleaning frequency and in reducing the total amount of sediment and associated pollutants discharged to nearby receiving water bodies compared to catch basin cleaning alone. Key conclusions from the pilot test are listed below:

- Sweeping streets every other week *did not reduce* the measurable catch basin accumulation, which indicates that sweeping may not affect catch basin maintenance requirements. However, based on the amount of sediment that did accumulate in catch basins at both swept and unswept test sites, it appears that catch basins in the three study areas would only need to be cleaned about once every 3 to 7 years. Measures used to develop this conclusion include:

  - The median value of the estimated daily catch basin accumulation in the unswept sites (0.11, 0.06, and 0.07 g/m^2/day) *was not significantly different* than in the swept sites (0.10, 0.11, and 0.08 g/m^2/day) in the West Seattle, Southeast Seattle, and Duwamish Diagonal study areas, respectively.

  - Most of the catch basins monitored during the pilot study were less than 10 percent full at the end of the study period, and ranged from 1 to 43 percent full in all of the catch basins that were monitored (median values ranged from 3 to 8 percent and 75th percentiles ranged from 9 to 17 percent). If catch basins are cleaned whenever sediment reaches 60 percent of capacity, as required under Seattle's NPDES permit, these results suggest that most (75 percent) of catch basins may need to be cleaned about once every 3 to 7 years.

  - Sweeping streets every other week *did reduce* the total amount of sediment and associated pollutants discharged to nearby receiving water bodies compared to catch basin cleaning alone.

- For the total 12.7 acres of roadway area evaluated during the 12-month pilot study (7 months for the Diagonal Duwamish study area), sweeping is estimated to remove 2,700 lb/acre/year (300 g/m^2/year) of sediment, while annual cleaning of the approximately 70 catch basins in the swept areas is estimated to remove only about 500 lb/acre/year (56 g/m^2/year) of sediment.

Street Dirt

Previous studies have suggested that street dirt accumulates in a non-linear fashion and that there is a limit to the mass that can accumulate between storms, regardless of the length of dry periods (OTAK 1991). The rate of street dirt accumulation typically peaks several days following a rainfall or street cleaning event, followed thereafter by a decrease in the accumulation rate that eventually approaches zero. These findings suggest that wind and vehicle movement may ultimately limit the accumulation of street dirt, and that street dirt is in a dynamic equilibrium whereby it changes rapidly, but does not exhibit a net accumulation after extended periods of time.

The amount of dirt present on the street was measured every four weeks during the pilot study at approximately one to two days before sweeping. To enable comparisons between the different test areas, street dirt measurements were converted to yield (i.e., mass per unit area), by dividing the total sample weight (g) by the area of street surface vacuumed (m^2). Results are summarized in a box plot format in Figure 11 and time series format in Figure 12. Table 7 presents the monthly results and summary statistics for each site in units of g/m^2, and the mean/median areal and lineal street dirt yield values in units of lb/street acre and lb/curb mile, respectively, for comparison to literature values. In addition, Table 7 shows the percent reduction in street dirt yield calculated as the difference between the unswept and swept sites, divided by the unswept site. Because street dirt accumulations can fluctuate daily, the monthly street dirt yield measurements recorded in this study represent a small sample of the potential range of street dirt present on city streets at any one time.

Summary of Results

A discussion of the street dirt yield results is provided in the following sections. Major conclusions are summarized below in order of significance:

- ***Street dirt yield at unswept sites***. As shown in Table 7, the street dirt yield in the unswept (control) sites was significantly higher in the residential study areas (13 to 160 g/m^2) than in the industrial Duwamish Diagonal study area (17 to 54 g/m^2), possibly due to differences in sampling period, street width, previous sweeping of the industrial streets, adjacent surface characteristics, street surface age, or unknown site-specific loading factors.

- ***Street dirt yield at swept sites***. The median monthly street dirt yield was not significantly different between the three swept sites, ranging from 4 to 64 g/m^2 (see Table 7).

- ***Street dirt yields between swept versus unswept sites***. Differences between swept and unswept site monthly street dirt yields were significant ($p < 0.05$) for West Seattle ($p = 0.007$) and Southeast Seattle ($p = 0.002$), but were not significant for Duwamish Diagonal ($p = 0.086$) due to the low yield observed in the unswept site.

- ***Reductions in street dirt yield***. Sweeping reduced the amount of dirt on the street in all three study areas, with median differences between test and control sites ranging from 48 percent at the Duwamish Diagonal study area to 90 percent at the Southeast Seattle study area (see Table 7).

- ***Temporal trends in street dirt yield***. No consistent temporal trends were observed in street dirt yield over the one-year study period in the unswept test sites (see Table 7), which supports observations by others that a maximum accumulation of street dirt occurs within a period of days regardless of seasonal patterns in rainfall wash-off or vegetation deposition (with the exception of inputs from winter street sanding activities that occurred an unknown number of times during this study on arterial streets).

- ***Street dirt accumulation rates***. Daily street dirt yield values varied between positive and negative values throughout the year on both swept and unswept streets, which is consistent with other studies and further confirms the dynamic nature of street dirt accumulation (see Table 8).

- ***Comparisons with other studies***. As shown in Table 9, median monthly values for lineal street dirt yield (150, 240, and 350 lb/curb mile, for West Seattle, Southeast Seattle, and Duwamish Diagonal, respectively) for all of the samples collected in the swept basins were between the median value reported for Madison, Wisconsin (150 lb/curb mile) (USGS 2007) and the mean value reported for Baltimore, Maryland (645 lb/curb mile) (Center for Watershed Protection 2008). In the unswept sites, the median lineal street dirt yields (790, 1,010, and 1,110 lb/curb mile, for Duwamish Diagonal, Southeast Seattle, and West Seattle, respectively) were in the upper range of median values reported by these and other studies (146 to 1,110 lb/curb mile).

Comparison of Street Dirt Yield at Unswept Sites

The monthly street dirt yield in the unswept sites ranged from 13 to 160 g/m^2. As shown in Table 7, the median value was approximately 120 percent higher in the West Seattle (74 g/m^2) and Southeast Seattle (75 g/m^2) sites compared to the Duwamish Diagonal site (34 g/m^2). The same trend is evident when comparing monthly lineal street dirt yields, where the median value at the Duwamish Diagonal site (790 lb/curb mile) was only 75 percent of the value observed in the residential sites (1,110 and 1,010 lb/curb mile in the West Seattle and Southeast Seattle sites, respectively). These differences were determined to be significant ($p = 0.001$) using a Kruskall Wallis test and a nonparametric multiple comparison test (see Appendix A, Table A-11). This observation is contrary to what might otherwise be expected for streets in industrial and residential areas. The lower street dirt yields observed in the Duwamish Diagonal (industrial) unswept site may be attributable to several factors:

- **Sampling period:** The Duwamish Diagonal unswept site was not sampled during the first quarter of the study (July through October 2006), when some of the highest monthly street dirt yields (defined as greater than or equal to the 75^{th} percentile of the monthly yields), occurred at the residential sites. Two of the six monthly measurements (120 and 161 g/m^2) that were above the 75^{th} percentiles at the two residential unswept sites occurred during the first quarter. These higher street dirt yields may be associated with dry weather and sampling procedures, which initially included material in pavement joints and cracks.

- **Street width**: Most of the streets are twice as wide in the Duwamish Diagonal study area (i.e., 44 feet, with the exception of one arterial in the swept site having a width of 22 feet) compared to the residential study areas (i.e., 22 feet, with the exception of one arterial in each residential site having a width of 44 feet). Therefore, because the vacuum samples are collected from the curb to the centerline, a greater proportion of the sample area in the Duwamish Diagonal study area is located further than 3 feet from the curb (where most dirt accumulates), essentially diluting the areal yield of accumulated street dirt.

- **Previous sweeping:** In the Duwamish Diagonal study area, 6th Avenue S (which represents 62 percent of the street area in the unswept site), had been swept prior to the study as part of Seattle's routine street sweeping program; whereas, only California Avenue SW in the West Seattle study area and 51st Avenue S in the Southeast Seattle study area had been previously swept (each of which represents less than 20 percent of the street area in those study areas).

- **Adjacent surfaces:** Surfaces adjacent to the streets were typically paved in the Duwamish Diagonal study area and vegetated in the residential study areas. Thus, leaves and other organic debris, as well as erosion of exposed soil on properties adjacent to the roadways in the residential study areas may have contributed more material to adjacent streets than the Duwamish Diagonal study area.

- **Street surface age:** Although street construction data are not available (Hansen 2007), the concrete street surface appeared to be newer in the Duwamish Diagonal study area than in the residential study areas based on qualitative observations of pitting and patching. Therefore, streets in the Duwamish Diagonal study area may have been less susceptible to weathering and contributed less street surface material to the street dirt samples.

One factor that does not support the lower street dirt yields in the Duwamish Diagonal unswept site is the potential effect of sanding operations. Unfortunately, sanding operations were not tracked during the pilot study. SDOT sanded major arterials in the City during snow events that occurred during the pilot study in November 2006 and January 2007. Sanding likely occurred on Sixth Avenue S, which represents 62 percent of the street surface area in the Duwamish Diagonal unswept site. Therefore, unless SDOT swept the streets following the sanding operations, the sanding events should have increased the street dirt yield in the Duwamish Diagonal unswept site compared to the other unswept sites because sanded arterials make up a larger proportion of the Duwamish Diagonal unswept site (62 percent) than in the other unswept sites (14 percent in West Seattle and 23 percent in Southeast Seattle, and street dirt samples were not collected from the arterial in Southeast Seattle).

Comparison of Street Dirt Yield at Swept Sites

The monthly street dirt yield in the swept sites ranged from 4 to 64 g/m^2. The median yield was somewhat higher in the Duwamish Diagonal swept site (19 g/m^2) than the West Seattle swept site (15 g/m^2) and Southeast Seattle swept site (9 g/m^2) (see Table 7), but these differences were not statistically significant ($p = 0.099$). See Appendix A, Table A-11 for a description of statistical analyses performed as part of this study.

As explained in the previous section, the monthly street dirt yield on the unswept streets in the Duwamish Diagonal study area (median value = 34 g/m^2), was significantly lower than the yields recorded at the two residential unswept sites (74 to 75 g/m^2). The fact that the opposite result was observed on the swept streets in the Duwamish Diagonal study area (industrial streets contained a higher, but not statistically significant amount of street dirt each month than the residential streets), suggests that the test and control sites in the Diagonal industrial study area may not have been well matched with regard to land use activity.

Comparisons of Street Dirt Yields Between Swept Versus Unwept Sites

As shown in Figure 12 and Table 7, the median monthly areal and lineal street dirt yields were lower in the swept sites than the unswept sites for all three study areas indicating that sweeping was effective in reducing the amount of dirt on the street. Based on a Wilcoxon signed-rank test of areal street dirt yields ($\alpha = 0.05$), differences between swept and unswept sites were significant for West Seattle ($p = 0.007$) and Southeast Seattle ($p = 0.002$) (see Appendix A). However, differences in street dirt yields between swept and unswept sites were not significant in the Duwamish Diagonal study area ($p = 0.086$). This result may be attributable to differences in street dirt accumulation rates between the industrial swept and unswept sites. Identifying comparable test and control sites for this pilot study was a problem in the City's industrial areas because of the wide variability in industrial activities from location to location.

Monthly areal street dirt yields were lower in the swept sites than the unswept sites for all but two of the 33 sample pairs of samples collected during the study (see Table 7). One anomalous sample pair was collected in the Duwamish Diagonal study area in January 2007, when the street dirt yield was much higher in the swept site (64 g/m^2) than the unswept site (34 g/m^2). This apparent anomaly may have been due to a street sanding event and the missed sweeping event prior to sample collection in January, both of which were related to the same snowfall event. Sand was observed at all study sites following a snowfall in the month of January 2007, but information on sanding locations and frequency was not available from the City.

The second anomalous swept/unswept sample pair results occurred at West Seattle in June 2007, when the swept site exhibited one of the highest monthly street dirt yields for the year (52 g/m^2) and the unswept site exhibited the lowest yield for the year (13 g/m^2). A likely explanation for this may be that routine sweeping of California Avenue SW was reinitiated before the final sampling date in June 2007. While California Avenue SW represents approximately 15 percent of the total street area in the unswept site, field observations of samples collected previously from the West Seattle unswept site indicated that this major arterial contributed as much as 25 to 50 percent of the street dirt mass collected at the site for most samples. Therefore, the sweeping that occurred on California Avenue SW in the unswept (control) site during June may have significantly reduced the corresponding yield.

Reductions in Street Dirt Yield

One obvious benefit of street sweeping is the observed reduction in the amount of dirt that is present on city streets. For this study, the percent reduction of street dirt yield by street sweeping was calculated for each basin using the following equation:

$$\text{Reduction in street dirt yield (\%)} = \frac{(SD_u - SD_s)}{SD_u}$$

Where: SD_U = Street dirt yield at the unswept site (g/m^2)

SD_S = Street dirt yield at the swept site (g/m^2).

Reductions in street-dirt yield are presented along with the street dirt sample data in Table 7.

The median reduction in street dirt yield over the study period was highest in Southeast Seattle (90 percent) followed by West Seattle (74 percent), and was lowest in the Duwamish Diagonal test site (48 percent). However, as shown in Table 7, monthly reductions in street-dirt yield varied widely in every test area (from -310 percent to 95 percent). As described in the previous section, the lower reductions in street-dirt yield observed in the Duwamish Diagonal area may be related to differences in street dirt accumulation rates between the test and control sites rather than differences in sweeping effectiveness.

Temporal Trends in Street Dirt Yield

A time series plot of the monthly street dirt yields (in g/m^2) is provided in Figure 12. Daily precipitation data are plotted as inverted bars on Figure 12 for comparison of street dirt accumulation during periods of no rainfall (July to mid-September), moderate rainfall (generally less than 0.5 inches/day from mid-September through October and early January through June), and heavy rainfall (commonly greater than 0.5 inches/day from November to early January).

Other than higher accumulations observed at the unswept sites during the late summer (which was likely due to a temporary change in sampling methods that included sampling of dirt in pavement joints and cracks) and winter (which was likely due to unusual street sanding activities), no significant seasonal/rainfall-related trends were observed in the monthly measurements of street dirt yields during the pilot study.

Unswept Sites

As shown on Figure 12, the areal monthly street dirt yields in the unswept residential sites were low in the initial July 2006 measurements but increased in August and early September 2007. This difference was likely caused by changes in sampling methods rather than actual changes in the amount of dirt accumulating on the street. The July 2006 sample (the first sample collected at each site) was collected by simply vacuuming the street at randomly spaced transects. However, in August and September (the second and third samples at each site), dirt from cracks/joints and plant roots were manually dislodged (scraped) prior to vacuuming and included in the samples. After September and for the duration of the study, street dirt samples were collected using only the vacuum, without attempting to sample material wedged in cracks and pavement joints that typically remained in place when vacuumed. Monthly yields for the four samples collected using the scraping technique ranged from 99 to 160 g/m^2, compared to a range of 13 to 150 g/m^2 during the remaining sampling period.

Excluding the August and September data, the amount of dirt accumulating on the unswept streets in the residential areas was fairly constant from July through about November (45 to 63 g/m^2 in West Seattle and 55 to 81 g/m^2 in Southeast Seattle) and again from April through June (13 to 85 g/m^2 in West Seattle and 66 to 69 g/m^2 in Southeast Seattle). However, a distinct increase in the monthly street dirt yield was observed in both of the residential unswept sites from December to January that remained elevated through March (44 to 110 g/m^2 in West Seattle and 53 to 150 g/m^2 in Southeast Seattle). There were no apparent trends at the Duwamish Diagonal unswept site where monthly street dirt yields ranged from about 17 to 54 g/m^2.

The higher monthly street dirt yields observed during the winter months (44 to 150 g/m^2) coincides with observations of street sanding on arterial streets following snow events. By April 2007, monthly street dirt yields generally returned to levels observed in July 2006.

Swept Sites

As expected, the monthly street dirt yields were much lower and less variable in the swept sites. With the exception of the January 2007 yield at Duwamish Diagonal (64 g/m^2), monthly street dirt yield ranged from 4 to 55 g/m^2 at the swept sites.

Street Dirt Accumulation Rates

Daily street dirt accumulation rates were calculated each month by subtracting the previous month's yield from the current month's yield, and dividing by the number of days between samples (see Table 8):

$$\text{Daily street dirt accumulation rate (g/m}^2\text{/day)} = \frac{(MSDY_m - MSDY_{m-1})}{(D_m - D_{m-1})}$$

Where: $MSDY_m$ = Monthly street dirt yield (g/m^2) at month m

D_m = Sample date at month m.

Accumulation rates were quite variable, ranging from -2.8 to +4.1 g/m^2/day. (The large negative value [-12 g/m^2/day] estimated for April at the Southeast Seattle unswept site is considered to be an outlier). Daily accumulation rates were not significantly different ($p > 0.05$) between the swept and unswept sites, and were not significantly different from zero at any site during the pilot study (as determined by a binomial test of ranked accumulation rate data versus zero; see Appendix A, Table A-11). This result is consistent with other studies which showed that the accumulation of dirt on the street is highly dynamic and may be limited by wind and vehicle movement rather than the accumulation time period (i.e., time between storms or sweeping events).

Comparisons with Other Studies

USGS (1999) reports that in residential areas of Madison, Wisconsin, street dirt yields measured in the spring, winter, and fall can be as high as 8,000 pounds per curb mile (due to street sanding) and drop to 400 pounds per curb mile in the summer months. In the Seattle pilot study, lineal street dirt yields ranged from a low of 69 pounds per curb mile in December 2006 at the Southeast Seattle swept site to a high of 2,200 pounds per curb mile in September 2006 at the Southeast Seattle unswept site. The median monthly street dirt yield was 995 and 220 pounds per curb-mile for all unswept and swept test sites, respectively.

Monthly street dirt yields for the swept and unswept sites in Seattle are compared to literature values for other cities in Table 9. This comparison is presented for reference only as the results are not directly comparable due to difference in sweeping frequency, sampling frequency, sampling methodology, and basin characteristics. For example, both the Baltimore (Center for Watershed Protection 2009) and Madison (USGS 2007) studies swept twice as frequently as this pilot study, and many other studies removed large organic material from street dirt samples to specifically focus on the inorganic content and small particle sizes present. Also, sampling was not conducted during fall and winter for some studies because of the presence of snow or wet street surfaces. However, the comparison does indicate that the pilot study street dirt yields fall within a reasonable range.

As shown in Table 9, median monthly values for lineal street dirt yield (240, 150, and 350 lb/curb mile for West Seattle, Southeast Seattle, and Duwamish Diagonal, respectively) for samples collected in the swept sites were between the median value reported for Madison, Wisconsin (150 lb/curb mile) (USGS 2007) and the mean value reported for Baltimore, Maryland (645 lb/curb mile) (Center for Watershed Protection 2008). In the unswept sites, the median lineal street dirt yields (1,108, 1,010, and 790 lb/curb mile, for West Seattle, Southeast Seattle, and Duwamish Diagonal, respectively) were in the upper range of median values reported by these and other studies (146 to 1,110 lb/curb mile).

Sweeper Waste

The monthly measurements of sweeper waste yield (in dry g/m^2) during the pilot study at each of the three test sites are presented in Table 10. A summary comparison of the three test sites is provided in the box plots shown in Figure 11. Cumulative sweeper waste yields are presented in Figure 12. Calculation of the annualized yield is discussed below in the Sweeper Waste Yield section. Daily sweeper waste yields were calculated each month by subtracting the previous month's yield from the current month's yield, and dividing by the number of days between samples (see Table 11).

$$\text{Daily sweeper waste yield (g/m}^2\text{/day)} = \frac{(MSWY_m - MSWY_{m-1})}{(D_m - D_{m-1})}$$

Where: $MSWY_m$ = Monthly sweeper waste yield (g/m^2) at month m

D_m = Sample date at month m.

Summary of Results

General conclusions regarding sweeper waste yields are summarized below:

- Sweeper waste yield:
  - On an areal yield basis (i.e., sweeper waste mass per square meter of street surface), *no significant difference* was observed between the three test sites.
  - The overall daily sweeper waste removal rate (total yield divided by total study days) was similar (0.7 to 0.9 g/m^2/day) and not significantly different among the three sites (p=0.654).
  - The initial sweeping of a site did not consistently result in a maximum daily sweeper waste yield.
  - The increase in the sweeper waste yield at the Southeast Seattle site in November 2006 (1.6 g/m$^{2/}$day) was apparently caused by leaves, since this site had the most tree cover of all three test sites.

- Street sweeper pickup efficiency:
  - The median monthly street sweeper pickup efficiency (calculated by comparing the quantity of sweeper waste removed from each swept site in each month to the street dirt mass measured before sweeping in that site in that month) was similar among the study areas, ranging from 51 percent in West Seattle to 68 percent in Southeast Seattle.
  - The absence of a relationship between residential sweeper waste yield and number of parked cars suggests that the street sweeper continues to collect sediment from the center of the street when it is diverted from the curb, and the number of parked vehicles may be less important than other factors affecting sweeper efficiency because less than 25 percent of the total curb length was blocked by parked cars when the most cars were observed.

Sweeper Waste Yield

Street sweeping removed approximately 7,100, 17,600, and 5,900 dry pounds (3,200, 8,000, and 2,700 dry kilograms) of material during the study period at the West Seattle, Southeast Seattle, and Duwamish Diagonal test sites, respectively. Note that the West Seattle and Southeast Seattle sites were monitored for a 12-month period, while testing at the Duwamish Diagonal site lasted only 7 months. On an annualized basis, the areal sweeper waste yields are 250, 300, and 350 g/m^2 street per year (2,200, 2,700, and 3,100 lb/acre/year), and the lineal sweeper waste yields are 3,800, 4,700, and 6,400 lb/curb mile/year for the West Seattle, Southeast Seattle, and Duwamish Diagonal test sites, respectively (see Table 10).

On an areal yield basis (i.e., sweeper waste mass per square meter of street surface), no significant difference was observed between the three test sites based on the results of a Kruskal-Wallis test at $\alpha = 0.05$ (see Appendix A, Table A-11)

The highest sweeper waste removal rates were observed during the initial measurements made in July 2006 for Southeast Seattle (2.6 g/m^2/day) and in November 2006 for Duwamish Diagonal (5.3 g/m^2/day) (see Table 11). These initial rates were most likely higher than all other rates measured later in the study because most of the streets had not been swept in these swept sites prior to this study. Although S Industrial Way in the Duwamish Diagonal swept site had been swept by a mechanical sweeper prior to the study, it only represents approximately 25 percent of the street area in the swept site. However, at the West Seattle site, the highest removal rate occurred in February (1.2 g/m^2/day compared to 0.8 g/m^2/day in July 2006), showing that the initial sweeping of a site did not consistently result in the maximum amount of sweeper waste collected. One possible explanation for the lower initial rate observed in West Seattle is that California Avenue SW had been routinely swept before the inception of the study as part of the City's existing street sweeping program. Although California Avenue SW represents less than 20 percent of the street surface, visual observations by the sampling crew indicate that street dirt mass was substantially higher on this arterial street compared to the side streets.

Additional sweeper waste sampling events were required in November 2006 at the two residential sites due to the large amount of leaves that had been deposited on the streets, which filled up the dumpsters prior to the scheduled sampling event. Daily sweeper waste yields were higher in November (1.6 g/m^2/day) than most other months (0.1 to 1.2 g/m^2/day) at the Southeast Seattle site, but not in West Seattle (0.5 g/m^2/day versus 0.3 to 1.2 g/m^2/day). The Southeast Seattle study area is an older neighborhood that has much more tree cover than West Seattle (see Figures 5, 6, and 7) and may be expected to have more leaves deposited on the street and a higher sweeper waste yield in the fall. However, the total organic carbon (TOC) data discussed below indicate that leaf drop may not have been entirely responsible for this difference because both residential sites exhibited a maximum TOC concentration during the second quarter of the pilot study (November 2006 through January 2007), but the second quarter TOC concentration was higher at the West Seattle site (11, 28, 4.4, and 8.8 percent for each consecutive quarter) than the Southeast Seattle site (10, 20, 9.7, and 14 percent for each consecutive quarter).

The higher sweeper waste yield measured in November 2006 at the Duwamish Diagonal swept site may be related to both the fall leaf drop and the fact that this was the first sweeping event at this site (with the exception that S Industrial Way, representing approximately 25 percent of the Duwamish Diagonal swept site, had been swept by a mechanical sweeper prior to the study). Although there are relatively few trees along the streets in the Duwamish Diagonal swept site, the TOC concentration was somewhat higher during the second quarter (9.6 percent for the first set of samples collected from the industrial site in November 2006 to January 2007) compared to the last two quarters of the pilot study (6.7 and 7.5 percent), but was lower than the TOC concentrations measured during the second quarter at the two residential swept sites (28 percent at West Seattle and 20 percent at Southeast Seattle).

Sweeper Collection Efficiency

Street sweeper efficiency was not directly measured during this study. Typically, sweeper efficiency is measured by comparing the amount dirt on the street immediately before and after sweeping. However, an approximate measure can be made for this study by comparing the monthly sweeper waste yield to the street dirt yield that was measured one to two days before sweeping. Results of the street sweeper collection efficiency estimates are presented in Table 12. These results are useful for comparison between sites, but should not be compared to before and after measurements reported in the literature because of the different sampling methodology used in this study.

Although monthly sweeper collection efficiencies varied widely over the course of the study, the median efficiencies were similar for all three sites (51 to 68 percent). In the West Seattle site, the estimated street sweeping efficiency ranged from 10 to 105 percent with a median efficiency of 51 percent. In the Southeast Seattle site, street sweeping efficiency ranged from 9 to 505 percent with a median removal efficiency of 68 percent. In the Duwamish Diagonal site, street sweeping efficiency ranged from 16 to 303 percent with a median removal efficiency of 67 percent.

In order to operate effectively, the street sweeper needs to be able to access the curb line where most of the dirt accumulates. For this reason, parking was not allowed on the side of the street to be swept on street sweeping days. Residents were well informed of the sweeping dates by street signs that were installed throughout the sites before the study began (see Parking Management below). During the first eight months of the study, parked vehicles were given a warning notice reminding them about the street sweeping program and asking them to comply with the no parking signs. In February 2007, the city began issuing tickets to vehicles that did not move on the scheduled street sweeping days. The absence of a relationship between residential sweeper waste yield and number of parked cars suggests that the street sweeper continues to collect sediment from the center of the street when it is diverted from the curb, and the number of parked vehicles may be less important than other factors affecting sweeper efficiency because less than 25 percent of the total curb length was blocked by parked cars when the most cars were observed.

The numbers of parked vehicles in each residential swept site was recorded on a weekly basis throughout the study, and are presented on a monthly basis in Table 13. Before ticketing began in February 2007, the monthly average number of parked vehicles was three times higher in West Seattle (43 cars/curb mile) than Southeast Seattle (14 cars/curb mile). Assuming each parked vehicle blocks approximately 30 feet of curb from sweeper access, the average percentage of curb length blocked by parked vehicles before ticketing was 24 percent in West Seattle and 8 percent in Southeast Seattle. The higher proportion of curb length blocked by parked vehicles may explain the lower median sweeper collection efficiency for West Seattle (51 percent) compared to Southeast Seattle (71 percent).

After ticketing was enforced, the number of parked vehicles was reduced by approximately 70 percent in both residential study areas, but the monthly average number of parked vehicles remained three times higher in West Seattle (13/curb mile) than Southeast Seattle (4/curb mile). However, the sweeper collection efficiencies (see Table 12) and the sweeper waste yield (see Table 11) did not noticeably increase when ticketing began in February 2007. This observation suggests that the lower sweeper collection efficiency noted above for West Seattle may not have been due to the higher number of parked vehicles.

Comparisons with Other Studies

Comparison of sweeper waste yields with other studies is difficult because it is highly variable and dependent on site specific conditions such as street dirt loading, land use, pavement type and condition, sweeping frequency, and sweeper efficiency. In addition, most studies estimate sweeping efficiency using measurements of street dirt before and after sweeping, and this study estimated sweeping efficiency by comparing measurements of street dirt before sweeping to measurements of sweeper waste removed. However, Schilling (2005) reports that high-efficiency street sweepers remove up to 70 percent of street dirt with biweekly to monthly sweeping, which is similar to the estimated removal efficiencies of 51, 76, and 67 percent for the West Seattle, Southeast Seattle, and Duwamish Diagonal swept test sites, respectively.

Catch Basin Sediment

The total amount of sediment that accumulated in test site catch basins was determined by measuring the depth of sediment at multiple catch basins within each test site over the study period. A total of 12 catch basins were measured/sampled at each test site, which represents most of the catch basins in the swept and unswept sites in the West Seattle study area (16 and 18 total catch basins, respectively) and the Duwamish Diagonal study area (16 and 17 total catch basins, respectively), and approximately one-third of the catch basins in the swept and unswept sites in the Southeast Seattle study area (38 and 36 total catch basins, respectively).

Sediment depth measurements were made approximately every month. Sediment mass was estimated on a quarterly basis from depth measurements and sample analysis results. Sediment volume was calculated as the average sediment depth multiplied by the catch basin area. Sediment mass was calculated as the sediment volume multiplied by the bulk density and solids content of each quarterly catch basin sediment sample. The sediment accumulation per unit area in each catch basin was then calculated as the sediment mass divided by the street area draining to the sampled catch basin. This calculated value (in g/m^2) represents the amount of sediment removed by each catch basin per unit area of street. Daily sediment accumulation rates (in $g/m^2/day$) were estimated by taking the difference in accumulation and dividing by the number of days between sampling dates. The median sediment accumulation value (in g/m^2 and $g/m^2/day$) of the 12 sampled catch basins is presented for each sampling date because the data are not normally distributed. Annual sediment accumulation rates were calculated as follows:

$$\text{Annual catch basin sediment accumulation rate (kg/year)} = \frac{\sum_{i=1}^{n} M_i}{\sum_{i=1}^{n} A_i} \times A_s \times \frac{365 \text{ days/year}}{T_s}$$

Where: M_i = Dry sediment mass in monitored catch basin *i* at the end of the study (kg)

A_i = Street area draining to monitored catch basin *i* (m^2)

A_s = Total street area in test site (m^2)

T_s = Study period from initial cleaning to final measurement (days).

In the Duwamish Diagonal study area, all catch basins were inadvertently cleaned by a contractor on an unknown date between April 25, 2007 (when sediment depths were measured) and May 16, 2007, when the cleaning was discovered by SPU. Seattle rain gage RG18 (located in southeast Seattle at Rainier Avenue S and S Kenny Street) recorded 0.48 inches of rain during this period, with a maximum 1-day total of 0.30 inches on May 2, 2007. If the cleaning occurred before May 2, 2007, it is likely that runoff transported sediment into the catch basins during this period was removed by the accidental cleaning and was not accounted for in this study.

The amount of sediment that accumulated in the catch basins each quarter and estimated daily accumulation rates are presented in Table 14. Time series plots of catch basin sediment depth and daily accumulation rates (in $g/m^2/day$) are shown in Figure 12. Median values of the

12 sampled catch basins are presented in Table 14 and Figure 12 because the data are not normally distributed due to occasional high values (see Figure 14). Catch basin accumulation and estimated catch basin capacity utilization (i.e., percent full) at the end of the study are summarized for all catch basins in the box plots shown in Figure 14. Percent full is calculated as the ratio of sediment depth to sump depth in the catch basin.

Summary of Results

General conclusions regarding sweeper waste measurements are summarized below:

- Street sweeping did not significantly affect the amount or rate of sediment accumulation in the study area catch basins. No differences were observed between the swept/unswept sites in West Seattle where a total of 580 kg of dry sediment remained in the 12 monitored catch basins at the end of the study period at the swept site and 610 kg remained in the catch basins at the unswept site (57 g/m^2/year versus 60 g/m^2/year for swept and unswept sites, respectively). Similar results were observed at the Duwamish Diagonal site (200 kg versus 140 kg of total sediment accumulation and 34 g/m^2/year versus 24 g/m^2/year, at the swept and unswept sites, respectively). Catch basin accumulation was higher in the swept site compared to the unswept site in Southeast Seattle (630 kg versus 260 kg and 70 g/m^2/year versus 35 g/m^2/year, respectively), but these differences were not statistically significant.

- It was difficult to accurately measure catch basin accumulation because very little sediment accumulated in the catch basins (0.6 to 3.9 inches) over the study period. Daily catch basin accumulation rates were highest (0.20 to 0.45 g/m^2/day) during the fall quarter of the study when rainfall was most frequent. Little if any sediment accumulated in the catch basins during the winter and spring quarters (-0.16 to 0.12 g/m^2/day).

- Most of the catch basins monitored during the pilot study were less than 10 percent full at the end of the study period, regardless of whether the streets were swept or not. Because of the limited duration of the study, it is difficult to accurately establish an area-wide catch basin cleaning frequency. However, if catch basins are cleaned whenever sediment reaches 60 percent of capacity, as required under Seattle's NPDES permit, these results suggest that, on average, catch basins may need to be cleaned about once every 3 to 7 years.

Changes in Catch Basin Accumulation as a Result of Street Sweeping

Overall, the 12 catch basins that were monitored in the swept sites captured more material (1,400 kg or 3,100 lbs dry weight) than the control/unswept sites (1,000 kg or 2,200 lbs dry weight) during the 7- to 12-month study period. However, this difference was primarily due to the Southeast Seattle area where much more sediment accumulated in the catch basins located in the swept site (630 kg) compared to the unswept site (260 kg). There were no differences in catch basin accumulation between the swept and unswept sites in West Seattle (580 and 610 kg, respectively) and Duwamish Diagonal (200 and 140 kg, respectively).

Individual catch basin measurements were extrapolated over the total street area for each site on an annual basis as described above. These annual sediment accumulation rates are presented in Table 14 and are summarized as follows:

- West Seattle
  - Swept site: 510 lb/acre/year (57 g/m^2/year), 900 lb/curb mile/year
  - Unswept site: 540 lb/acre/year (60 g/m^2/year), 900 lb/curb mile/year
- Southeast Seattle
  - Swept site: 620 lb/acre/year (70 g/m^2/year), 1,100 lb/curb mile/year
  - Unswept site: 320 lb/acre/year (35 g/m^2/year), 480 lb/curb mile/year
- Duwamish Diagonal
  - Swept site: 300 lb/acre/year (34 g/m^2/year), 620 lb/curb mile/year
  - Unswept site: 220 lb/acre/year (24 g/m^2/year), 560 lb/curb mile/year.

Measured differences in catch basin accumulation between the swept and unswept sites were not statistically significant using a Mann-Whitney U-test (a non-parametric equivalent to the students' t-test for independent samples of data collected in this study). The p values between swept and unswept test sites ranged from 0.13 to 0.96 (see Appendix A). Because of the low sediment accumulation (less than 3 inches over the study period), differences in catch basin sediment accumulation may have been masked by natural variability and measurement error. Differences between treatments might have been revealed to be statistically significant if the study had been carried out for a longer period of time and more sediment had accumulated in the catch basins.

Temporal Trends in Catch Basin Sediment Accumulation

Within each basin, the swept and unswept sites generally responded similarly throughout the year with some minor differences in sediment accumulation as shown in Figures 12 and 13. After the catch basins were cleaned in June 2006, they remained empty until the first significant rainfall occurred in September 2006 and mobilized sediment into the storm drain system. In the residential study areas, sediment accumulation generally increased from October 2006 to early January 2007, decreased during dry weather in late January, and increased to an annual maximum in April or May 2007. Rainfall declined to 0.8 to 1.6 inches per month in May and June, during which time the sediment depth in the catch basins generally decreased to levels similar to those measured in January 2007. Settling and consolidation of sediment in the catch basins likely contributed to the decreases in sediment depth observed during these relatively dry periods, because it is unlikely that sediment was scoured from the catch basins during these dry periods due to low inflow rates.

As explained earlier, monitoring in the Duwamish Diagonal area began in November 2006. Because of heavy rain and runoff in November 2006, a baseline measurement could not be made to confirm that all catch basins were cleaned prior to the start of the pilot study. Thus, the initial sediment depth may not have been zero for the Duwamish Diagonal basin as was previously determined for the residential basins (see Figure 12). Sediment measurements indicate that at least one of the catch basins at the unswept (control) site (DDW-12) was not cleaned before the pilot study started. Sediment depth in the Duwamish Diagonal catch basins exhibited very little change between the initial measurement in November 2006 (median depth of 0.06 inches in the 24 catch basins that were monitored at the swept and unswept sites) and the measurement made in April 2007 (median depth of about 0.1 inches in the monitored catch basins).

It was difficult to accurately measure the depth of sediment in the catch basins because very little sediment accumulated over the study period (0.6 to 3.9 inches) and because measurements were generally made with 2 to 3 feet of water in the catch basin (catch basin sumps were not dewatered prior to measuring sediment depth). The precision of catch basin sediment depth measurements was assessed on May 23, 2007 by collecting duplicate depth measurements in the 12 catch basins at the Southeast Seattle swept site. The results show that the difference in average sediment depths for the 12 re-measured catch basins ranged from 0.00 to 0.07 feet, a relative percent difference of 0 to 42 percent. The median value changed 0.03 feet (15 percent) from 0.19 to 0.22 feet. These duplicate measurements, while not a definitive description of the sample variability, suggest that the small decreases in sediment depth and mass observed between January and July 2007 are within the range of possible error associated with the measurement procedures. These results provide further evidence that the street sweeping treatment did not have a measurable effect on catch basin sediment accumulation.

Daily catch basin accumulation rates were estimated each quarter by subtracting the previous quarter's measurement from the current quarter's estimate and dividing by the number of days between measurements. Daily accumulation rates were highest during the fall quarter of the study (0.17 to 0.45 g/m^2/day from mid-October to mid-January) when rainfall is most frequent. Rainfall during October to January typically accounts for two-thirds of the annual rainfall total (see Figure 12 and Table 14 for catch basin data and Table 5 for rainfall data). Accumulation rates were lowest during the following winter and spring quarters (-0.16 to 0.12 g/m^2/day from mid-January to mid-June). As noted above, measurement error may account for the negative values observed during the latter half of the study period.

Catch Basin Cleaning Frequency

Under its NPDES municipal stormwater permit, Seattle is required to inspect each catch basin in the City every year and to clean those where the sediment depth exceeds 60 percent of the sump depth or where the minimum clearance between the sediment surface and the invert of the lowest pipe is less than 6 inches (Ecology 2005, 2007). The ratio of sediment depth to sump depth (i.e., percent full or catch basin utilization) in all of the catch basins monitored was generally less than 10 percent at the end of the 7- to 12-month study period, but ranged from 1 to 43 percent (see Figure 14). At the two residential study areas, the median catch basin utilization ranged from 3 to 7 percent full and the 75th percentile ranged from 9 to 17 percent full at the end of the 1-year study. Following the 60 percent rule and assuming that sediment continues to accumulate at the rate observed during this pilot study, these results indicate that most (75 percent) catch basins in these areas would need to be cleaned about once every 4 to 7 years. However, given the relatively short duration of the pilot study, the difficulty in accurately measuring sediment depths in the catch basins, and the variability between individual catch basins, it is difficult to identify a single area-wide catch basin cleaning frequency. Additional information is needed to determine a reasonable cleaning frequency for catch basins in these areas.

Sediment accumulation in the Duwamish Diagonal catch basins was measured for only about a 7-month period because of the delayed start. Because catch basins were accidentally cleaned by a City contractor in May 2007, sediment accumulations at the end of the study period were estimated by adding measurements made prior to cleaning to measurements made at the end of the study. The median catch basin utilization was 8 percent full (2 inches) at the swept and unswept site, and the 75th percentile at the two sites was 9 and 11 percent full at the end of the 7-month period. Assuming that sediment continues to accumulate at the rate observed during this pilot study (see Figure 13), 75 percent of these catch basins would need to be cleaned about once every 3 to 4 years. Again, given the relatively short duration of the pilot study and the difficulty in accurately measuring sediment depths in the catch basins, additional information is needed to assess cleaning frequencies.

Comparisons with Other Studies

It is difficult to compare pilot study results with other studies because of the relatively short duration of our study (7 to 12 months) and differences in sampling techniques. As part of the Nationwide Urban Runoff Program, Pitt (undated) measured the amount of sediment accumulating in catch basins over a 3-year period at two mostly residential test sites located in Bellevue, Washington. Measurement frequency varied from every month to every 8 months during the study period. The results indicated that sediment accumulation reached a steady state after the sump became about 60 percent full of sediment. The author referred to this maximum accumulation depth as the “stable volume” and noted that the stable volume was reached after 1 to 2 years at the two sites. Very little washout or accumulation of sediment occurred in the catch basins once the stable volume was reached, even after large storm events. Based on these results, the author recommended that catch basin cleaning be conducted on an annual basis (Pitt undated).

Catch basins in the three areas monitored as part of this pilot study (Southeast Seattle, West Seattle, and Duwamish Diagonal) were typically less than 10 percent full at the end of the 7- to 12-month study period. Given the relatively flat shape of the catch basin accumulation curves shown in Figure 12, it does not appear that the catch basins in the Seattle street sweeping pilot study would have approached 60 percent full in the 1- to 2-year period determined by Pitt (undated) for the sites in Bellevue, WA. It is unclear why so little sediment accumulated in the pilot study catch basins compared to the Bellevue study. Street dirt quantities and characteristics were fairly similar in the two studies. The Pitt (undated) study reported that street dirt loadings (i.e., yields) ranged from about 300 to 700 lbs/curb mile after 15 days of accumulation regardless of whether or not the streets were swept, while the median monthly yields at the three Seattle test areas ranged from about 150 to 350 lb/curb mile in the swept areas and 790 to 1,100 lbs/curb mile in the unswept test areas. Although grain size data from the Bellevue study are limited to two street dirt samples collected when the streets were not swept, the particle size distribution in these two samples was only slightly more coarse than the unswept street dirt samples from the Seattle sites, and therefore should not have affected the transport or accumulation of sediment in the catch basins. Street dirt samples from the Pitt (undated) study contained about 4 percent silt and clay, 14 to 16 percent fine sand, 54 to 61 percent coarse sand, and 19 to 26 percent gravel, compared to median values from unswept samples in the Seattle area of 8 to 9 percent silt and clay, 16 to 27 percent fine sand, 48 to 53 percent coarse sand, and 9 to 23 percent gravel. Further investigation of catch basin accumulation is needed to determine the best frequency for cleaning catch basins in the Seattle area.

Sediment Physical and Chemical Properties

Results of the physical and chemical analysis of all catch basin, street dirt, and sweeper waste study samples are presented in a series of tables in Appendix A (Tables A-1 through A-8). Each table presents the results for all samples collected during each round of sampling (i.e., from July to October 2006, October to January 2007, January to April 2007, and April to July 2007). The first four tables in Appendix A present concentrations of each analytical parameter on a dry weight basis and the second set of tables present organic carbon normalized concentrations for specific organic compounds. Organic carbon normalized concentrations are presented to enable comparison of these results to the Washington state marine sediment management standards.

The Duwamish Diagonal study area drains to the Duwamish Waterway (marine), the West Seattle study area discharges directly to Puget Sound (marine), and the Southeast Seattle study area drains to Lake Washington (freshwater). The chemical test results are compared to both marine and freshwater sediment criteria in data tables and figures. Criteria comparisons are discussed in the following sections. For the purposes of the pilot study, all results are compared to both the marine and freshwater sediment criteria, regardless of where the test site is located.

Although there are no regulatory standards for sweeper waste, street dirt, and catch basin sediment, the available sediment/soil criteria described below were used as benchmarks to assess the overall quality of all samples collected:

- Washington State freshwater sediment guidelines based on the apparent effects threshold (AET) (Avocet 2003). AETs relate chemical concentrations in sediments to synoptic biological indicators of injury (i.e., sediment bioassays or diminished benthic infaunal abundance). The guidelines recommend two levels:
  - Lowest apparent effects threshold (LAET) is the lowest value of the four biological indicators used to develop AETs. Concentrations

below the LAET are expected to have no adverse effects on the benthic community (Avocet 2002).

  - Second lowest apparent effects threshold (2LAET) is the second lowest value of the four biological indicators used to develop AETs. Concentrations above the 2LAET are expected to have more significant adverse effects and/or effects may occur in a greater percentage of benthic species (Avocet 2002).

- Sediment management standards (SMS) for marine sediments in Washington State (WAC 173-204). The SMS establish two levels:

  - Sediment quality standard (SQS): Concentrations below the SQS are expected to have no adverse effects on biological resources and no significant human health risk.

  - Cleanup screening level (CSL): Minor effects level used to identify areas of potential concern. The CSL is equivalent to the Minimum Cleanup Level (MCUL).

  If the total organic carbon (TOC) content of the sample is within 0.5 to 4.0 percent, sediment standards for most organic compounds are based on TOC-normalized concentrations. When TOC concentrations are outside this range, the marine sediment standards are based on the LAET and 2LAET values instead of the TOC-normalized SQS and CSL values. Because the TOC content of all pilot study samples was above 4, the results for all organic compounds are compared to the LAET and 2LAET.

- Model Toxic Control Act (MTCA) Method A Soil Cleanup Levels for unrestricted use in Washington State (WAC 173-340).

Comparison of street dirt and storm drain sediment to these criteria is considered conservative. If sample concentrations are below a standard/criterion, there is little chance that stormwater discharges would have an adverse impact on receiving water sediments. However, a concentration that is above the standard/criterion does not necessarily indicate that the sediment offshore of the outfall will exceed standards, because sediment discharged from storm drains disperses into the receiving environment and mixes with sediment from other sources before being deposited.

Median values for selected parameters of concern are presented in Table 15 and ranges of values for all samples are presented in Table 16. Box plots of parameter concentrations are presented in Figures 15 through 19. Summary statistics for all measured parameters are presented in Appendix A in Table A-12. These statistics include the number of samples, mean, median, minimum, 25th percentile, 75th percentile, and maximum for each of the six sites and three media types (street dirt, sweeper waste, and catch basin sediment), as well as summary statistics comparing all of the swept sites to all of the unswept sites. All results are presented on a dry weight basis. Sediment physical and chemical testing results are summarized separately for the following groups of analytical parameters:

- Particle size distribution
- Organic matter
- Nutrients
- Metals
- Petroleum hydrocarbons
- Polycyclic aromatic hydrocarbons (PAHs)
- Phthalates
- Polychlorinated biphenyls (PCBs)
- Miscellaneous organic compounds.

Summary of Results

Although the pilot test showed that street sweeping was effective in removing a significant amount of dirt and associated contaminants from the roadways, street sweeping did not significantly affect the physical or chemical composition of the material remaining on the street or the sediment that accumulated in catch basins. For example, as shown in Figure 15, the relative distribution of gravel, coarse sand, fine sand, and silt/clay in the street dirt and catch basin samples was fairly similar between the swept and unswept test sites. While there were some differences for specific sites, there was no consistent pattern observed across all sites. Catch basin sediment at the unswept site at West Seattle contained a greater proportion of coarse-grained material (72 to 83 percent) than the sediment collected from the swept site (53 to 75 percent), which suggests that street sweeping may be more effective in removing coarse-grained materials. However, this observation was not repeated for the Southeast Seattle and Duwamish Diagonal study areas, where coarse-grained material comprised 67 to 87 percent and 57 to 77 percent, respectively, of the sediment in catch basins from the swept site versus 71 to 84 percent and 50 to 74 percent, respectively, of the sediment in the unswept sites (Table 17).

In general, chemistry results were more variable than the physical measures (e.g., grain size), which made it difficult to identify differences between media types (i.e., sweeper waste, catch basin sediment, and street dirt), as well as between swept versus unswept sites. These difficulties may have also been related to the fact that only 3 to 4 composite samples per media type were analyzed at each test site. Although samples were collected from numerous locations within each test site (12 catch basins and 16 street dirt samples) each month, the monthly samples were then archived and composited each quarter for chemical analysis. As a result, only three samples were analyzed per media type at the Duwamish Diagonal study area and four samples were analyzed at the two residential study areas. For this reason, statistical analyses were not performed on the physical/chemical test results. For the purposes of this discussion, results are simply presented in tables and box plots.

Another factor affecting the comparison of chemistry results may be the difficulty in identifying test (swept) and control (unswept) sites that contained similar land use, street use, and traffic patterns. This was particularly difficult in the industrial areas of Seattle where there are many small businesses that change from block to block. Ideally, the pilot study would have included a first phase designed to evaluate solids/pollutant loadings without sweeping the streets and a second phase designed to evaluate swept conditions at a single test site. Because of project time constraints and available resources, the field study had to be completed within 1 year, which required that test and control sites be used to evaluate sweeping performance.

General conclusions regarding the physical and chemical characteristics of street dirt, sweeper waste, and catch basin sediment area summarized below:

- The grain size data indicate that regenerative air sweepers used in the pilot study may have been more effective in picking up coarse-grained materials than the finer particles present on the street surface. Sweeper waste samples contained larger proportions of coarse sand and gravel (70 to 97 percent) and smaller proportions of fine silt and clay (<1 to 9 percent) than was found in the street dirt samples (56 to 98 percent and 1 to 15 percent, respectively).

- Except for petroleum hydrocarbons and some phthalates, concentrations of most pollutants measured in the street dirt, sweeper waste, and catch basin sediment samples (55 total samples) were below sediment and soil standards/guidelines. Chemicals with measured concentrations above one or more of the sediment standards/guidelines in the samples analyzed included:

Zinc:	10	(18 percent)
Chromium:	8	(15 percent)
Lead:	4	(7 percent)
Silver:	4	(7 percent)
Copper:	1	(2 percent)
Petroleum hydrocarbons (diesel):	4	(7 percent)
Petroleum hydrocarbons (motor oil):	42	(76 percent)
Carcinogenic PAHs (cPAH):	52	(95 percent)
Di-n-octylphthalate:	36	(65 percent)
Bis(2-ethylhexyl)phthalate (BEHP):	32	(58 percent)
Butylbenzylphthalate (BBP):	19	(35 percent)
Di-n-butylphthalate:	16	(29 percent)
PCBs:	20	(44 percent)

- Samples were not tested to evaluate whether materials require special disposal. The Stormwater Manual for Western Washington (Ecology 2005) notes that solids collected from street sweeping and catch basin cleaning activities do not ordinarily classify as dangerous waste, but are considered a solid waste and should be tested before considering for reuse. The City of Seattle routinely disposes street sweeper waste and catch basin sediment at a solid waste landfill.

- Concentrations of many chemicals (i.e., cadmium, lead, zinc, diesel, motor oil, BEHP, and PCBs) were higher in the samples collected from the industrial site (Duwamish Diagonal) compared to the two residential sites (Southeast Seattle and West Seattle). The differences were most pronounced for zinc where concentrations in the Duwamish Diagonal catch basins samples (489 to 1,100 mg/kg) were as much as 5 times greater than in the residential catch basin samples (223 to 314 mg/kg) and for lead where concentrations in the Duwamish Diagonal sweeper samples (159 to 361 mg/kg) were 2 to 13 times greater than in the residential sweeper samples (27 to 88 mg/kg).
- In most cases, concentrations of cadmium, copper, lead, and zinc were greater in the catch basin samples than the other media sampled. Differences were most pronounced in the Duwamish Diagonal study area where zinc concentrations in catch basin samples (489 to 1,100 mg/kg) were up to 6 times greater than the Duwamish Diagonal street dirt (238 to 541 mg/kg) and sweeper waste samples (170 to 324 mg/kg).

Particle Size Distribution

The sediment samples were analyzed for 15 different particle size fractions (see Appendix A). Particle size distribution results are presented as box plots in Figure 15. Median values are presented in Table 15 and ranges are presented in Table 16 for the following four size classes:

- Gravel (>2 mm)
- Coarse sand (0.25 to 2 mm)
- Fine sand (75 to 250 µm)
- Silt/clay (<75 µm).

The finer-grained particles (silt/clay and fine sand) are important for water quality because this material is easily suspended in street runoff and these particles can remain suspended in the water column in the receiving water body. In addition, fine-grained particles often contain higher concentrations of pollutants because this material provides more adsorptive surface area by weight compared to larger particles. However, while the smaller grain size particles are important from a water quality perspective, this material may not be as critical for in-waterway sediment contamination because the fine-grained materials tend to be dispersed throughout the receiving water body rather than accumulating in a narrow area offshore of a particular outfall. Table 17 compares percentages of fine grained particles (less than 250 µm) to coarse-grained particles (greater than 250 µm) in street dirt and catch basin sediment samples collected at the swept and unswept sites.

Results from the particle size analysis are summarized below:

- Coarse sand (0.25 to 2 mm) was the most abundant size class for all types of samples (ranging from 27 to 63 percent of the sample), while silt/clay was the least abundant size class (ranging from <1 to 28 percent of the sample) for all sample types (Table 16).

- All but 2 of the 11 sweeper waste samples contained larger proportions of coarse sand and gravel (70 to 97 percent) than the street dirt samples (56 to 98 percent). On average, the sweeper samples contained 15 percent more coarse-grained material than the street dirt samples. Sweeper waste also contained a smaller proportion (<1 to 9 percent) of silt/clay (<75 µm) than catch basin sediment (<1 to 28 percent) or street dirt (1 to 15 percent). The proportion of fine sand was also somewhat lower in the sweeper waste samples (2 to 21 percent) compared to catch basin (10 to 27 percent) and street dirt samples (2 to 33 percent). These differences suggest that the regenerative air sweepers used in the pilot study may have been more effective in removing coarse-grained materials than the finer particles present on the street surface, but differences in sweeper waste and street dirt particle size also may be explained by differences in vacuum pressure between the industrial vacuum (used to collect the street dirt samples) and the regenerative air sweeper.

- The Duwamish Diagonal study area generally exhibited somewhat higher percentages of fine-grained particles (fine sand plus silt/clay) for all three media (27 to 48 percent in street dirt, 21 to 30 percent in sweeper waste, and 24 to 51 percent in catch basin sediment) than in the two residential basins (2 to 41 percent in street dirt, 3 to 24 percent in sweeper waste, and 10 to 51 percent in catch basin sediment). Streets in the Duwamish Diagonal study area experience a large amount of truck traffic. It is possible that this may have contributed to the larger amount of fine-grained material present on the streets.

Organic Matter

The amount of organic matter present in the samples was measured as total organic carbon (TOC) and total volatile solids (TVS). Data for both parameters are presented as box plots in Figure 16; median values are summarized in Table 15 and ranges are summarized in Table 16. The results were variable, with few consistent patterns observed between swept and unswept test sites or geographic areas. Key results are listed below:

- TOC concentrations in all pilot study samples were greater than 4 percent, which is above the acceptable range for comparison with the TOC-normalized concentrations set by the state marine sediment management standards for most organic contaminants. The highest TOC concentration occurred in the street dirt sample collected during the second quarter (November 2006 to January 2007) at the Southeast Seattle swept site (38 percent). This high TOC was likely related to fall leaf drop. Median TOC results and overall ranges (shown in parentheses) observed at the swept and unswept sites are summarized below for the various locations and sample media:

Residential catch basins:	11 to 15%	(5.7 to 24%)

Residential street dirt:	9.9 to 11%	(4.3 to 38%)
Residential sweeper waste:	9.9 to 12%	(4.4 to 28%)
Industrial catch basins:	14.5 to 20%	(11 to 28%)
Industrial street dirt:	11%	(6.1 to 26%)
Industrial sweeper waste:	7.5%	(6.7 to 9.6%)

- TVS concentrations in the pilot study samples followed patterns similar to the TOC concentrations. Median TVS results and overall ranges (shown in parentheses) for the various locations and sample media are summarized below:

Residential catch basins:	17 to 18%	(11 to 22%)
Residential street dirt:	15 to 16%	(6.2 to 58%)
Residential sweeper waste:	14%	(7.1 to 67%)
Industrial catch basins:	28 to 40%	(20 to 54%)
Industrial street dirt:	13 to 14%	(6.7 to 20%)
Industrial sweeper waste:	9.5%	(7.3 to 29%)

- Catch basin sediment samples collected from the Duwamish Diagonal study area exhibited higher levels of organic matter (20 to 54 percent TVS and 11 to 28 percent TOC) than the two residential sites (11 to 22 percent TVS and 5.7 to 24 percent TOC), but this same trend was not observed in the street dirt and sweeper waste samples. The amount of organic matter in street dirt samples from the Duwamish Diagonal study area (6.7 to 20 percent TVS and 6.1 to 26 percent TOC) were comparable to the levels observed at the two residential study areas (6.2 to 58 percent TVS and 4.3 to 38 percent TOC) and the sweeper samples from the Duwamish Diagonal study area contained lower levels of organic matter (7.3 to 29 percent TVS and 6.7 to 9.2 percent TOC) than the two residential samples (7.1 to 67 percent TVS and 4.4 to 28 percent TOC). It is not clear why the catch basins in the Duwamish Diagonal area appeared to accumulate more organic material than the two residential test areas. Concentrations of organic contaminants were generally higher in the Diagonal catch basins samples, but there was not enough difference to cause percentage level changes in the organic matter content.

- Street dirt samples and sweeper waste samples at all three sites exhibited a wide range of TVS concentrations (6 to 58 percent and 7 to 67 percent, respectively) and TOC concentrations (5 to 38 percent and 4 to 28 percent, respectively). The highest concentrations were generally observed in samples collected between October 2006 and January 2007, which may have been related to the fall leaf drop. At the Southeast Seattle study area, organic matter was consistently higher in the street dirt at the swept site (14 to 58 percent TVS and 9 to 38 percent TOC) than the unswept site

(9 to 19 percent TVS and 4 to 15 percent TOC), but this trend was not observed at the other two study areas (see Figure 16).

Nutrients

The samples were analyzed for total phosphorus (TP) and total Kjeldahl nitrogen (TKN) to assess the potential benefits of street sweeping on eutrophication (nutrient enrichment) impacts to receiving waters. Primary productivity is typically limited by phosphorus in freshwaters and nitrogen in marine waters (i.e., excess phosphorus may degrade freshwaters and excess nitrogen may degrade marine waters). Median nutrient concentrations are presented in Table 15, ranges of nutrient concentrations are presented in Table 16, and box plots of the data are shown in Figure 17. Major conclusions from these results include the following:

- Nutrient concentrations in all samples were highly variable, ranging from 191 to 1,610 mg/kg for total phosphorus and from 49 to 36,600 mg/kg for TKN.
- TP concentrations were similar in street dirt (376 to 1,020 mg/kg), sweeper waste (300 to 723 mg/kg), and catch basin sediment (191 to 1,610 mg/kg).
- TKN concentrations were also similar in street dirt (1,320 to 9,100 mg/kg), sweeper waste (49 to 36,600 mg/kg), and catch basin sediment (2,080 to 13,200 mg/kg).
- No differences in nutrient concentrations were observed between the three study areas or between the swept and unswept sites.

Metals

Metals are contaminants of concern in sediment because of their toxicity to aquatic organisms. Box plots for cadmium, chromium, copper, and zinc are presented in Figure 18. Medians and ranges for these four metals in addition to lead, mercury, and silver are presented in Tables 15 and 16 for each media and site. Ranges for all samples (swept and unswept sites) collected at each study area are presented in Table 18. Median metal concentrations reported in the literature are presented in Table 19 for comparison. Key results are summarized below:

- Concentrations of cadmium, chromium, copper, lead, mercury, silver, and zinc were above at least one of the sediment standards/guidelines in at least one the 55 samples collected as part of the pilot study. Most of the samples that were above the standards/guidelines (64 percent) were collected from the industrial Duwamish Diagonal study area. Zinc and chromium were the metals that most frequently above the standards/guidelines:
  - Zinc concentrations were above regulatory standards/guidelines in 10 of the 55 samples (18 percent). Eight of these samples were

collected from the Duwamish Diagonal study area. All of the six catch basin samples (489 to 1,100 mg/kg) and two of the street dirt samples (461 and 541 mg/kg) collected from the Duwamish Diagonal study area were above the SQS for marine sediment (410 mg/kg). Only four catch basin samples (698 to 1,100 mg/kg) and no street dirt samples were above the freshwater sediment LAET (683 mg/kg).

- Chromium concentrations were above one or more of the sediment standards/guidelines in eight of the samples (15 percent). All but one of these samples was collected from the two residential study areas during the first sampling period (July through October 2006). During the first round, the concentration of chromium in all of the street dirt samples and three of the four catch basin samples in both the swept and unswept test sites (95.4 to 371 mg/kg) was above one or more of the criteria. However, only one sample collected during the subsequent sampling events (a street dirt sample collected from the swept site in West Seattle, 120 mg/kg) was above the freshwater standard/guideline (the freshwater LAET, 95 mg/kg). No samples collected after the first round were above marine sediment standards for chromium.

- Copper (466 mg/kg), lead (279 to 361 mg/kg), mercury (0.8 mg/kg), and silver (0.8 to 1.1 mg/kg) concentrations were above the sediment standards/guidelines in 1, 4, 1, and 4 samples, respectively. Eight of these 10 samples were collected from the Duwamish Diagonal study area.

▪ Cadmium, lead, and zinc concentrations were generally higher at the industrial Duwamish Diagonal study area compared to the two residential study areas (West Seattle and Southeast Seattle) and the highest concentrations were generally found in catch basin sediment. Median concentrations (in bold) and overall ranges (shown in parentheses) for the various locations and media are summarized below (mg/kg):

Sample Media	Cadmium	Copper	Lead	Zinc
Residential catch basins	**0.8-1.1** (0.6-1.7)	**50.9-73.2** (41.4-198)	**67.5-137** (65-166)	**263-333** (223-535)
Residential street dirt	**0.5-0.7** (0.4-1.1)	**39.7-49.3** (25.4-466)	**44-63.5** (26-222)	**165-231** (119-492)
Residential sweeper waste	**0.5-0.7** (0.3-0.8)	**34.6-37.6** 21.5-75.5)	**51.5-63.5** (26-88)	**176-180** (109-273)
Industrial catch basins	**2.6-2.8** (2-4)	**146-158** (136-183)	**120-331** (91-354)	**698-959** (489-1,100)
Industrial street dirt	**1.1-1.5** (0.9-1.6)	**61.7-76.5** (55.3-92.3)	**57-193** (159-361)	**304-403** (238-541)
Industrial sweeper waste	**0.7** (0.6-0.8)	**72.6** (48.6-76.2)	**192** (159-361)	**211** (170-324)

- Differences were most pronounced for zinc where concentrations in the Duwamish Diagonal catch basin samples (489 to 1,100 mg/kg) were as much as five times greater than in the residential catch basin samples (223 to 535 mg/kg) and for lead where concentrations in the Diagonal sweeper waste samples (159 to 361 mg/kg) were 2 to 13 times greater than in the residential samples (26 to 88 mg/kg). The street dirt at the Duwamish Diagonal swept site contained much higher concentrations of lead (118 to 279 mg/kg) than the Duwamish Diagonal unswept site (45 to 75 mg/kg), which indicates that the swept and unswept sites may not have been well matched. The higher lead concentrations in the street dirt at the Duwamish Diagonal swept site were also reflected in the catch basin samples, which contained 296 to 354 mg/kg compared to the 91 to 130 mg/kg at the unswept site.

- One major exception occurred for copper, where a street dirt sample collected during the last quarter (May – July 2007) at the Southeast Seattle unswept site contained the highest concentration (466 mg/kg) recorded during the pilot study.

- In most cases, concentrations of cadmium, copper, lead, and zinc were higher in the catch basin samples than the other media sampled. Differences were most pronounced in the Duwamish Diagonal study area where zinc concentrations in catch basin samples (489 to 1,100 mg/kg) were up to six times greater than the Diagonal street dirt (238 to 541 mg/kg) and sweeper waste samples (170 to 324 mg/kg). This difference is likely related to the greater proportion of fine-grained material found in the catch basin sediment since finer material is more effective in adsorbing pollutants than coarse-grained material (e.g., sand and gravel).

Petroleum Hydrocarbons

Tabulated summary results for diesel range hydrocarbon and motor oil concentrations are presented on a dry weight basis in Tables 15 (medians) and 16 (ranges) for each site and media. A box plot of motor oil concentrations is presented in Figure 19. Key results are summarized below:

- Diesel range hydrocarbons were detected in all project samples, ranging from 100 to 3,300 mg/kg. Concentrations were below the MTCA Method A soil cleanup level (2,000 mg/kg) in all samples collected from the two residential areas (100 to 1,700 mg/kg). However, four of the 15 samples (27 percent) collected in the Duwamish Diagonal study area (2,600 to 3,300 mg/kg) were above the soil cleanup level.

- Diesel range hydrocarbon concentrations were typically greater in the catch basin sediment samples than the other media sampled and were generally higher at the industrial study area (Duwamish Diagonal) compared to the two residential study areas (West Seattle and Southeast Seattle). Median results and overall ranges (shown in parentheses) observed at the swept and unswept sites are summarized below for the various locations and sample media:

Residential catch basins:	805 to 860 mg/kg	(540 to 1,700 mg/kg)
Residential street dirt:	205 to 475 mg/kg	(100 to 1,600 mg/kg)
Residential sweeper waste:	365 to 485 mg/kg	(260 to 1,000 mg/kg)
Industrial catch basins:	1,800 to 3,100 mg/kg	(980 to 3,300 mg/kg)
Industrial street dirt:	400 to 460 mg/kg	(320 to 840 mg/kg)
Industrial sweeper waste:	390 mg/kg	(330 to 420 mg/kg)

- Motor oil (heavy to oil range hydrocarbons) was also detected in all project samples. Motor oil concentrations were typically higher in the samples collected from the Duwamish Diagonal study area where 14 of the 15 (93 percent) samples (2,200 to 18,000 mg/kg) were above the MTCA Method A soil cleanup level (2,000 mg/kg) compared to 28 of the 40 (70 percent) samples collected from West Seattle and Southeast Seattle (2,100 to 7,100 mg/kg). The highest concentrations were found in the catch basin samples collected from the Duwamish Diagonal study area with concentrations in samples collected from the unswept site ranging from 7,800 to 18,000 mg/kg and from 4,200 to 10,000 mg/kg in the swept site.

- Motor oil range hydrocarbon concentrations were typically greater in the catch basin samples than the other media sampled and were generally higher at the industrial study area (Duwamish/Diagonal) compared to the two residential study areas (West Seattle and Southeast Seattle). Median results and overall ranges (shown in parentheses) observed at the swept and unswept sites are summarized below for the various locations and sample media:

Residential catch basins:	3,250 to 4,100 mg/kg	(2,200–7,100 mg/kg)
Residential street dirt:	1,200 to 2,950 mg/kg	(740–6,000 mg/kg)
Residential sweeper waste:	1,800 to 2,050 mg/kg	1,400–6,600(mg/kg)
Industrial catch basins:	7,500–14,000 mg/kg	(4,200–18,000 mg/kg)
Industrial street dirt:	2,400 to 4,000 mg/kg	(1,900–5,600 mg/kg)
Industrial sweeper waste:	2,800 mg/kg	(2,200–3,600 mg/kg)

Polycyclic Aromatic Hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) originate primarily from motor vehicles, but atmospheric deposition from forest fires and coal combustion are also important sources. The pilot study samples were analyzed for seven low molecular weight polycyclic aromatic hydrocarbons (LPAHs) and 10 high molecular weight polycyclic aromatic hydrocarbons (HPAHs) listed below:

- LPAHs: 2-methylnaphthalene, acenaphthene, acenaphthylene, anthracene, fluorene, naphthalene, phenanthrene.
- HPAHs: benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(g,h,i)perylene, benzo(a)pyrene, chrysene, dibenz(a,h)anthracene, fluoranthene, indeno(1,2,3-cd)pyrene, pyrene.

Results are compared to freshwater and marine sediment criteria (based on dry weight and organic carbon concentrations, respectively) in Appendix A. Sums for total LPAHs, total HPAHs, and total carcinogenic PAHs (cPAHs) are included in Appendix A. Concentrations of cPAHs are calculated according to MTCA as the sum of the toxicity equivalency factors for the following PAHs: (benzo(a)pyrene, benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, indeno(1,2,3-c,d)pyrene, and dibenz(a,h)anthracene). Concentrations of cPAHs are presented in Figure 19. Median values of cPAHs, total LPAHs, and total HPAHs are presented in Table 15, and ranges are presented in Table 16.

Similar patterns were observed among concentrations of LPAHs, HPAHs, and cPAHs. Key results are summarized below:

- Concentrations of individual PAHs, total LPAHs, and total HPAHs were below the freshwater sediment guidelines and the marine sediment management standards in most samples. The exceptions occurred in two catch basins samples collected from the Southeast Seattle swept site where 2-methylnaphthalene (710 and 1,100 µg/kg dry weight) was above the 2LAET (555 µg/kg dry weight)
- Total carcinogenic PAHs were detected in 84 percent of the samples with concentrations ranging from 59 to 3,300 µg/kg dry weight. Concentrations were above the MTCA Method A soil cleanup level for unrestricted use (100 µg/kg dry weight) in all but three of the samples where cPAHs were detected. The highest concentrations were measured in a street dirt sample from the West Seattle swept site (3,300 µg/kg dry weight) and the Duwamish Diagonal unswept site (2,500 µg/kg dry weight), and in a catch basin sediment from the Duwamish Diagonal unswept site (2,700 µg/kg dry weight).
- The variability in cPAH concentrations observed at each test site made it difficult to distinguish trends between the different media or study areas. For example, cPAH concentrations in the street dirt (310 to 3,300 µg/kg dry weight) and catch basin sediment (1,000 to 1,300 µg/kg dry weight) from the swept site in West Seattle were much higher than in the unswept site (85 to 160 µg/kg dry weight and 120 to 740 µg/kg dry weight,

respectively). However, the reverse trend was observed at Duwamish Diagonal study area, where cPAH concentrations in street dirt and catch basin sediment collected from the swept sites (280 to 800 µg/kg dry weight and 610 to 1,500 µg/kg dry weight, respectively) were lower than in the unswept test sites (450 to 2,500 µg/kg dry weight and 630 to 2,700 µg/kg dry weight, respectively). No difference was observed between swept and unswept test sites in Southeast Seattle.

Phthalates

Phthalates are a group of chemical compounds that are primarily used as plasticizers and are known contaminants of concern in sediment in Seattle urban waterways (Windward 2002, Anchor and Windward 2008). Pilot test samples were analyzed for the following six phthalates:

- Bis(2-ethylhexyl)phthalate (BEHP)
- Butylbenzylphthalate (BBP)
- Di-n-butylphthalate
- Di-n-octylphthalate
- Diethylphthalate
- Dimethylphthalate.

Results are compared to freshwater sediment guidelines and marine sediment management standards in Appendix A.

Elevated levels of BEHP have been measured in waterway sediment collected from the Lower Duwamish Waterway (Windward 2002), as well as in source sediment samples collected from storm drains discharging to the waterway (SPU 2008). Therefore, this report focuses on evaluating BEHP test results. Dry weight results for BEHP are presented in Figure 19, and median values and ranges of the four most commonly detected phthalates are presented in Table 15 and 16, respectively. Key results are summarized below:

- Bis(2-ethylhexyl)phthalate (100 percent), butylbenzylphthalate (45 percent), di-n-butylphthalate (38 percent), and di-n-octylphthalate (69 percent), dimethylphthalate (7 percent), and diethylphthalate (2 percent) were detected in the 55 pilot test samples. Chemicals that were above the sediment management standards included di-n-octylphthalate standards (65 percent), BEHP (60 percent), BBP (35 percent), and di-n-butylphthalate (29 percent).

- For the individual test sites, chemicals that were above the sediment standards/guidelines in the West Seattle, Southeast Seattle, and Duwamish Diagonal study areas include BEHP (60, 30, and 100 percent, respectively), BBP (15, 5, and 100 percent, respectively), di-n-butylphthalate (15, 10, and 73 percent, respectively), and di-n-octylphthalate (70, 40, and 93 percent, respectively).

- Phthalate concentrations, particularly BEHP, were greater in the catch basin samples than the other media sampled and were generally higher at the industrial study area (Duwamish Diagonal) compared to the two residential study areas (West Seattle and Southeast Seattle). Median BEHP results and overall ranges (shown in parentheses) observed at swept and unswept sites are summarized below for the various locations and sample media:

Residential catch basins:	4,450 to 7,450 mg/kg	(2,200 to 11,000 mg/kg)
Residential street dirt:	1,250 to 2,300 mg/kg	(820 to 7,200 mg/kg)
Residential sweeper waste:	1,950 to 2,600 mg/kg	(900 to 3,100 mg/kg)
Industrial catch basins:	14,000 to 16,000 mg/kg	(11,000 to 130,000 mg/kg)
Industrial street dirt:	4,000 to 4,200 mg/kg	(3,300 to 7,700 mg/kg)
Industrial sweeper waste:	3,600 mg/kg	(3,300 to 4,800 mg/kg)

Polychlorinated Biphenyls (PCBs)

The samples were analyzed for PCB Aroclors. Results for each Aroclor and total PCBs are compared to freshwater sediment guidelines and marine sediment management standards in Appendix A. Dry weight results of total PCBs are presented in Figure 19, median values of the three detected Aroclors and total PCBs are presented in Table 15, and their ranges are reported in Table 16. Key findings are summarized below:

- Overall, PCBs were detected in less than 50 percent of the samples at detection limits ranging from 18 to 79 µg/kg dry weight. As shown below, PCBs were detected most frequently in samples collected from the Duwamish Diagonal study area:
  - Duwamish Diagonal: 13 of 15 samples (87 percent)
  - West Seattle: 5 of 15 samples (33 percent)
  - Southeast Seattle: 2 of 15 samples (13 percent).

- PCB concentrations were above the LAET (62 µg/kg dry weight) in 20 of the 45 samples analyzed (44 percent) during the pilot study. Nearly half of these samples (nine) were collected from the Duwamish Diagonal study area. The highest PCB concentrations were measured in two sweeper waste samples (1,300 µg/kg dry weight at West Seattle, and 910 µg/kg dry weight at Duwamish Diagonal), both of which exceeded the 2LAET (354 µg/kg dry weight).

- With the exception of one sweeper waste sample, PCB concentrations in the Duwamish Diagonal study area (34 to 910 µg/kg dry weight) were typically higher than the concentrations measured in the two residential study areas (<19 to 73 µg/kg dry weight). The highest concentration of PCBs was observed in the last sweeper waste sample (representing the period of April through July 2007) collected from West Seattle

(1,300 µg/kg dry weight). This sample exceeded the MTCA Method A soil cleanup level (1,000 µg/kg dry weight) and the 2LAET (354 µg/kg dry weight), and was also higher than the Duwamish Diagonal sweeper sample collected over the same period (240 µg/kg dry weight).

- Aroclor 1254 and Aroclor 1260 were the most commonly detected PCBs (see Appendix A).

Miscellaneous Organic Compounds

The street dirt, catch basin sediment, and sweeper waste samples were analyzed for 43 miscellaneous semi-volatile organic compounds (SVOCs) including chlorinated hydrocarbons, phenols, and other acid/base-extractable compounds. The results are compared to freshwater sediment guidelines and marine sediment management standards in Appendix A. Table 15 presents median concentrations and Table 16 presents ranges of the following four compounds that exhibited values exceeding sediment criteria: 4-methyl phenol, benzoic acid, benzyl alcohol, and phenol. Key findings are summarized below:

- The following SVOCs were detected in at least one of the 55 pilot study samples:
  - 4-Methylphenol (45 percent)
  - Benzoic acid (36 percent)
  - Phenol (35 percent)
  - Carbazole (33 percent)
  - Benzyl alcohol (15 percent)
  - Pentachlorophenol (5 percent)
  - Dibenzofuran (2 percent).

- SVOCs that were above the sediment standards/guidelines in the West Seattle, Southeast Seattle, and Duwamish Diagonal study areas are summarized below:
  - 4 Methylphenol (40, 40, 40 percent, respectively)
  - Benzoic acid (35, 40, and 13 percent, respectively)
  - Benzyl alcohol (15, 20, and 5 percent, respectively)
  - Phenol (15, 15, and 40 percent, respectively)
  - Pentachlorophenol (0, 0, and 7 percent, respectively).

- The highest concentrations of SVOCs were typically observed in the catch basin sediment samples. Nearly 70 percent of the samples that were above the sediment guideline/standards were collected from catch basins.

Parking Management

Overview

Parking management was a significant component of the overall success of the street sweeping effort. It was considered critical that the sweeper have access to the gutter and curb line in the study areas because the vast majority of street sediment (and associated pollutants) have been found in previous studies to be located within a few feet of the curb face (see Background section). Simply put, the sweeper had to be able to sweep the gutter clean in order to maximize pollutant removal. This meant that vehicles parked in the path of the sweeper needed to be moved in a manner that conformed to the sweeping schedule. Seattle does not have restrictive parking measures for street sweeping in neighborhood areas; therefore, a community outreach program was required to sufficiently explain the intent of the study and the importance of neighborhood participation in terms of parking management.

Community Outreach – Parking Schedule

The street sweeping schedule was designed to minimize the impact on neighborhood residences and businesses. In the residential neighborhoods of West Seattle and Southeast Seattle, sweeping occurred during the day when vehicles were most often away from home. However, sweeping in the Duwamish Diagonal study area, which is in a light industrial area, occurred between 10:00 p.m. and midnight.

For all sweeping locations, streets were clearly marked with new “No Parking” signs installed approximately 100 feet apart. The dates and times that the street was to be cleared of vehicles were included on the signs. In addition, a sweeping schedule was sent to neighbors and businesses with explicitly defined days identifying which side of the street was available for parking. Sweeping occurred on one side of the street during one week, and the sweeper returned the following week to sweep the other side. This cycle was then repeated throughout the entire study period. Examples of signs, routing information, and schedules used in the study are provided on Figure 20.

The neighborhoods of Southeast Seattle and West Seattle are core communities within Seattle proper. Many of the streets in each neighborhood contain wide parking strips that, while owned by the City, have been used as de facto extensions of nearby residential properties. The importance of neighborhood acceptance of the pilot could not be underestimated, and concern over the installation of “No Parking” signs in these parking strips needed to be handled with care. Letters were written to the community notifying approximate times that parking surveyors would be present in their neighborhood, when the signs would be installed, and confirming that the signs would be removed at the end of the 12-month study period.

Tracking Parking Management and Effectiveness

It was determined early in the study that SPU would monitor the effectiveness of the parking initiative, and that parking tickets would not be issued when cars were not moved as directed by the "No Parking" signs. Each week SPU surveyed the residential neighborhoods to assess parking compliance. Vehicles in violation received a flyer on their windshield reiterating the importance of moving their vehicle in support of the sweeping activity. The Duwamish Diagonal study area was surveyed for compliance only twice during the pilot, due to both the late hours of operation and the industrial nature of the area.

Compliance was excellent when the pilot first launched but declined significantly by December 2006, which caused the sweeper to frequently veer away from the curb face to avoid parked cars. SPU worked with the Seattle Police Department's Parking Enforcement Division who began issuing parking tickets in February 2007. SPU staff communicated the upcoming ticket enforcement procedures in an effort to reach as many neighborhood residents as possible via email, the project website, and direct mailings.

Parking Survey Results

The parking statistics revealed the following categories of information for each study area:

- Total cars in violation
- Number of times offended
- Percentage of times offended
- Number of warnings given (total per month)
- Number of tickets issued (total per month)
- Most problematic streets
- Land use of the most problematic streets.

The street sweeper typically swept the residential streets in West Seattle and Southeast Seattle between 9:00 and 10:00 a.m. each Tuesday. The "No Parking" signs indicated that parking was not allowed between the hours of 8:00 a.m. and 4:00 p.m. in anticipation of providing a reasonable degree of flexibility with the sweeping operations. Statistics provided in Tables 20 through 22 and Figure 21 are based on visual confirmation of violations at the time of the 'drive by' surveys, which were typically between the hours of 9:00 and 10:30 a.m. each day.

It is worth noting that the actual number of parking tickets issued by the Seattle Police Department during the study may be substantially higher than the number shown in Tables 20 and 21 because parking tickets may have been issued before or after daily SPU field surveys were performed.

Number of Cars Violating the "No Parking" Restrictions

Over the course of the year, SPU counted the number of cars that were not moved on the designated street sweep days. For each basin, the total number of unique cars (as identified by license plate number) that failed to re-locate over the course of the year is presented in Table 20.

Monthly statistics are shown in Table 21 and Figure 21. The number of violations increased each month when parking was not enforced, reaching a peak in January 2007. During January, SPU staff communicated a parking ticket "grace period" to local residents and, in February, the Seattle Police Department began issuing tickets. After tickets were issued, the number of violations dropped below those counted in the first 7 months of the pilot study. It should be noted that while the peak number of documented parking offenders occurring in the study took place in January 2007 in the West Seattle basin (113), it is estimated that these vehicles blocked curb access by the sweeper to less than 25 percent of the total lineal feet of street length swept in West Seattle. However, parked cars blocked less than 10 percent of the street length during most other months of the pilot study. This is mentioned to emphasize that while the number of "No Parking" warning violations escalated until monetary fines were imposed, the street space taken up by these violators was still proportionately small.

Repeat Offenders

Over the course of the year, SPU witnessed repeat offenders, as shown in Table 20. Although there were many repeat offenders throughout the study period, only one car received more than one ticket once parking enforcement was implemented.

Problem Streets and Street Use

The total number of parking violations are summarized by street for each residential swept site in Table 22. Some streets were more problematic than others. West Seattle had the most violations, even though this study area in the pilot was smaller than the Southeast Seattle study area. The prevailing attributes contributing to these results center on land use:

- The corners of California Avenue SW and SW Findlay St are home to multifamily housing. SPU had difficulty reaching all residents when the initial communication went out.

- California Avenue SW is an arterial with heavy daytime commercial use.

Summary

Results show that implementing parking enforcement is necessary to support an effective street sweeping program. While neighborhood parking compliance was initially high, it began to fall off over a period of several months as the study progressed. It appears that a growing number of residents neglected to move their vehicles when they found that there were no financial repercussions to ignoring "No Parking" signs on sweeping days. Ultimately, the Seattle Police Department was contacted and parking tickets began to be issued in the eighth month of the 12-month study. The immediate result shown in Figure 21 and Table 21 was that the number of parking violations dropped over five-fold from 197 to 34 in the first month that tickets were issued (February 2007). For the remaining months of the study, a small core group of parking offenders continued to receive violations (e.g., 7 percent of residents in West Seattle and 9 percent of residents in Southeast Seattle received five or more such violations).

The Effectiveness of Street Sweeping as a Stormwater Management Action

The two major hypotheses tested in the pilot study were:

- Street sweeping will reduce the accumulation rate of sediment in catch basins, and thus will reduce the frequency that catch basins would need to be cleaned.
- Street sweeping will increase the total amount of sediment removed from a catchment compared to the amount removed by catch basin cleaning alone, and thus will reduce the sediment loading to receiving waters.

An evaluation of the study results indicated that for the time period studied:

- Sweeping streets every other week *did not reduce* the accumulation rate of sediment in catch basins, and thus will *not reduce* the frequency that catch basins would need to be cleaned.
- Sweeping streets every other week *increased* the total amount of sediment removed from the test area compared to the amount removed by catch basin cleaning alone, and thus *will reduce* the sediment loading to nearby receiving water bodies.

In addition, key findings indicate that:

- Sweeping streets every other week is an effective source control strategy. Street sweeping prevents a significant amount of sediment and associated contaminants from being discharged to receiving waters, approximately 190 pounds of dry sediment per curb mile swept.
- Sweeping streets every other week is an effective management action when compared to annual catch basin cleaning, increasing the annual sediment removed by four times that of annual catch basin cleaning alone in the residential basins (250 to 300 g/m^2/year versus 57 to 70 g/m^2 /year) and by 10 times in the light industrial area (350 g/m^2/year versus 34 g/m^2 /year).
- Sweeping streets every other week is likely to be more cost-effective than annual catch basin cleaning. Predicted life-cycle costs, on a wet weight basis, are approximately 10 percent less than annual catch basin cleaning ($0.34 versus $0.38/wet kg), as is currently required under the City's NPDES permit.

- Because many roadways in Seattle are not curbed, street sweeping will not be effective in all areas of the city. An effective stormwater management program will need to include a combination of street sweeping and structural BMPs. Although street sweeping is expected to be less effective than structural BMPs in removing pollutants, its lower life cycle cost may provide a higher value to the City's ratepayers.

Pollution Reduction Effectiveness

The study results clearly indicate that sweeping streets every other week removes a significant amount of sediment from the street, ultimately preventing it and associated contaminants from discharging to nearby receiving water bodies. Therefore, street sweeping may have the potential to offer a cost effective solution to reduce the amount of pollution discharged from roadways. Roadway runoff carries a wide range of pollutants, including metals and petroleum hydrocarbons that are harmful to human and aquatic health. Transportation corridors (including city streets and state or federal highways) constitute the single largest pollution generating surface in Seattle, accounting for approximately 23 percent of the total land area in the City. However, pilot study results do not allow us to directly measure the effectiveness of street sweeping as a stormwater management action. Therefore, two models were used to evaluate the effectiveness of street sweeping:

- A *sediment load reduction (SLR) mass balance model*, developed in Appendix F, which indicates that the SLR attributable to street sweeping is simply the mass of sediment removed by street sweeping because street sweeping does not impact catch basin accumulation rates.

- A *predictive stormwater load model,* developed in Appendix C, which estimates the relative loading of pollutants as a function of land use. Total suspended solids (TSS) and total copper were selected as representative contaminants of concern for this discussion.

Street Sweeping Versus Catch Basin Cleaning

Sweeping streets every other week prevented approximately five times more sediment from entering the receiving water body than catch basin cleaning alone. For the total 12.7 acres of roadway area evaluated during the 12-month pilot study (7 months for the Duwamish Diagonal site) on an annualized basis, sweeping is estimated to have removed approximately 33,800 pounds (15,400 kg) of dry sediment, while annual cleaning of catch basins in the area is estimated to remove only about 6,200 pounds (2,800 kg) dry sediment.

Street Sweeping Versus Structural BMPs

As stated previously, street sweeping may not be appropriate everywhere in the City due to a variety of factors including the condition of the streets, lack of curbs and gutters, and parking constraints. Similarly, structural BMPs (e.g., local or regional stormwater treatment facilities) are not appropriate everywhere in the City because Seattle is largely built-out, which severely limits the amount of land available to construct treatment facilities and creates a number of other conflicts in siting new treatment facilities (e.g., utility conflicts, duplicative treatment concerns, and hydraulic head requirements). Therefore, a combination of street sweeping and structural BMPs will likely be needed to address Seattle's urban stormwater quality issues, particularly those related to street runoff. Although street sweeping is expected to have lower removal efficiencies than structural BMPs, the lower unit costs and more flexible operating conditions may provide higher value overall.

By estimating the fraction of the total mass of sediment removed by sweeping that is transported in runoff as TSS, we can compare the effectiveness of street sweeping with basic treatment structural BMPs. This adjustment is necessary because the performance of stormwater treatment facilities is typically evaluated based on TSS removal. TSS represent the solids suspended in the water column and do not generally include the heavier fraction that is transported as bedload material.

The relative load of TSS for each site has been estimated based on land use conditions and median literature values for TSS (Pitt et. al., 2005). Calculations are provided in Appendix C. Results for street sweeping versus basic stormwater treatment are compared in Figure 22. The box plots presented in Figure 22 illustrate the range of annual TSS loadings predicted for stormwater runoff from each study area. The median value is shown as the line between the gray and blue portion of the box, the boxes represent the 25th and 75th percentile values, and the whiskers represent the range of values. TSS removal estimates for street sweeping and stormwater treatment BMPs (for basic treatment as defined in the City code) are also plotted on each graph.

Under Seattle's NPDES permit and code requirements, stormwater treatment facilities are designed to achieve 80 percent TSS removal for influent concentrations ranging from 100 to 200 mg/L or an effluent goal of 20 mg/L TSS for influent concentrations less than 100 mg/L at the design flow rate. In addition, treatment facilities are designed to treat at least 91 percent of the annual runoff volume estimated using an Ecology-approved continuous simulation model.

Street sweeping is estimated to remove approximately 360, 840, and 980 kilograms TSS per year for the West Seattle, Southeast Seattle, and Duwamish Diagonal basins, respectively (Table 23). This estimate is based on the following assumptions:

- The portion of street sweeper waste that would be transported in stormwater as TSS includes the fine sand (75 to 250 µm) and silt and clay (<75 µm) fractions. This assumption was based on a local study of particle size distribution in stormwater runoff along SR 167 (Taylor 2002). In that study, more than 97 percent of TSS consisted of particles less than 250 µm in diameter.

- That portion of street sweeper waste that would be transported primarily as bed load includes the gravel (>2,000 µm) and coarse to medium sand

(250 to 2,000 µm) fractions. Although the bed load is removed by both street sweeping and structural BMPs, the effectiveness of a structural BMP is based on the ability to remove TSS.

- To account for stormwater sampling bias, it is assumed that approximately 20 percent of the TSS is trapped within the bed load and is therefore not available for measurement. This assumption is based on grain size measurements for 20 inline grab samples collected from City storm drains discharging to the Lower Duwamish Waterway, which showed that inline or bedload material contained approximately 20 percent fine silt and clay by weight (SPU 2008).

- Stormwater runoff TSS concentrations are typically measured using flow-weighted composite autosamplers which, due to the sample inlet size (1/4 inch or 6,350 µm) and location (slightly above the pipe bottom), do not accurately collect the bed load or particles greater than approximately 250 µm (James 1999).

As shown in Figure 22, street sweeping conducted during the pilot test removed approximately 39, 45, and 61 percent of the estimated median total suspended solids (TSS) load for the West Seattle, Southeast Seattle, and Duwamish Diagonal basins, respectively (see Appendix C). These load reductions are comparable to values reported in the literature for high efficiency sweepers, which report expected TSS removal rates of 60 to 70 percent depending on sweeping frequency (Schilling 2005).

In comparison, under the City's NPDES permit and existing stormwater code, structural BMPs for new and redevelopment projects in the City are required to achieve 80 percent TSS removal. Although street sweeping removed only 49 to 76 percent of the TSS predicted to be removed by a structural BMP (i.e., comparing 39 to 61 percent to the 80 percent performance goal), it is considerably less expensive to sweep streets compared to constructing and maintaining stormwater treatment facilities. Based on estimates for recent stormwater treatment projects in Seattle, on a life-cycle cost basis, the cost of street sweeping ($5/kg TSS removed) is about 15 to 50 percent of the cost for an equivalent regional-scale structural BMP ($10 to $30/kg TSS removed) and may be in the 5 to 10 percent range when compared to small scale, local transportation projects.

TSS is commonly used as an indicator of stormwater quality because many of the pollutants present in urban stormwater runoff are fairly insoluble and tend to sorb onto the particulates present in runoff. For this reason, stormwater management activities and treatment technologies have targeted TSS removal. However, there are no water quality standards for TSS. Other contaminants of concern in urban runoff include metals, particularly copper, and petroleum hydrocarbons. Copper is highly toxic to aquatic organisms and is generated by transportation activities. Estimates of the relative load of total copper for each site are provided in Appendix C and are compared with the load removed by street sweeping and basic stormwater treatment facilities (assuming a removal efficiency of 50 percent) in Figure 23.

Street sweeping removed approximately 63, 108, and 111 percent of the predicted relative median total copper load for the West Seattle, Southeast Seattle, and Duwamish Diagonal basins, respectively, compared with 50 percent removal for stormwater treatment facilities. These model results suggest that street sweeping is extremely effective, or more likely that the method used to estimate copper loads from streets underestimates the copper load. However, these model results clearly show that street sweeping does reduce the copper load discharging to the receiving water body.

Cost Effectiveness

This section does not attempt to perform a full triple bottom line (economic, social, and environmental) benefit/cost analysis of street sweeping in general, or the Seattle Street Sweeping Pilot Study in particular. While the cost effectiveness of street sweeping regarding downstream pollution reduction as well as its effect on operations and maintenance activities is examined in this section, many difficult to quantify costs and benefits were not included in the analysis. These include:

- Hard to quantify benefits of street sweeping:
  - Reduced flooding caused by clogged storm drain inlets
  - Enhanced aesthetics/litter reduction
  - Increased environmental stewardship
  - Improved regulatory compliance potential
  - Greater planning flexibility
  - Increased pavement life
  - Improved air quality from reduced street dust.
- Hard to quantify costs of street sweeping:
  - Increased carbon dioxide emissions from sweeper trucks
  - Increased neighborhood social disruption due to moving parked cars on sweeping days.

It is hoped that many of these factors, as well as any others that may prove to be appropriate, can be included as part of a full triple bottom line benefit (environmental, financial, social)/cost analysis of street sweeping in the near future or as part of any forthcoming expansion of the City’s existing street sweeping program.

It should also be noted that cost calculations in this section include only the billings received from the Seattle Department of Transportation (SDOT) for the sweeping itself and do not contain other tangible costs related to parking management, which were extensive during the pilot study. These costs include items such as project-related public relations expenditures, street sweeping-specific parking sign installation costs, and ticket infraction administration expenses. Previous benchmarking efforts performed by SPU have shown that the monetary benefits of a street sweeping-related parking management program (i.e., revenue from parking infractions) exceeded costs in every municipal program queried. Therefore, parking management, including all of its associated expenditures, is conservatively assumed to be cost neutral for the purposes of this analysis.

The Seattle Street Sweeping Pilot Study showed street sweeping to be a very cost effective strategy for removing sediment and its associated pollutants from roadways. This translated to a significant reduction in pollutant loadings to downstream receiving water bodies.

Pilot Study Costs

Pilot study cost estimates are presented in Table 23. The fourth row from the bottom of the table shows the calculated cost per (dry) kilogram for collecting and disposing of sweeper waste in each of the three study areas. These costs varied from a low of about $4/kg in the Duwamish Diagonal basin to a high of about $6/kg in the West Seattle basin and an average across all sites of approximately $5 per kilogram of dry sediment removed.

SDOT's sweeping costs billed to SPU were artificially high given the unique limitations and requirements of the study. In short, the sweeper was used much less efficiently than would normally be the case in a typical city-wide sweeping program. Due to constraints of the study, the sweeper contracted from SDOT spent the vast majority of its time driving long distances to sweep relatively small areas while making frequent side trips to offload waste for later measurement. Consequently, street sweeping costs during the study were much higher (approximately $420/curb mile) than would typically occur during routine street sweeping operations (approximately $59/curb mile as described below).

Projected Street Sweeping Program Costs

Estimated life cycle costs of $0.62/kg dry sediment removed were projected for a future stormwater quality street sweeping program using data from this study and current City of Seattle operating costs. The estimated cost breakdown and associated assumptions include:

- **Actual sweeping costs (76 percent of the total cost).** SDOT's 2006 programmatic unit sweeping cost per curb mile of $35 was inflated at three percent over two years and a contingency of 15 percent was applied to account for additional costs associated with the program such as performance tracking. The resulting estimate for street sweeping is approximately $45 per curb mile swept.

- **Solids handling and trucking (10 percent of the total cost)** – SPU's 2005 unit solids loading and trucking cost of $31 per wet ton was inflated at three percent over three years, which yields a total cost of approximately $34/wet ton.

- **Sediment/debris disposal (14 percent of the total cost).** Rabanco's (the City's solid waste hauler) current cost for disposing non-dangerous waste ($43.50 per wet ton).

These costs therefore represent those one would expect to see if a larger scale and less intensively monitored sweeping effort were implemented in areas similar to the West Seattle, Southeast Seattle, and the Duwamish Diagonal study areas. The result is an approximate eight-fold reduction in the pilot cost of collecting and disposing of sweeper waste ($0.62/kg dry solids) compared to the cost of the pilot project ($4 to $6/kg dry solids).

Schilling (2005) reports estimated vacuum street sweeping operation and maintenance costs of $20/curb mile and $630/curb mile/year for biweekly sweeping in 2005 dollars, which are equivalent to approximately $22/curb mile and $393/curb mile/year when inflated at three percent to 2008 dollars.

The estimated literature costs are significantly less than the projected full-scale street sweeping program costs, which are approximately $59/curb mile with $14/curb mile for handling and disposal and approximately $1,400/curb mile/year with $331/curb mile/year for handling and disposal.

Street Sweeping Versus Structural BMPs

As described above, to enable a reasonable comparison between street sweeping costs and stormwater treatment costs, the total mass of solids removed by street sweeping were adjusted to estimate the fraction that would be transported in runoff as TSS. As shown in Table 23, the estimated life cycle costs of $5/kg TSS removed/year for a future stormwater quality street sweeping program are very favorable when compared to typical water quality structural BMP life cycle costs, which range from $10 to $30/kg TSS removed/year for regional-scale projects and may increase to $30 to $50/kg TSS removed/year for small scale, local transportation projects.

Lifecycle TSS removal costs are currently used by SPU to compare the cost effectiveness of differing water quality capital improvement project options. All of the projected TSS removal lifecycle costs for street sweeping shown in Table 23 are significantly lower than any water quality capital improvement project options developed for major projects at SPU to date.

Street Sweeping Versus Catch Basin Cleaning

The estimated life cycle costs for a full-scale sweeping program in Seattle ($0.34 per wet kilogram of material removed) are approximately 90 percent of typical SPU catch basin cleaning costs ($0.38 per wet kilogram of material removed). For comparison with catch basin cleaning operations, costs are presented on a wet weight basis because SPU is charged on a wet weight basis to dispose of its catch basin wastes and does not routinely measure the moisture content of this material.

The difference in cost between street sweeping and catch basin cleaning would be larger if calculated on a dry weight basis because sweeper waste is fairly dry compared to catch basin sediment. For comparison purposes, dry weight costs were estimated based on a moisture content of 41 to 49 percent in sweeper waste measured during the pilot study and assuming a moisture content of 75 to 85 percent in catch basin solids. Using these values, the life cycle costs for a full-scale sweeping program are about 20-40 percent of catch basin cleaning costs ($0.51 to $0.77 per kilogram dry street waste with an average of $0.62 per kilogram dry street waste solids versus $1.50-$2.50 for catch basin cleaning).

The citywide catch basin cleaning program includes inspection, collection, handling, and disposal costs. It should be noted however, that these catch basin-related sediment removal costs are rough estimates with less than perfect data. Additional cost analysis information is needed regarding the catch basin inspection and cleaning program, particularly with respect to the accurate measurement of the dry weight of catch basin waste removed annually from SPU's drainage system.

Effect of Street Sweeping on Operations and Maintenance Costs

One of the primary initial drivers for the Seattle Street Sweeping Pilot Study was the belief that frequent street sweeping would reduce existing drainage system maintenance costs. It was hoped that these lower costs would be manifested by decreased sediment buildup in catch basins, leading to the need for less frequent catch basin inspection and cleaning. Seattle's catch basin maintenance program, which involves using a two-person inspection crew with a flatbed truck followed by a two-person cleanout crew with a combination jet/vactor truck, is typically expensive and labor-intensive.

As explained in the Results and Discussion section of this report, the pilot study results showed that neither the catch basin sediment mass accumulation nor the sediment accumulation rates showed significant differences between swept and unswept catchments in any of the three study areas. The low accumulation rates observed at all study sites suggest that only a small portion of the sediment load to the catch basins is retained in the sumps. However, because of the low accumulation rates, differences in catch basin sediment accumulation may be explained by natural variability or measurement error. These results are still somewhat surprising, particularly since street sweeping removed significant sediment mass from the swept basins during the study period. It is possible that the act of street sweeping itself may have simultaneously removed material from the street while also mobilizing sediment adhered to the street surface into catch basins by its mechanical operations. This effect has been noticed in other areas of Seattle as a part of SDOT's existing programmatic street sweeping operations, most notably on the West Seattle Bridge.

In any event, study results showed the effect of street sweeping on catch basin sediment accumulation rates to be inconclusive at best, and insignificant at worst. Should further sweeping pilot studies be performed, it is recommended that the effect of street sweeping on drainage system maintenance costs be revisited.

Conclusions

The Street Sweeping Pilot Study provided valuable data for understanding the effect of sweeping streets every two weeks with a regenerative air sweeper on the amount and characteristics of dirt present on the streets, sediment accumulation in catch basins, and materials removed by the sweeper. Data collected for this study clearly show that sweeping each side of the street every other week is very effective in reducing the amount of sediment and associated pollutants discharged from city streets.

The overall study conclusions include:

- Sweeping streets every other week was effective in reducing the amount of dirt present on the streets and the amount of sediment that enters the storm drain system:
  - Street sweeping reduced the street dirt yield (amount of dirt present per unit area of street) in all three study areas. Median monthly reductions in street dirt yield were 48, 74, and 90 percent in the Duwamish Diagonal, West Seattle, and Southeast Seattle study areas, respectively.
  - Sweeping removed between 2,200 and 3,100 pounds of material per acre of street swept per year (referred to as sweeper waste yield) and the amount removed was similar at each of the three test areas:
    - West Seattle (2,200 lb/street acre/year)
    - Southeast Seattle (2,700 lb/street acre/year)
    - Duwamish Diagonal (3,100 lb/street acre/year).
  - Sweeping removed an average of 4,900 pounds of dry sediment per curb mile swept per year, and the highest lineal (i.e., per curb mile) yield was observed in the industrial Duwamish Diagonal study area:
    - West Seattle (3,800 lb/curb mile/year)
    - Southeast Seattle (4,700 lb/curb mile/year)
    - Duwamish Diagonal (6,400 lb/curb mile/year).
  - Street sweeping removed approximately 39, 45, and 61 percent of the estimated median total suspended solids (TSS) load for the West Seattle, Southeast Seattle, and Duwamish Diagonal study areas, respectively. These load reductions are comparable to literature values, which report expected TSS removal rates of 60 to 70 percent for high efficiency sweepers depending on sweeping frequency (Schilling 2005). In comparison, under the City's NPDES permit

and existing stormwater code, structural BMPs for new and redevelopment projects in the City are required to achieve 80 percent TSS removal.

- Sweeping streets every other week *did not reduce* the amount of sediment that accumulated in catch basins, which indicates that sweeping *may not reduce* the frequency that catch basins would need to be cleaned. However, because of the short timeframe of this pilot study and the difficulty in accurately measuring sediment depth in the catch basins, there is still considerable uncertainty about the effect of sweeping on catch basin cleaning frequency.

  - There was little difference between the rate of sediment accumulation in catch basins between the swept and unswept test sites, which indicates that sweeping streets every two weeks may not reduce the need for catch basin maintenance. However, this result must be qualified based on the fact that very little sediment accumulated in the study catch basins regardless of whether the streets were swept (0.6 to 3.9 inches over the 7- to 12-month study period) or not (0.6 to 4 inches over the 7 to 12 month study period), as well as the difficulty in accurately measuring sediment depth in the catch basins.

  - On average, catch basins were less than 10 percent full at the end of the 7- to 12-month study period (1 to 43 percent full overall), which is well below the 60 percent threshold established by the State of Washington for when catch basins need to be cleaned.

- Sweeping streets every other week increased the total amount of sediment removed from the area compared to the amount that would be removed by catch basin cleaning alone, and thus will reduce the sediment loading to nearby receiving water bodies. On an annual basis, street sweeping prevented between four times (in the residential areas) and 10 times (in the industrial area) more sediment from entering the storm drain system and thus reduced the amount of material discharged to the receiving water body than catch basin cleaning alone. For the total 12.7 acres of roadway area evaluated during the 12-month pilot study (7 months for the Diagonal Duwamish site), sweeping is estimated to remove 2,700 lb/acre/year (300 g/m^2/year) of dry sediment, while annual cleaning of the approximately 70 catch basins in the swept areas is estimated to remove only about 480 lb/acre/year (54 g/m^2/year) dry sediment.

- Grain size data indicate that the high efficiency regenerative air sweepers used in the pilot study may have been less effective in removing the fine-grained particles that are present on the street surface (e.g, fine silt and clay). Sweeper waste generally contained less fine material (<0.25 mm) and more coarse material than street dirt or catch basin sediment. On average, the sweeper samples contained 15 percent more coarse sand and gravel than the street dirt samples.

- Contaminants that were above the sediment/soil standards and guidelines most frequently in the 55 samples collected during the pilot study (total of all street dirt, sweeper waste, and catch basin samples) included zinc (18 percent), chromium (15 percent), motor oil (82 percent), carcinogenic PAHs (78 percent), di-n-octylphthalate (65 percent), bis(2-ethylhexyl)phthalate (60 percent), butylbenzylphthalate (35 percent), and di-n-butylphthalate (29 percent).

- Contaminant concentrations were generally higher in the Duwamish Diagonal industrial study area than in the two residential study areas, and were generally higher in catch basin sediment than in street dirt and sweeper waste samples.

  - Zinc concentrations in the Duwamish Diagonal catch basin samples (489 to 1,100 mg/kg) were as much as 5 times greater than in the residential catch basin samples (223 to 535 mg/kg).

  - Lead concentrations in the Duwamish Diagonal sweeper waste samples (159 to 361 mg/kg) were 2 to 13 times greater than in the residential sweeper samples (27 to 88 mg/kg).

  - Motor oil concentrations were higher in the Duwamish Diagonal study area with 14 of the 15 (93 percent) samples (2,200 to 18,000 mg/kg) above the MTCA Method A soil cleanup level (2,000 mg/kg) compared to 28 of the 40 samples (70 percent) collected from the West Seattle and Southeast Seattle test areas (2,100 to 7,100 mg/kg).

  - Concentrations of cadmium, copper, lead, zinc, diesel, motor oil, BEHP, were typically higher in the catch basin samples than in the street dirt and sweeper waste samples. Differences were most pronounced in the Duwamish Diagonal study area where zinc concentrations in the catch basin samples (489 to 1,100 mg/kg) were up to 6 times greater than the street dirt (238 to 541 mg/kg) and sweeper waste samples (170 to 324 mg/kg).

- The number of parked vehicles did not appear to affect the ability of the street sweeper to access the curb lane during the pilot study. During the worst month (January 2007) only about 10 percent of the curb lane was blocked in the West Seattle study area, which experienced the most parking violations. Most residents obeyed the parking restrictions and moved their vehicles as directed during the first month of the study, but compliance declined steadily (from 52 to 197 violations per month) until February 2007 when the Seattle Police Department started ticketing violators. After ticketing began, the number of total parking violations declined to 34 to 58 per month for the remainder of the pilot study from February through June 2007. Considering the level of attention paid to parking management during the pilot study, parking enforcement will likely be needed for a large scale street sweeping program to be effective.

- Street sweeping has the potential to be a cost effective strategy for removing sediment and associated pollutants from roadways in the City of Seattle. Sweeping streets every other week is likely to be more cost-effective than annual catch basin cleaning or structural controls.

  - Although estimated unit costs for collecting and disposing of sweeper waste in each of the three study basins, which ranged from a low of $4/dry kg in the Duwamish Diagonal basin to a high of $6/dry kg in the West Seattle basin, were fairly high during the pilot study, the projected full-scale sweeping costs are estimated to be in the range of $0.51 to $0.77 per dry kg.

  - Predicted street sweeping life-cycle costs, on a wet weight basis, are approximately 10 percent less than annual catch basin cleaning ($0.34 versus $0.38/wet kg), as is currently required under the City's NPDES permit. On a dry weight basis, street sweeping life-cycle costs are estimated to be in the range of 20 to 40 percent of catch basin cleaning life-cycle costs.

  - It is less expensive to sweep streets compared to constructing and maintaining stormwater treatment facilities. Based on estimates for recent stormwater treatment projects in Seattle, on a life-cycle cost basis, the cost of street sweeping ($5/kg TSS removed) is about 15 to 50 percent of the cost for an equivalent regional-scale structural BMP ($10 to $30/kg TSS removed) and may be in the 5 to 10 percent range when compared to small scale, local transportation BMP projects.

Recommendations

Based on the pilot study findings, it is recommended that the City begin pursuing an expanded street sweeping program to reduce the amount of pollution discharged to area receiving water bodies from City streets. The following are suggested next steps:

- Given the success of the pilot study, it is recommended that the City begin developing a strategy for how to begin expanding the area covered by the existing street sweeping program. The strategy should start by prioritizing areas within the City where water/sediment quality improvements are most needed. SPU's water quality program has already developed an initial prioritization plan for area watersheds. This information could be used as a guide and adjusted as necessary to address issues specific to street sweeping. Items to consider in identifying potential areas for an expanded sweeping program are listed below:

  - Focus initially on separated drainage areas that are not located in the combined sewer service area and where streets are curbed.

  - Prioritize basins that drain to sensitive receiving water bodies such as those that have known water/sediment quality problems, provide significant habitat or fish migration corridors, or lack ability to assimilate pollutants (e.g., Duwamish Waterway, Lake Washington, Lake Union/Ship Canal).

  - Prioritize those drainage basins with a high potential to pollute (e.g., major transportation corridors, Duwamish basin, Lake Union/Ship Canal basin).

  - Consider existing street parking density when expanding the street sweeping program. Neighborhoods containing a large amount of on-street parking should be thoroughly analyzed to ensure that effective parking management and street sweeping may both occur.

  - Identify areas where parking limitations could impact street sweeping operations, and work with SDOT to develop a strategy for managing parking/sweeping operations in these areas.

- Maintain a sweeping frequency of once every two weeks for any new areas and increase the frequency for the existing arterial street sweeping efforts to once every two weeks from the current monthly frequency employed by SDOT. The pilot study showed that a sweeping frequency of once every 2 weeks was effective in removing sediment. In addition, sweeping alternate sides of the street on the same day each week is a simple and easy program for sweeper operations, parking management, and public relations.

- Conduct additional research to evaluate whether street sweeping can also be cost effective in areas without curbs. SPU should complete a brief literature review and survey of other jurisdictions about their experiences in sweeping uncurbed streets. Depending on the results of the research, SPU should consider additional field testing to determine the effectiveness of sweeping streets without curbs.

- Continue to evaluate street sweeping performance by monitoring the mass of sweeper waste removed and tracking how mass removal rates vary with the type of streets swept (e.g., land use, traffic volume, number of parked cars, and the absence of curbs). Sweeper waste monitoring may also be used to evaluate how sweeper efficiency may vary with sweeping frequency. Sweeper waste monitoring is relatively simple and inexpensive, and it provides useful data for evaluating the overall effectiveness of a street sweeping program. Sweeper waste samples should be separated into fine and coarse size fractions by sieving the sample through a 0.25 mm mesh screen to estimate the suspendable sediment mass. The collection of additional data on street dirt mass, catch basin sediment mass, and sediment pollutant concentrations are not necessary to evaluate the effectiveness of the expanded street sweeping program.

- Continue to evaluate the cost effectiveness of the expanded street sweeping program in comparison to other stormwater BMPs.

- Continue to evaluate the effectiveness of street sweeping at reducing drainage system maintenance costs. While this study showed that sweeping had a negligible effect on reducing catch basin sediment buildup, this result is counterintuitive and should continue to be studied as it has the potential to save the City considerable money if justified by further analysis.

- Develop a parking management public relations plan as well as continue to work closely with the Seattle Police Department's Parking Enforcement Division regarding implementation of any future ticketing.

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TABLES AND FIGURES

Table 1. Roadway characteristics.

Study Area	Site Area [a] (acres)	Street Area [b] (acres)	Street Length (feet)	Street Width (feet)	Number of Catch Basins	Curb Length (feet)
West Seattle						
Swept	24	3.1	4,722	22-44	16	9,443
Unswept	28	3.2	5,041	22-44	18	10,082
Southeast Seattle						
Swept	41	6.4	9,509	22-44	38	19,018
Unswept	35	5.2	9,013	22-44	35	18,026
Duwamish Diagonal						
Swept	23	3.2	4,117	12-44	16	8,233
Unswept	23	3.5	3,508	22-44	17	7,015

[a] Site area estimates include all land potentially draining to the street (see Figures 5 through 8).
[b] Street area includes only the area of the pavement from curb to curb as defined in the City's GIS database.

Table 2. Number of street sweeping events.

Test Location	Number of Sweeping Opportunities	Actual Number of Sweeping Events
West Seattle	53	50
Southeast Seattle	53	51
Duwamish Diagonal	30	29

Table 3. Sampling design summary.

Sampling Procedure Summary	Sample Analyses
Street dirt 1. Collect one street dirt sample from swept and unswept areas at each test site once every 4 weeks starting at Week 4. 2. Measure weight of each sample and archive for future analysis. 3. Combine samples collected during three consecutive 4-week periods into one composite sample for each site representing a 12-week period. 4. Analyze the composite samples for all physical and chemical parameters.	Percent debris >2cm (field) Bulk density [a] Total solids [b] Total volatile solids Grain size Total organic carbon Total phosphorus Total Kjeldahl nitrogen Arsenic, cadmium, chromium, copper, lead, mercury, silver, and zinc Total petroleum hydrocarbons Semivolatile organic compounds PCBs
Sweeper waste 1. Measure wet weight of decanted sweeper waste in dumpster for each swept test site once every 4 weeks starting at Week 4. 2. Collect one sample from each dumpster once every 4 weeks. Analyze each sample for total solids. 3. Combine samples collected during three consecutive 4-week periods into one composite sample for each dumpster (site) representing a 12-week period 4. Analyze the composite samples for all physical and chemical parameters.	
Catch basin sediment 1. Measure total volume of sediment in 12 catch basins in the swept and unswept areas at each test site once every 4 weeks starting at Week 0 (before sweeping). 2. Collect one sediment sample from each catch basin after the first 16 weeks of the study, and then once every 12 weeks starting at Week 16. 3. Measure the bulk density and total solids content of each sediment sample. 4. Combine the 12 catch basin sediment samples into one composite sample per site. 5. Analyze the composite samples for all physical and chemical parameters.	

[a] Bulk density is analyzed for each catch basin sample prior to compositing, but is not analyzed for the sweeper waste and street dirt samples.
[b] Total solids is analyzed for all samples prior to compositing and for the composite samples.
Note: Monitoring was conducted over a 52-week period at West Seattle and Southeast Seattle test sites, and over a 32-week period at the Duwamish-Diagonal test sites.

Table 4. Sample analysis methods.

Parameter	Method Number [a]	Method Type
Total solids	EPA 160.3	Dry at 110°C
Total volatile solids	EPA 160.4	Combustion
Particle size [b]	ASTM D422	Sieve
Total organic carbon	EPA 9060 [c]	Combustion
Total phosphorus	EPA 365.2	Manual ascorbic acid
Total Kjeldahl nitrogen	EPA 351.4	Automated ISE
Metals [d] except mercury	EPA 6010	ICP
Mercury	EPA 7471	CVAA
Petroleum hydrocarbons	NWTPH-Dx	GC-FID
Semi-volatile organic compounds	EPA 8270	GC-MS
PCBs	EPA 8082	GC-ECD

[a] Approved methods in EPA (1986), Ecology (1997), APHA et al. 1992, ASTM 2002, and PSEP (1997).
[b] Particle size categories (sieve size): >75 mm, 50 mm, 37.5 mm, 19 mm, 12.5 mm, 9.5 mm, 4.75 mm, 2.0 mm, 850 µm, 425 µm, 250 µm, 150 µm, <75µm.
[c] EPA method 9060 modified by PSEP for sediments.
[d] Metals include arsenic, cadmium, chromium copper, lead, silver, and zinc.
ICP – Inductively coupled plasma spectrometer.
ISE – Ion selective electrode.
CVAA – Cold vapor atomic absorption.
GC-MS – Gas chromatograph-mass spectrometer.
GC-FID – Gas chromatograph-flame ionization detection.
PCBs – Polychlorinated biphenyls.

Table 5. Monthly precipitation (inches) measured at rain gauges located in the approximate vicinity of the study areas compared to normal monthly precipitation data measured at Seattle-Tacoma International Airport.

Rain Gauge	July 2006	August 2006	September 2006	October 2006	November 2006	December 2006	January 2007	February 2007	March 2007	April 2007	May 2007	June 2007	Total
City of Seattle [a]	0.04	0.04	1.57	1.20	13.04	7.35	4.02	2.32	4.39	1.03	1.63	0.79	37.42
Sea-Tac Airport	0.06	0.02	1.43	1.55	15.63	7.30	6.22	3.38	4.42	0.60	1.46	1.34	43.41
Seattle gauge RG16 mean annual precipitation [b]													32.6
Seattle gauge RG18 mean annual precipitation [b]													34.8
Sea-Tac Airport Monthly Normals (1970-2000)	0.79	1.02	1.63	3.19	5.90	5.62	5.13	4.18	3.75	2.59	1.78	1.49	37.07

[a] Precipitation data from 6/1/06 – 3/11/07 are from rain gauge RG16, which is located in the approximate geographic center of the three monitored catchments. Precipitation data from 3/12/07 – 6/17/07 are from rain gauge RG18, which is located near the Southeast Seattle study area, because gauge RG16 was temporarily disconnected to accommodate construction activities at the pump station.

[b] Mean annual precipitation from 1978 to 2002 (Analyses of Precipitation-Frequency and Storm Characteristics for the City of Seattle prepared by MGS Consulting for Seattle Public Utilities, December 2003.)

Table 6. Sampling periods for estimating daily yields at swept and unswept sites.

	Sampling Schedule	West Seattle Swept	West Seattle Unswept	Southeast Seattle Swept	Southeast Seattle Unswept	Duwamish Diagonal Swept	Duwamish Diagonal Unswept
Street Dirt	Frequency	Every 4 weeks	Every 4 weeks	Every 4 weeks	Every 4 weeks	Every 4 weeks	Every 4 weeks
	First day of street dirt collection	7/18/2006	7/18/2006	7/17/2006	7/17/2006	12/7/2006	12/7/2006
	Sampling period end	6/11/2007	6/11/2007	7/2/2007	7/2/2007	6/14/2007	6/14/2007
Street Sweeping	Frequency	Every 2 weeks	-	Every 2 weeks	-	Every 2 weeks	-
	Sampling period start	6/6/2006	-	6/6/2006	-	11/10/2006	-
	First day of sweeping	6/20/2006	-	6/20/2006	-	11/24/2006	-
	Sampling period end	6/19/2007	-	6/19/2007	-	6/15/2007	-
	Sampling period (days)	378	-	378	-	217	-
Catch Basins	Frequency	Every 4 weeks	Every 4 weeks	Every 4 weeks	Every 4 weeks	Every 4 weeks	Every 4 weeks
	Sampling period start:	6/16/2006	6/16/2006	6/16/2006	6/16/2006	11/16/2006	11/16/2006
	Sampling period end	6/11/2007	6/13/2007	6/19/2007	6/18/2007	7/6/2007	7/6/2007
	Sampling period (days)	360	362	368	367	232	232

Table 7. Street dirt yield (dry weight) in the three study areas.

West Seattle				Southeast Seattle				Duwamish Diagonal			
Sample Date	Swept (g/m^2)	Unswept (g/m^2)	Percent Reduction [a]	Sample Date	Swept (g/m^2)	Unswept (g/m^2)	Percent Reduction [a]	Sample Date	Swept (g/m^2)	Unswept (g/m^2)	Percent Reduction [a]
7/18/06	40	45	11	7/17/06	30	55	46	No sample	-	-	-
8/21/06[b]	21	120	82	8/21/06	11	99	89	No sample	-	-	-
9/4/06 [b]	53	110	50	9/5/06	50	160	69	No sample	-	-	-
10/2/06	10	63	84	10/2/06	8	81	90	No sample	-	-	-
12/5/06	15	48	69	12/6/06	4	53	92	12/7/06	18	41	57
12/18/06	15	44	67	12/30/06	7	140	95	12/28/06	9	17	48
1/29/07	55	110	50	1/29/07	11	150	92	1/25/07	64	34	-85 [d]
2/26/07	13	87	85	No sample	-	-	-	2/16/07	6	23	73
No sample	-	-	-	3/26/07	14	120	88	3/15/07	19	32	41
3/26/07	13	110	88	4/2/07	20	68	71	3/29/07	6	54	89
4/23/07	10	47	79	4/30/07	8	66	88	4/20/07	23	51	54
5/7/07	16	85	82	5/14/07	7	66	90	5/25/07	27	44	39
6/11/07	52	13	-310 [d]	7/2/07	4	69	94	6/14/07	19	29	35
Median	15	74	74		9	75	90		19	34	48
Minimum	10	13	11		4	53	46		6	17	35
Maximum	55	120	88		50	160	95		64	54	89
Median (lb/curb mile) [c]	240	1,110			150	1,010			350	790	
Median (lb/ street acre)	140	660			84	670			170	310	

[a] Percent reduction is calculated as (unswept - swept)/unswept x 100.
[b] Samples collected in August and September 2006 included scraping dirt from street cracks and joints, whereas only vacuuming was used to collect samples on all other dates.
[c] Street mass unit conversion from grams/square meter to pounds/curb mile is a function of street width and conversion factors ranged from 14 to 23 among test sites.
[d] Negative values are included in median, but not in the minimum.

Table 8. Daily street dirt accumulation rates (dry weight) in the three study areas.

West Seattle			Southeast Seattle			Duwamish Diagonal		
Sample Date	Swept ($g/m^2/day$)	Unswept ($g/m^2/day$)	Sample Date	Swept ($g/m^2/day$)	Unswept ($g/m^2/day$)	Sample Date	Swept ($g/m^2/day$)	Unswept ($g/m^2/day$)
7/18/06	–	–	7/17/06	–	–	No sample	–	–
8/21/06	-0.5	2.2	8/21/06	-0.5	1.3	No sample	–	–
9/4/06	2.3	-0.9	9/5/06	2.6	4.1	No sample	–	–
10/2/06	-1.5	-1.6	10/2/06	-1.6	-2.8	No sample	–	–
12/5/06	0.1	-0.2	12/6/06	-0.1	-0.4	12/7/06	–	–
12/18/06	0.0	-0.2	12/30/06	0.1	3.6	12/28/06	-0.4	-1.2
1/29/07	1.0	2.1	1/29/07	0.1	0.3	1/25/07	2.0	0.6
2/26/07	-1.5	-1.0	No sample	–	–	2/16/07	-2.6	-0.5
3/26/07	0.0	0.6	3/26/07	0.1	-0.5	3/15/07	0.5	0.3
No sample	–	–	4/2/07	0.8	-12	3/29/07	-0.9	1.5
4/23/07	-0.1	-2.5	4/30/07	-0.4	-0.1	4/20/07	0.8	-0.1
5/7/07	0.4	2.8	5/14/07	-0.1	0.0	5/25/07	0.1	-0.2
6/11/07	1.0	-2.1	7/2/07	0.0	0.1	6/14/07	-0.4	-0.8
Median	0.0	0.2		0.0	0.0		-0.2	-0.2
Minimum	-1.5	-2.5		-1.6	-12		-2.6	-1.2
Maximum	2.3	2.8		2.6	4.1		2.0	1.5

Table 9. Comparison of street dirt yield (dry weight) in Seattle pilot test to literature values.

Street Dirt Yield (lbs/curb mile)	Location	Sampling Frequency	Reference
Swept Streets			
645 (mean)	Baltimore, MD	Periodic [a]	Center for Watershed Protection (2008)
350 (median)	**Seattle, WA**	**Monthly** [b]	**Pilot Study Diagonal Duwamish industrial land use**
240 (median)	**Seattle, WA**	**Monthly** [b]	**Pilot Study Southeast Seattle residential land use**
150 (median)	**Seattle, WA**	**Monthly** [b]	**Pilot Study West Seattle residential land use**
150 (median)	Madison, WI	Weekly [c]	USGS (2007)
Unswept Streets			
1,100 (mean)	Baltimore, MD	Periodic [d]	Center for Watershed Protection (2008)
408 (mean)	Champaign, IL	Unknown	Bender and Terstriep (1984)
391 (mean)	U.S. Nationwide	Unknown	Sartor and Boyd (1972)
381 (mean)	Bellevue, WA	Unknown	Sutherland (1991)
310 (mean)	San Jose, CA	Unknown	Pitt (1979)
255 (mean)	Jackson, MI	Unknown	Tetra Tech (2001)
146 (mean)	Portland, OR	Unknown	HDR (1993)
1,110 (median)	**Seattle, WA**	**Monthly**	**Pilot Study West Seattle residential land use**
1,010 (median)	**Seattle, WA**	**Monthly**	**Pilot Study Southeast Seattle residential land use**
790 (median)	**Seattle, WA**	**Monthly**	**Pilot Study Diagonal Duwamish industrial land use**
705 (median)	Bellevue, WA	Unknown	Pitt (1985)
670 (median)	Madison, WI	Weekly	USGS (2007)
212 – 638 (range)	Portland, OR	Unknown	OTAK (1988)

[a] Streets swept twice a week in one basin and once per week in the other with a vacuum sweeper. Samples collected 24 hours after a sweeping or a rain event from July 2006 through April 2007.
[b] Streets swept biweekly with a regenerative air sweeper.
[c] Streets swept weekly with a regenerative air sweeper.
[d] Six control samples were collected in a non-swept street from July 2006 through April 2007.

Table 10. Sweeper waste yield (dry weight) in the three swept sites.

West Seattle			Southeast Seattle			Duwamish Diagonal			
Sample Date	**Number of Sweeping Events**	**Yield (g/m^2)**	**Sample Date**	**Number of Sweeping Events**	**Yield (g/m^2)**	**Sample Date**	**Number of Sweeping Events**	**Yield (g/m^2)**	**All Sites**
7/11/06	3	17	7/11/06	3	54	No sample	–	–	
8/8/06	4	26	8/8/06	4	33	No sample	–	–	
9/5/06	4	18	9/5/06	4	28	No sample	–	–	
10/3/06	4	12	10/3/06	4	12	No sample	–	–	
10/31/06	4	14	10/31/06	4	20	No sample	–	–	
11/28/06	3	15	11/28/06	4	44	11/24/06	1	37	
12/26/06	4	21	12/26/06	4	20	12/22/06	4	70	
1/23/07	3	30	1/23/07	3	2	1/12/07	3	12	
2/20/07	4	33	2/20/07	4	17	2/9/07	3	20	
3/20/07	4	17	3/20/07	4	26	3/16/07	5	32	
4/17/07	4	27	4/17/07	4	17	4/13/07	4	9	
5/15/07	4	13	5/15/07	4	11	5/11/07	4	12	
6/19/07	5	11	6/19/07	5	27	6/15/07	5	10	
Total	50	250		51	310		29	200	
Median	4	17		4	20		4	16	
Total sweeper waste (lb)		7,100			17,600			5,900	30,700 (total)
Annual sweeper waste (lb/year) [a]		6,900			17,000			10,000	33,900 (total)
Lineal yield (lb/curb mile/year) [a]		3,800			4,700			6,400	4,900 (average)
Areal yield (lb/ street acre/year) [a]		2,200			2,700			3,100	2,700 (average)
Areal yield (g/m^2 street/year) [a]		250			300			350	300 (average)
Total sweeper waste (kg)		3,200			8,000			2,700	13,900 (total)
Annual sweeper waste (kg/year) [a]		3,100			7,700			4,500	15,400 (total)

[a] Annual values were calculated as: total mass removed / number of days swept x 365 days/year.

Table 11. Estimated daily sweeper waste yields (dry weight).

West Seattle		Southeast Seattle		Duwamish Diagonal	
Sample Date	Yield ($g/m^2/day$)	Sample Date	Yield ($g/m^2/day$)	Sample Date	Yield ($g/m^2/day$)
7/11/06	0.8	7/11/06	2.6	No sample	–
8/8/06	0.9	8/8/06	1.2	No sample	–
9/5/06	0.6	9/5/06	1.0	No sample	–
10/3/06	0.4	10/3/06	0.4	No sample	–
10/31/06	0.5	10/31/06	0.7	No sample	–
11/28/06	0.5	11/28/06	1.6	11/24/06	5.3
12/26/06	0.8	12/26/06	0.7	12/22/06	2.5
1/23/07	1.1	1/23/07	0.1	1/12/07	0.6
2/20/07	1.2	2/20/07	0.6	2/9/07	0.7
3/20/07	0.6	3/20/07	0.9	3/16/07	0.9
4/17/07	1.0	4/17/07	0.6	4/13/07	0.3
5/15/07	0.5	5/15/07	0.4	5/11/07	0.4
6/19/07	0.3	6/19/07	0.8	6/15/07	0.3
Median monthly yield	0.6		0.7		0.6
Overall yield	0.7		0.8		0.9
Overall yield (lb/curb mile/day)	10		13		17

Table 12. Street sweeper collection efficiency in the three swept sites.

West Seattle				Southeast Seattle				Duwamish Diagonal			
Sample Date [b]	Street Dirt Yield (g/m^2)	Sweeper Waste Yield (g/m^2)	Street Sweeper Efficiency (percent)	Sample Date	Street Dirt Yield (g/m^2)	Sweeper Waste Yield (g/m^2)	Street Sweeper Efficiency (percent)	Sample Date	Street Dirt Yield (g/m^2)	Sweeper Waste Yield (g/m^2)	Street Sweeper Efficiency (percent)
7/18/06	40	13	33	7/17/06	30	16	55	No sample	–	–	–
8/21/06	21	9	43	8/21/06	11	14	128 [b]	No sample	–	–	–
9/4/06	53	9	17	9/5/06	50	14	28	No sample	–	–	–
10/2/06	10	6	59	10/2/06	8	6	76	No sample	–	–	–
No sample	–	–	–	No sample	–	–	–	12/7/06	18	53	303 [b]
12/5/06	15	11	71	12/6/06	4	22	505 [b]	12/28/06	9	6	67
12/18/06	15	11	73	12/30/06	7	10	147 [b]	1/25/07	64	10	16
1/29/07	55	17	30	1/29/07	11	1	9	2/16/07	6	16	248 [b]
2/26/07	13	8	63	3/26/07	14	8	60	3/15/07	19	16	84
3/26/07	13	13	105 [b]	4/2/07	20	9	44	3/29/07	6	5	76
4/23/07	10	6	65	4/30/07	8	9	108 [b]	4/20/07	23	6	25
5/7/07	16	6	41	5/14/07	7	6	87	5/25/07	27	5	19
6/11/07	52	5	10	7/2/07	4			6/14/07	19	5	27
Median			51				68				67
Minimum			10				9				16
Maximum			>100				>100				>100

[a] Cars parked in violation of no parking signs were given a warning from June 2006 through January 2007. Ticketing of parked cars began in February 2007 and continued through June 2007
[b] Values exceeding 100 percent are included in median, but not in the maximum.

Table 13. Numbers of parked vehicles observed during street sweeping on a monthly basis in the swept residential catchments.

	West Seattle	Southeast Seattle
July 2006	71	53
August 2006	83	67
September 2006	75	46
October 2006	84	59
November 2006	61	16
December 2006	50	33
January 2007	113	84
February 2007 [a]	18	16
March 2007	28	30
April 2007	26	13
May 2007	21	24
June 2007	27	11
Total	657	452
Median	56	32
Before ticketing (July-Jan.)		
Monthly mean	77	51
Monthly mean/curb mile	43	14
Percent of curb blocked [b]	24	8
After ticketing (Feb.-June)		
Monthly mean	24	19
Monthly mean/curb mile	13	4
Percent of curb blocked [b]	8	3

[a] Ticketing of parked vehicles was initiated in February 2007.
[b] Assumes each parked vehicle blocks 30 feet of curb from sweeper access.

Table 14. Quarterly summary of sediment accumulation in catch basins.

	West Seattle			Southeast Seattle			Duwamish Diagonal [a]			All Sites [e]	
	Sample Date	Swept	Unswept	Sample Date	Swept	Unswept	Sample Date	Swept	Unswept	Swept	Unswept
Total mass (kg) [c]											
10/11/06 (first quarter)		44	148	10/11/06	302	135	No sample	–	–	350 (sum)	280 (sum)
1/10/07 (second quarter)		391	617	1/11/07	563	362	1/5/07	67	91	1,020 (sum)	1,070 (sum)
4/3/07 (third quarter)		564	570	3/27/07	474	246	4/3/07	146	134	1,180 (sum)	950 (sum)
6/11/07 (fourth quarter)		580	612	6/19/07	626	256	7/6/07	203	140	1,410 (sum)	1,010 (sum)
Areal accumulation (g/m2) d											
10/11/06		5	12	10/11/06	26	14	No sample	–	–	16 (mean)	13 (mean)
1/10/07		42	53	1/11/07	52	34	1/5/07	10	12	35 (mean)	33 (mean)
4/3/07		44	48	3/27/07	40	31	4/3/07	21	12	35 (mean)	30 (mean)
6/11/07		37	39	6/19/07	40	21	7/6/07	18	15	32 (mean)	25 (mean)
Areal accumulation rate (g/m^2/day) [d]											
10/11/06		0.05	0.10	10/11/06	0.22	0.12	No sample	–	–	0.14 (mean)	0.11 (mean)
1/10/07		0.40	0.45	1/11/07	0.28	0.22	1/5/07	0.20	0.25	0.29 (mean)	0.31 (mean)
4/3/07		0.02	-0.06	3/27/07	-0.16	-0.05	4/3/07	0.12	0.00	-0.01 (mean)	-0.04 (mean)
6/11/07		-0.10	-0.13	6/19/07	0.00	-0.11	7/6/07	0.02	0.01	-0.03 (mean)	-0.08 (mean)
Study period median		0.10	0.11	–	0.11	0.06	–	0.08	0.07	0.10 (mean)	0.08 (mean)
Number of catch basins											
Catch basins monitored		12	12	–	12	12	–	12	12	36 (sum)	36 (sum)
Catch basins in study area		16	18	–	38	35	–	16	17	70 (sum)	70 (sum)
Street area											
Street area drained by monitored catch basins (acres)		2.5	2.5	–	2.2	1.8	–	2.3	2.3	7.0 (sum)	6.6 (sum)
Total street area in study area (acres)		3.1	3.2	–	6.4	5.2	–	3.2	3.4	13 (sum)	12 (sum)
Accumulation rate [e]											
(kg/year)		730	780	–	1,800	740	–	440	340	1,100 (mean)	700 (mean)
(g/m2/year)		57	60	–	70	35	–	34	24	56 (mean)	43 (mean)
(lb/acre/year)		510	540	–	620	320	–	300	220	500 (mean)	390 (mean)
(lb/curb mile/year)		900	900		1,100	480		620	560	1,020 (mean)	650 (mean)

[a] Duwamish Diagonal data presented for July 2007 are based on the sum of measurements made on 4/25/07 (before the catch basins were inadvertently cleaned by a contractor) and the final measurement made on 7/6/07.

[b] Calculated as the sum of the values from the three study areas for total mass, and the average (mean) of the values from the three study areas for areal and lineal mass.

[c] Total dry sediment mass measured in the 12 catch basins monitored as part of this pilot study.

[d] Median accumulation per unit area of street served for the 12 catch basins that were monitored.

[e] Annual accumulation rate was calculated by correcting for catch basin drainage areas and time periods that were not sampled. Total sediment accumulated at each site was estimated as the sum of sediment mass in the 12 monitored catch basins at the end of the study, divided by the area draining to those 12 catch basins, and multiplied by the total street area in the study site. The annual accumulation rate was then calculated as the total sediment accumulation divided by the number of days since the catch basins had been cleaned, and multiplied by 365 days.

Table 15. Median values for selected physical and chemical properties of samples collected for the pilot study.

Parameter	Freshwater Sediment Apparent Effects Threshold [a]		Marine Sediment Management Standard [b]		MTCA Method A Soil Cleanup Level [c]	Catch Basin Sediment						Street Dirt						Sweeper Waste		
						West Seattle		Southeast Seattle		Duwamish Diagonal		West Seattle		Southeast Seattle		Duwamish Diagonal				
	LAET	2LAET	SQS/ LAET	CSL/ 2LAET		Swept	Unswept	Swept	Unswept	Swept	Unswept	Swept	Unswept	Swept	Unswept	Swept	Unswept	West Seattle	Southeast Seattle	Duwamish Diagonal
Conventional parameters																				
Gravel (>2 mm) (%)	–	–	–	–	–	12	20	29	24	17	24	18	21	25	23	12	9	26	39	24
Coarse sand (0.25-2mm) (%)	–	–	–	–	–	53	58	47	54	49	40	51	48	51	53	51	49	55	48	54
Fine Sand (75-250 ל) (%)	–	–	–	–		22	15	13	13	22	22	21	21	15	16	27	27	12	9	20
Silt/Clay (<75ל) (%)	–	–	–	–	–	14	8	13	12	11	15	7	8	8	8	13	9	3	3	7
Total volatile solids (%)	–	–	–	–	–	18	18	12	21	28	40	17	13	20	13	14	13	14	14	9
Total organic carbon (%)	9.82	–	–	–	–	14	13	13	9	15	20	11	10	12	8	11	11	10	12	8
Total phosphorus (mg/kg dry weight)	–	–	–	–	–	759	657	603	1,030	847	788	636	488	906	570	530	528	648	633	516
Total Kjeldahl nitrogen (mg/kg dry weight)	–	–	–	–	–	3,750	3,010	3,130	5,470	4,830	8,660	4,320	3,130	3,800	4,740	1,770	2,070	3,090	3,170	3,540
Metals (mg/kg dry weight)																				
Cadmium	2.39	2.9	5.1	6.7	2	1.1	0.8	0.8	0.8	2.6	2.8	0.5	0.6	0.7	0.6	1.1	1.5	0.7	0.5	0.7
Chromium	95	133	260	270	100	38.0	30.7	34.5	27.5	76.0	49.0	77.0	63.6	25.1	37.7	69.5	38.9	24.1	33.3	62.0
Copper	619	829	390	390	–	53.3	50.9	62.0	73.2	146	158	39.7	49.3	49.1	48.6	76.5	61.7	34.6	37.6	72.6
Lead	335	431	450	530	250	137	89.5	71.0	67.5	331	120	62.5	63.5	54.5	44.0	193	57.0	51.5	63.5	192
Mercury	0.8	3.04	0.41	0.59	1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1 U	0.1	0.1
Silver	0.545	3.5	6.1	6.1	–	0.8 U	0.6 U	0.7 U	0.8 U	1.0	1.0	0.3	0.4	0.4	0.4	0.5	0.7	0.5 U	0.4 U	0.5 U
Zinc	683	1,080	410	960	–	333	263	303	275	698	959	165	215	231	220	304	403	180	176	211
Petroleum hydrocarbons (mg/kg dry weight)																				
Diesel range	–	–	–	–	2,000	810	805	825	860	1,800	3,100	475	355	465	205	410	700	485	365	360
Motor oil	–	–	–	–	2,000	4,100	3,800	3,250	4,100	7,500	14,000	2,800	2,250	2,950	1,200	2,400	4,000	2,050	1,800	2,800
Polycyclic aromatic hydrocarbons (ug/kg dry weight)																				
Total carcinogenic PAHs [d]	–	–	–	–	100	1,050	164	170	245	750	1,400	440	106	225	270	400	460	445	108	390
Total LPAHs	6,590	9,200	370	780	–	1,300	260	335	320	900	1,800	605	110	220	300	400	650	560	155	560
Total HPAHs	31,640	54,800	960	5,300	–	8,700	855	505	850	7,100	12,000	3,400	825	1,560	2,000	3,500	4,300	3,250	650	3,200
Phthalates (ug/kg dry weight)																				
Bis(2-ethylhexyl)phthalate	2,520	6,380	1,300[e]	1,900[e]	–	7,450	4,650	4,450	4,650	16,000	14,000	2,300	2,100	1,800	1,250	4,000	4,200	2,600	1,950	3,600
Butylbenzylphthalate	260	366	63[e]	900[e]	–	730 U	585	630 U	395 U	680	1,800	400	145	595	245	720	520	340	245	330
Di-n-butylphthalate	103	–	1,400[e]	5,100[e]	–	270 U	590	220	320 U	3,800	370 U	180 U	91	100	98 U	1,700	230	180	132	1,200
Di-n-octylphthalate	11	201	6,200[e]	--	–	515	970	320	390	800	840	205	110	120	81	200	250	145	130	180
Miscellaneous organic compounds (ug/kg dry weight)																				
4-Methylphenol	760	2,360	670[f]	670[f]	–	6,800	6,250	7,550	4,750	7,800	16,000	94	76 U	81 U	63 U	68 U	120 U	180	160	64 U
Benzoic acid	2,910	3,790	650[f]	650[f]	–	2,700	2,200	1,750	3,300	2,000	2,600 U	2,040	760	935	600	680 U	1,200 U	4,650	3,000	640 U
Benzyl alcohol	–	–	57[f]	73[f]	–	270 U	225 U	220 U	320 U	200 U	260 U	300	140	260	208	68 U	150	345	295	64 U
Phenol	–	–	420[f]	1,200[f]	–	355	630	420	355	470	560	380 U	94 U	120	81 U	68 U	120 U	210 U	160 U	64 U
Polychlorinated biphenyls (ug/kg dry weight)																				
Aroclor 1248	–	–	–	–	–	20 U	19 U	20 U	20 U	170	30 U	19 U	20 U	19 U	19 U	110	20 U	20 U	19 U	91
Aroclor 1254	230	294	–	–	–	40 U	50	59 U	40 U	310	66	19 U	20 U	20 U	19 U	120	40	20	19 U	85
Aroclor 1260	138	140	–	–	–	24	19	45	20 U	130	42	19 U	20 U	20 U	20 U	54	39	20	19 U	64
Total PCBs	62	354	130[e]	1,000[e]	1,000	24	70	45	40 U	630	110	19 U	20 U	20 U	20 U	330	59	20	19	240

[a] Lowest and second lowest apparent effects thresholds for freshwater sediments in Washington State, updated in 2003 (Avocet 2003).
[b] Washington State Marine Sediment Management Standards, Sediment Quality Standards (SQS) and Cleanup Screening Level (CSL) (WAC Chapter 173-204) unless noted by [e].
[c] Washington State Model Toxics Control Act (MTCA) Method A Cleanup Regulation for unrestricted land uses (Ecology 2001).
[d] Total carcinogenic PAHs represents the toxicity equivalent factor sum of the following polycyclic aromatic hydrocarbons: benzo(a)pyrene, benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, indeno(1,2,3-c,d)pyrene, dibenz(a,h)anthracene.
[e] SQS and CSL for these compounds are based on organic carbon normalized data. Because TOC concentrations in the pilot study samples are outside the acceptable range for organic carbon normalization (0.5 to 4 percent TOC), the LAET and 2LAET guidelines for marine standards are presented.
[f] SQS and CSL for these organic compounds are based on dry weight concentrations.
µg/kg micrograms per kilogram.
mg/kg milligrams per kilogram.
U The material was analyzed for, but was not detected. The associated numerical value is the reporting limit.
Shaded Value indicates the detected sample result is greater than the lowest LAET, SQS, or MTCA method A value.
Shaded Value indicates the detected sample result is greater than the 2LAET or CSL value.

Table 16. Range of values for selected physical and chemical properties of samples collected for the pilot study.

	Catch Basin Sediment						Street Dirt						Sweeper Waste		
	West Seattle		Southeast Seattle		Duwamish Diagonal		West Seattle		Southeast Seattle		Duwamish Diagonal			Southeast Seattle	Duwamish Diagonal
Parameter	**Swept**	**Unswept**	**Swept**	**Unswept**	**Swept**	**Unswept**	**Swept**	**Unswept**	**Swept**	**Unswept**	**Swept**	**Unswept**	**West Seattle**		
Conventional parameters															
Gravel (>2mm) (%)	10 - 18	15 - 26	13 - 46	19 - 38	10 - 28	12 - 28	12 - 39	16 - 50	16 - 65	18 - 33	9.9 - 19	6.2 - 26	22 - 70	22 - 53	18 - 24
Coarse sand (0.25-2mm) (%)	40 - 58	52 - 60	40 - 54	38 - 58	46 - 50	38 - 46	48 - 59	44 - 50	33 - 54	52 - 54	44 - 54	47 - 53	27 - 63	43 - 59	47 - 58
Fine sand (75-250u) (%)	18 - 27	15 - 20	10 - 19	10 - 18	16 - 22	16 - 23	10 - 28	6.0 - 26	1.8 - 23	12 - 21	21 - 30	21 - 33	2.5 - 16	3.9 - 16	16 - 21
Silt/Clay (<75u) (%)	4 - 24	3.0 - 11	0.1 - 14	4.0 - 13	9.0 - 23	10 - 28	1.0 - 13	0.8 - 13	0.3 - 13	3.7 - 11	6.0 - 15	6.9 - 15	0.7 - 8	0.7 - 7.4	4.9 - 8.8
Total volatile solids (%)	16 - 20	16 - 21	11 - 16	18 - 22	24 - 54	20 - 42	6.0 - 58	8.0 - 38	14 - 58	9.4 - 19	6.7 - 19	8.7 - 20	7.1 - 67	12 - 54	7.3 - 29
Total organic carbon (%)	10 - 24	12 - 20	6.0 - 14	7.0 - 15	14 - 28	11 - 25	5.0 - 17	8.78 - 18.8	9.0 - 38	4.3 - 15	8.0 - 17	6.1 - 26	4.4 - 28	9.7 - 20	6.7 - 9.6
Total phosphorus (mg/kg)	629 – 1,450	405 – 1,080	408 – 1,060	967 – 1,090	191 – 1,610	462 – 1,200	376 - 814	423 - 826	434 – 1,020	493 - 860	504 - 612	493 - 661	607 - 707	300 - 723	439 - 627
Total Kjeldahl nitrogen (mg/kg)	2,080 – 6,190	2,080 – 5,190	2,610 – 4,420	3,700 – 5,660	3,620 – 13,200	4,290 – 9,950	1,900 – 7,500	1,650 – 6,300	2,610 – 9,100	2,840 – 6,770	1,380 – 5,070	1,320 – 2,810	490 – 6,950	599 – 3,430	935 – 36,600
Metals (mg/kg dry weight)															
Cadmium	0.9 - 1.7	0.6 - 0.8	0.6 - 0.9	0.8 - 0.9	2.2 - 3.3	2 - 4	0.4 - 1.1	0.4 - 1	0.5 - 0.8	0.4 - 0.8	0.9 - 1.3	1.1 - 1.6	0.3 - 0.8	0.3 - 0.8	0.6 - 0.8
Chromium	28 - 79	29 - 95.4	23 - 167	22 - 189	64 - 92	33 - 50	32.2 - 371	53 - 317	19.4 - 119	28.9 - 219	53.1 - 70	36.8 - 47	10 - 33.8	15.9 - 52	45 - 83
Copper	44.6 - 80.7	41.4 - 76.4	51.7 - 103	43.8 - 198	136 - 174	137 - 183	29.8 - 63.7	33.6 - 163	26.6 - 77	25.4 - 466	55.3 - 90.9	58 - 92.3	21.5 - 47.8	23.2 - 75.5	48.6 - 76.2
Lead	109 - 166	70 - 102	65 - 114	65 - 83	296 - 354	91 - 130	32 - 222	59 - 175	36 - 156	26 - 74	118 - 279	45 - 75	26 - 77	29 - 88	159 - 361
Mercury	0.09 - 0.8	0.07 - 0.1	0.06 - 0.1	0.08 - 0.1	0.1 - 0.3	0.2 - 0.2	0.05 - 0.38	0.04 - 0.09	0.05 - 0.1	0.05 - 0.08	0.05 - 0.12	0.04 - 0.07	0.06 - 0.2	0.06 - 0.1	0.06 - 0.11
Silver	0.6 - 0.9	0.5 - 0.7	0.5 - 0.8	0.7 - 1	0.8 - 1.1	0.9 - 2	0.3 - 0.6	0.3 - 0.7	0.3 - 0.8	0.3 - 0.5	0.3 - 0.9	0.5 - 0.8	0.4 - 1	0.4 - 0.6	0.4 - 0.6
Zinc	236 - 535	223 - 303	243 - 314	241 - 323	489 - 846	575 – 1,100	158 - 295	178 - 276	119 - 308	139 - 492	238 - 461	370 - 541	109 - 226	120 - 273	170 - 324
Petroleum hydrocarbons (mg/kg dry weight)															
Diesel Range	760 - 880	640 - 970	540 - 1700	540 – 1,300	980 – 2,600	3,100 – 3,300	190 - 760	220 - 630	180 – 1,600	100 - 310	320 - 470	460 - 840	350 – 1,000	260 - 620	330 - 420
Motor Oil	3,500 – 5,400	2,900 – 4,700	2,200 – 7,000	2,600 – 7,100	4,200 – 10,000	7,800 – 18,000	1,200 – 6,000	1,600 – 2,800	1,500 – 4,500	740 – 1,800	1,900 – 3,800	3,800 – 5,600	2,000 – 6,600	1,400 – 2,600	2,200 – 3,600
Polycyclic aromatic hydrocarbons (mg/kg dry weight)															
Total carcinogenic PAHs	1,000 – 1,300	120 - 740	110 - 453	160 - 544	610 – 1,500	630 – 2,700	310 – 3,300	85 - 160	91 - 340	180 - 850	280 - 800	450 – 2,500	330 - 860	59 - 190	240 - 500
Total LPAHs	1,100 – 1,600	140 - 980	150 - 880	120 - 720	870 – 2,000	760 – 5,200	380 – 2,600	95 - 170	130 - 330	150 - 870	350 – 1,300	460 – 1,700	480 – 1,800	97 - 250	460 - 610
Total HPAHs	8,000 – 12,000	260 – 1,100	310 - 790	400 – 1,500	5,100 – 13,000	5,100 – 23,000	2,500 – 23,000	130 – 1,500	320 – 2,500	1,400 – 6,300	2,500 – 7,100	3,500 – 19,000	480 – 7,700	200 – 1,600	2,400 - 3900
Phthalates (mg/kg dry weight)															
Bis(2-ethylhexyl)phthalate	4,400 – 11,000	2,600 – 6,800	3,800 – 5,200	2,200 – 5,000	11,000 – 130,000	11,000 – 30,000	960 – 4,000	1,800 – 4,100	1,200 – 2,200	820 – 7,200	3,300 – 4,400	3,900 – 7,700	1,100 - 3100	900 - 2100	3300 - 4800
Butylbenzylphthalate	250 – 1,100	190 – 9,200	260 - 680	300 - 720	580 – 11,000	1,200 – 3,600	200 – 1,600	120 - 640	120 – 1,200	96 - 490	310 - 780	390 - 750	63 - 480	140 - 620	280 - 510
Di-n-butylphthalate	180 – 1,100	190 – 1,100	170 - 600	100 - 720	3,200 – 6,400	210 - 390	59 - 640	59 - 190	72 - 260	65 - 320	670 – 25,000	220 - 330	120 - 480	62 - 220	920 - 1500
Di-n-octylphthalate	380 – 1,100	540 – 2,200	290 - 600	300 - 720	730 - 880	550 – 1,200	100 - 640	77 - 170	85 - 120	59 - 100	140 - 750	220 - 380	78 - 480	56 - 200	130 - 600
Miscellaneous organic compounds (mg/kg dry weight)															
4-Methylphenol	5,800 – 28,000	3,700 – 18,000	4,300 – 8,700	930 – 5,400	7,400 – 14,000	12,000 – 19,000	59 - 360	64 - 120	64 - 120	59 - 96	40 - 120	57 - 220	120 - 480	62 - 200	63 – 120
Benzoic acid	1,200 – 3,200	1,900 – 9,800	1,600 – 2,600	1,300 – 7,200	1,100 – 2,000	2100 – 3,900	590 – 11,000	260 – 1,200	300 – 2,100	180 - 960	400 – 1,200	570 – 2,200	1,800 – 12,000	1,200 – 9,800	630 – 1,200
Benzyl alcohol	130 – 5,500	190 – 4,900	110 – 3,000	100 – 3,600	100 - 200	210 - 390	59 – 3,200	67 - 320	72 - 720	59 - 450	40 - 120	120 - 220	180 - 480	120 - 740	63 - 120
Phenol	250 - 730	220 – 1,100	270 - 570	300 - 720	380 - 890	520 - 930	59 - 810	64 - 790	72 – 1,400	59 - 160	40 - 120	57 - 220	180 - 480	62 - 230	63 - 120
Polychlorinated Biphenyls (mg/kg dry weight)															
Aroclor 1248	19 - 20	19 - 20	19 - 20	20 - 20	130 - 410	20 - 60	18 - 19	19 - 20	19 - 20	18 - 20	38 - 160	19 - 59	19 - 190	18 - 20	90 - 96
Aroclor 1254	19 - 69	19 - 73	19 - 60	20 - 79	290 - 330	50 - 72	18 - 19	19 - 20	19 - 29	18 - 20	38 - 130	36 - 59	19 - 530	18 - 20	77 - 470
Aroclor 1260	19 - 37	19 - 20	19 - 52	20 - 40	130 - 160	34 - 81	18 - 19	19 - 20	19 - 29	18 - 29	38 - 87	24 - 59	19 - 740	18 - 20	63 - 440
Total PCBs	19 - 37	19 - 73	19 - 52	20 - 79	550 - 720	34 - 150	18 - 19	19 - 20	19 - 29	18 - 29	38 - 330	40 - 60	19 - 1300	18 - 20	230 - 910

µg/kg micrograms per kilogram.
mg/kg milligrams per kilogram.
Total carcinogenic PAHs represents the toxicity equivalent factor sum of the following polycyclic aromatic hydrocarbons: benzo(a)pyrene, benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, indeno(1,2,3-c,d)pyrene, dibenz(a,h)anthracene.

Table 17. Comparison of coarse- and fine-grained material composition at swept and unswept sites for the Seattle Street Sweeping Pilot Study.

	Coarse-grained [a]		Fine-grained [b]	
	Swept	Unswept	Swept	Unswept
Catch Basin Sediment				
West Seattle	53-75%	72-83%	25-48%	17-28%
Southeast Seattle	67-87%	71-84%	14-33%	17-29%
Duwamish Diagonal	57-77%	50-74%	24-44%	26-51%
Street Dirt				
West Seattle	60-89%	62-94%	11-41%	6-38%
Southeast Seattle	65-98%	70-85%	2-36%	16-31%
Duwamish Diagonal	56-74%	58-72%	27-45%	28-43%

[a] Gravel + coarse sand (>250 µ)
[b] Fine sand + silt/clay (<250 µ)

Table 18. Range of metal concentrations (dry weight) in samples from both swept and unswept sites.

	Catch Basin (mg/kg)	Street Dirt (mg/kg)	Sweeper Waste (mg/kg)
Cadmium			
West Seattle	0.6-1.7	0.4-1.1	0.3-0.8
Southeast Seattle	0.6-0.9	<0.5-0.8	0.3-0.8
Duwamish Diagonal	2.0-4.0	0.9-1.6	0.6-0.8
Chromium			
West Seattle	28-95.4	32.2-371	10-33.8
Southeast Seattle	22-189	19.4-219	15.9-52
Duwamish Diagonal	33-92	36.8-70	45-83
Copper			
West Seattle	41.4-80.7	29.8-163	21.5-47.8
Southeast Seattle	43.8-198	25.4-466	23.2-75.5
Duwamish Diagonal	136-183	55.3-92.3	48.6-76.2
Lead			
West Seattle	70-166	32-222	26-77
Southeast Seattle	65-114	26-156	29-88
Duwamish Diagonal	91-354	45-279	159-361
Zinc			
West Seattle	223-535	158-276	109-226
Southeast Seattle	241-323	119-492	120-273
Duwamish Diagonal	489-1,100	238-541	170-324

Table 19. Summary of literature values for median metals concentrations (dry weight) in street dirt/dust, catch basins, and sweeper waste.

Material	Cadmium (mg/kg)	Chromium (mg/kg)	Copper (mg/kg)	Lead (mg/kg)	Zinc (mg/kg)	Location	Reference
Street dirt	0.3	42	41	65	110	Jackson, MI	Tetra Tech (2001)
Street dirt	–	–	–	542	–	Oahu, Hawaii	Sutherland (2003)
Street dirt	–	–	224	252	1,639	Port of Seattle, WA	Sutherland et al. (1998)
Street dust	1.7	–	177	236	358	Amman, Jordan	Al-Khashman (2007)
Street dust	22.3	42	183	514	48	Aviles, Spain	Al-Khashman (2007)
Street dust	72	144	–	697	152	Bahrain	Al-Khashman (2007)
Street dust	1.6	–	467	48	534	Birmingham, UK	Al-Khashman (2007)
Street dust	0.9	–	226	47	385	Coventry, UK	Al-Khashman (2007)
Street dust	10.1	73	67	166	–	Kayseri, Turkey	Al-Khashman (2007)
Street dust	3.5	–	155	1,030	680	London, UK	Al-Khashman (2007)
Street dust	–	–	113	265	653	Manchester, UK	Al-Khashman (2007)
Street dust	1.1	26	42	315	317	Luanda, Angola	Al-Khashman (2007)
Street dust	–	167	95	231	421	Xian, China	Al-Khashman (2007)
Street dust	3	33	378	69	–	Yozgat, Turkey	Al-Khashman (2007)
Catch basin sediment	–	–	47	91	373	Alameda County, CA	Mineart (2000)
Sweeper waste	0.2	16	19	40	87	Baltimore, MD	Stack (2007)

– = not analyzed.

Table 20. Number of repeat offenders and tickets issued for violating parking restrictions in the West Seattle and Southeast Seattle study areas.

	West Seattle		Southeast Seattle	
	Number	Frequency	Number	Frequency
Total Offenders	**369**	100%	**238**	100%
1 time offenders	243	65.8%	153	64.3%
2 time offenders	57	15.4%	33	13.9%
3 time offenders	20	5.4%	20	8.4%
4 time offenders	23	6.2%	11	4.6%
5 time offenders	8	2.2%	6	2.5%
6 time offenders	5	1.5%	3	1.3%
7 time offenders	5	1.5%	5	2.1%
8 time offenders	3	0.8%	4	1.7%
9 time offenders	1	0.3%	1	0.4%
10 time offenders	1	0.3%	0	0.4%
11 time offenders	1	0.3%	1	0.4%
12 time offenders	2	0.5%	0	0.8%
13 time offenders	0	0.0%	0	0.0%
14 time offenders	0	0.0%	1	0.4%
Total Tickets	**54**	100%	**7**	100%
Received 1 ticket	53	98.1%	7	100**%**
Received 2 tickets	0	0.0%	0	0.0%
Received 3 tickets	1	0.2%	0	0.0%

Table 21. Monthly number of parking violations and tickets issued in the West Seattle and Southeast Seattle study areas.

	West Seattle		Southeast Seattle		Total	
	Violations	Tickets	Violations	Tickets	Violations	Tickets
June	32	0	20	0	52	0
July	71	0	53	0	124	0
August	83	0	67	0	150	0
September	75	0	46	0	121	0
October	84	0	59	0	143	0
November	61	0	16	0	77	0
December	50	0	33	0	83	0
January	113	0	84	0	197	0
February	18	8	16	0	34	8
March	28	15	30	0	58	15
April	26	20	13	0	39	20
May	21	7	24	1	45	8
June	27	6	11	6	38	12

Table 22. Number of parking violations by street in the West Seattle and Southeast Seattle study areas.

West Seattle	Times Offended
SW Findlay from 42nd Ave SW to California Ave SW	94
California Ave SW from SW Brando SW Findlay Street	61
SW Findlay from 42nd Ave SW to California Ave SW	60
42nd Ave SW from SW Brando SW Findlay Street	58
SW Findlay from California Ave SW to 44th Ave SW	52
California Ave SW from SW Brando SW Findlay Street	46
46th Ave SW from SW Brando SW Findlay Street	39
42nd Ave SW from SW Brando SW Findlay Street	38
44th Ave SW from SW Brando SW Findlay Street	37
46th Ave SW from SW Brando SW Findlay Street	35
45th Ave SW from SW Brando SW Findlay Street	34
SW Findlay from California Ave SW to 44th Ave SW	29
44th Ave SW from SW Brando SW Findlay Street	27
SW Findlay from 44th Ave SW to 45th Ave SW	23
45th Ave SW from SW Brando SW Findlay Street	23
SW Findlay from 44th Ave SW to 45th Ave SW	16
SW Findlay from alley to 42nd Ave SW	11
SW Findlay from alley to 42nd Ave SW	5
SW Findlay from 45th Ave SW to 46th Ave SW	1
Southeast Seattle	**Times Offended**
51st Ave S from S Snoqualmie to S Alaska Street	39
48th Ave S from S Snoqualmie to S Alaska Street	31
49th Ave S from S Genesee to S Oregon Street	25
49th Ave S from S Snoqualmie to S Alaska Street	24
48th Ave S from S Snoqualmie to S Alaska Street	22
50th Ave S from S Genesee to S Oregon Street	20
48th Ave S from S Oregon S Snoqualmie Street	19
50th Ave S from S Genesee to S Oregon Street	18
48th Ave S from S Oregon S Snoqualmie Street	18
50th Ave S from S Oregon S Snoqualmie Street	17
51st Ave S from S Oregon S Snoqualmie Street	15
48th Ave S from S Genesee to S Oregon Street	15
50th Ave S from S Snoqualmie to S Alaska Street	14
50th Ave S from S Snoqualmie to S Alaska Street	14
49th Ave S from S Snoqualmie to S Alaska Street	12

Table 22 (continued). Number of parking violations by street in the West Seattle and Southeast Seattle study areas.

Southeast Seattle (continued)	Times Offended
51st Ave S from S Snoqualmie to S Alaska Street	11
51st Ave S from S Oregon S Snoqualmie Street	11
50th Ave S from S Oregon S Snoqualmie Street	11
49th Ave S from S Oregon S Snoqualmie Street	11
52nd Ave S from S Snoqualmie to S Alaska Street	11
S Oregon Street from 49th Ave S to 50th Ave S	10
49th Ave S from S Genesee to S Oregon Street	9
S Snoqualmie from 50th Ave S to 51st Ave S	8
52nd Ave S from S Oregon S Alaska Street	8
49th Ave S from S Oregon S Snoqualmie Street	8
48th Ave S from S Genesee to S Oregon Street	8
52nd Ave S from S Oregon S Snoqualmie Street	7
S Oregon Street from 48th Ave S to 49th Ave S	6
S Oregon Street from 48th Ave S to 49th Ave S	6
S Snoqualmie from 50th Ave S to 51st Ave S	6
S Genesee from 49th Ave S to 50th Ave S	5
S Snoqualmie from 49th Ave S to 50th Ave S	5
51st Ave S from S Genesee to S Oregon Street	5
S Genesee from 49th Ave S to 50th Ave S	4
S Oregon Street from 50th Ave S to 51st Ave S	4
51st Ave S from S Genesee to S Oregon Street	3
S Oregon Street from 47th Ave S to 48th Ave S	3
S Genesee from 50th Ave S to 51st Ave S	2
S Oregon Street from 50th Ave S to 51st Ave S	2
S Genesee from 48th Ave S to 49th Ave S	1
S Genesee from 50th Ave S to 51st Ave S	1
S Oregon street from 49th Ave S to 50th Ave S	1
S Snoqualmie from 48th Ave S to 49th Ave S	1
S Snoqualmie from 49th Ave S to 50th Ave S	1

Table 23. Street sweeping cost effectiveness summary for the Seattle Street Sweeping Pilot Study.

	West Seattle	Southeast Seattle	Diagonal Duwamish	Site Average	Study Total
Catchment Attributes					
Land Use	Residential	Residential	Light Industrial		
Site area (acres)	24	41	23	29	88
Street length per basin (miles)	0.9	1.8	0.8	1.2	3.5
Curb length per basin (miles)	1.8	3.6	1.6	2.3	7.0
Street area (acres)	3.1	6.4	3.2	4.2	12.7
Average street width (feet)	29	29	34	31	92
Sweeping Study Attributes					
Duration (months)	12	12	7	10	
Events per year	50	51	29	43	
Events per travel lane (biweekly sweeping)	25.0	25.5	14.5	22	
Curb length swept (miles)	44.8	91.8	22.6	60	159
Sweeper productivity (curb miles/year)	43.2	88.6	38	60	
Sweeper Waste Attributes					
Sediment removed (wet kg)	6,370	13,600	5,180	8,380	25,200
Sediment removed (dry kg)	3,230	8,000	2,670	4,630	13,900
Moisture content (%)	49%	41%	48%	45%	
Percent passing 250 microns	14%	14%	27%	18%	
Estimated Sediment Removal Rates					
Sediment (wet kg/year)	6,150	13,140	8,720	9,340	28,000
Sediment (dry kg/year)	3,120	7,740	4,520	5,130	15,380
Sediment (dry lb/year)	6,860	17,030	9,950	11,300	33,800
Sediment (dry g/m^2 street/year)	250	300	350	300	
Sediment (dry lb/curb mile swept)	160	190	260	200	
Estimated Total Suspended Solids (TSS) Removal Rates					
TSS (dry kg/year)	350	810	1,640	930	2,800
TSS (dry lb/year)	760	1,790	3,620	2,060	6,170
TSS (dry g/m^2 street/year)	28	31	130	63	
TSS (dry lb/curb mile swept)	18	20	95	44	
Estimated Future Stormwater Quality Street Sweeping Program Unit Costs					
Sweeping Program ($43/curb mile swept)	$1,900	$3,800	$1,600	$2,400	$7,300
Solids Handling & Trucking ($34/wet ton)	$200	$500	$300	$300	$1,000
Solids Disposal (non-dangerous waste at $43.5/wet ton)	$300	$600	$400	$400	$1,300
Total Cost ($/year)	$2,400	$4,900	$2,300	$3,200	$9,600
Total Cost ($/wet kg sediment)	$0.39	$0.37	$0.26	$0.34	
Total Cost ($/dry kg sediment)	$0.77	$0.63	$0.51	$0.64	
Total Cost ($/dry kg TSS)	$6.90	$6.00	$1.40	$4.80	
Total Cost ($/street acre/year)	$800	$800	$700	$800	
Total Cost ($/curb mile swept)	$56	$55	$60	$57	
Pilot Study Costs					
Sweeping Program ($404/curb mile swept)	$18,100	$37,100	$9,100		$64,300
Solids Handling & Trucking ($31/wet ton)	$200	$500	$200		$900
Solids Disposal (non-dangerous waste $43.5/wet ton)	$30	$700	$200		$930
Total Cost ($/study)	$18,600	$38,300	$9,500		$66,400
Total Cost ($/dry kg sediment removed)	$5.80	$4.80	$3.50	$4.70	
Total Cost ($/dry kg TSS removed)	$51.90	$45.50	$9.70	$27.10	
Total Cost ($/street acre)	$6,000	$6,000	$3,000	$5,100	
Total Cost ($/curb mile swept)	$416	$417	$418	$410	

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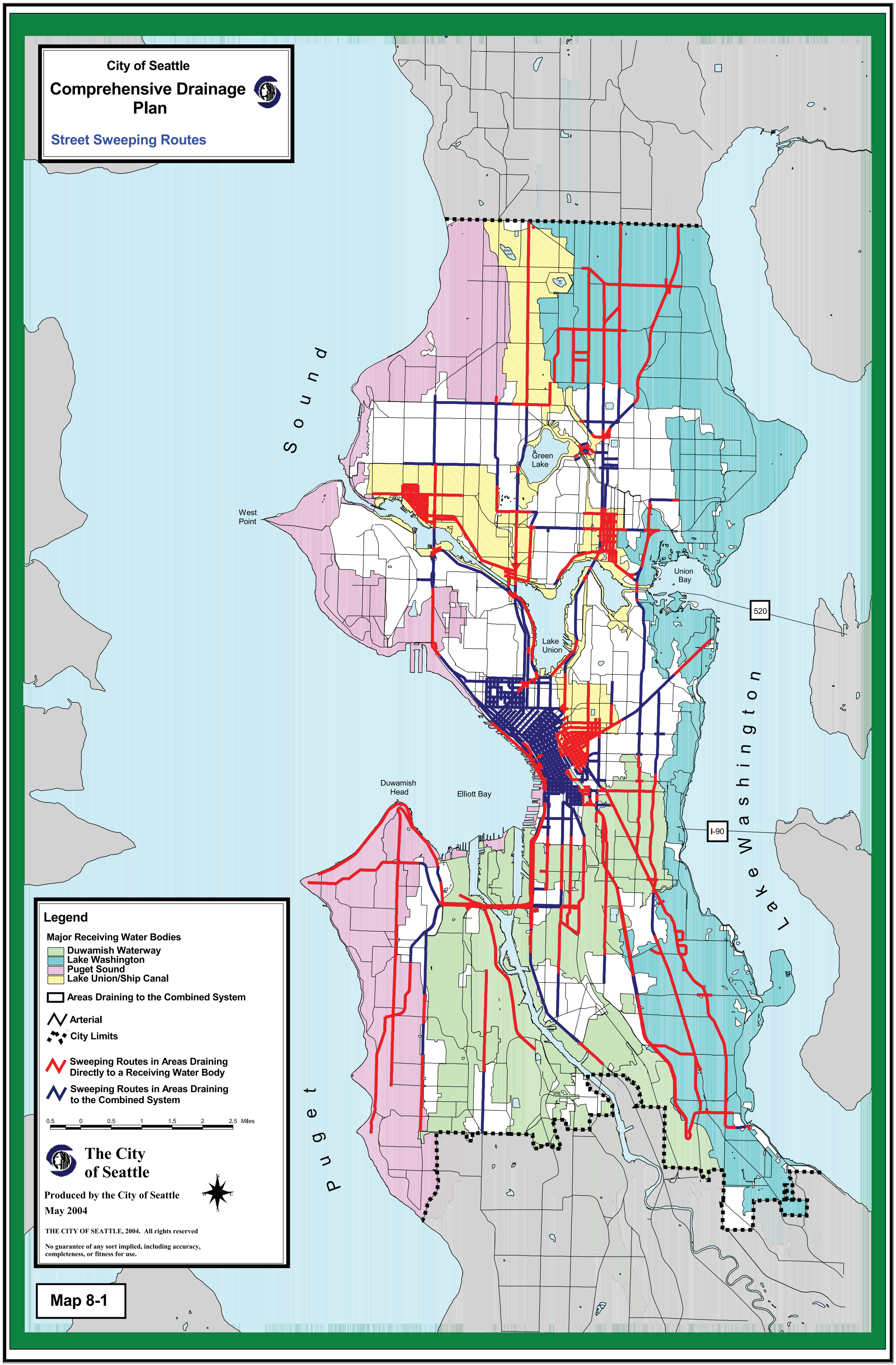


Figure 1. Seattle street sweeping routes.

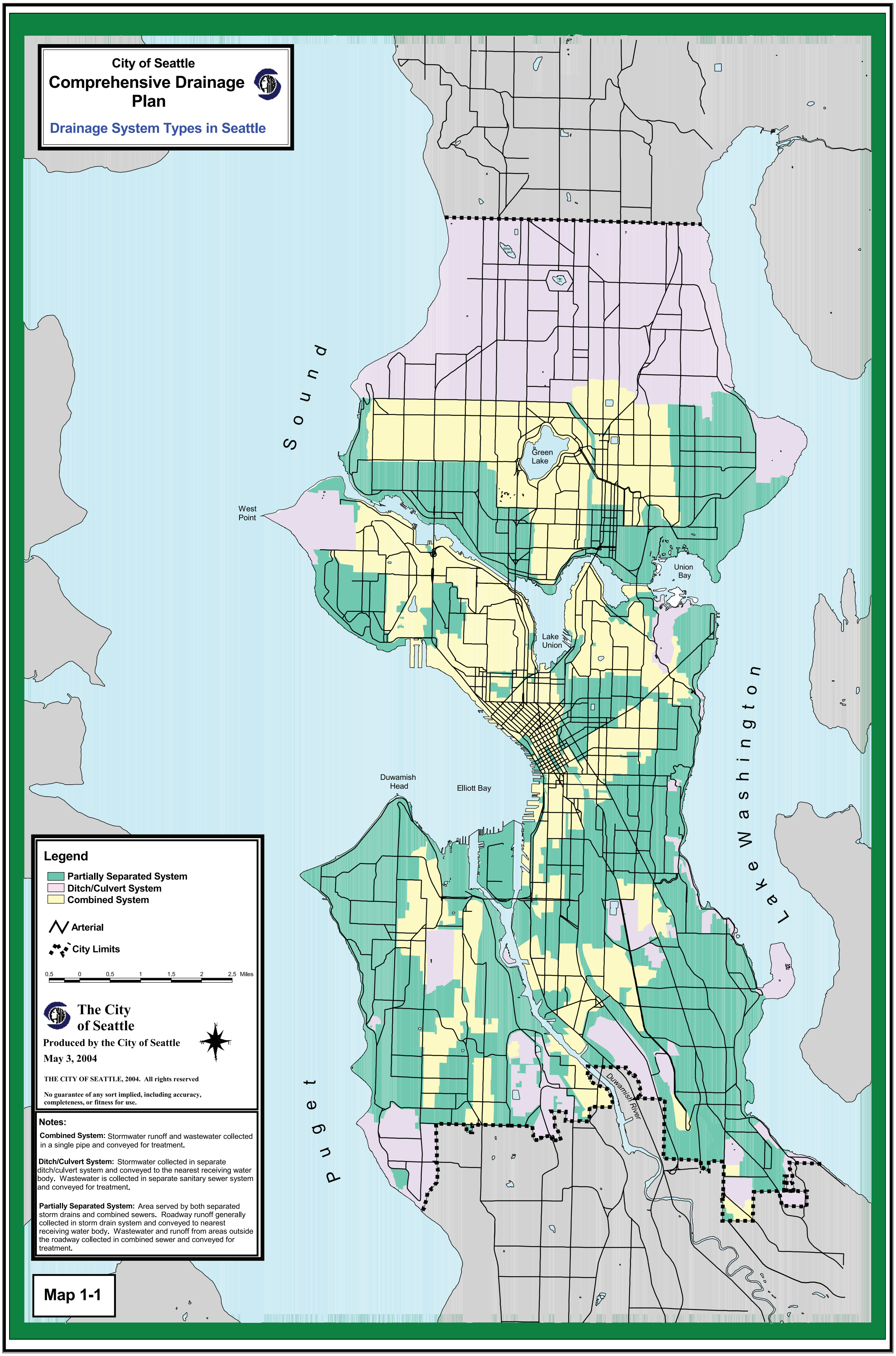


Figure 2. Seattle stormwater/sewer classification areas.

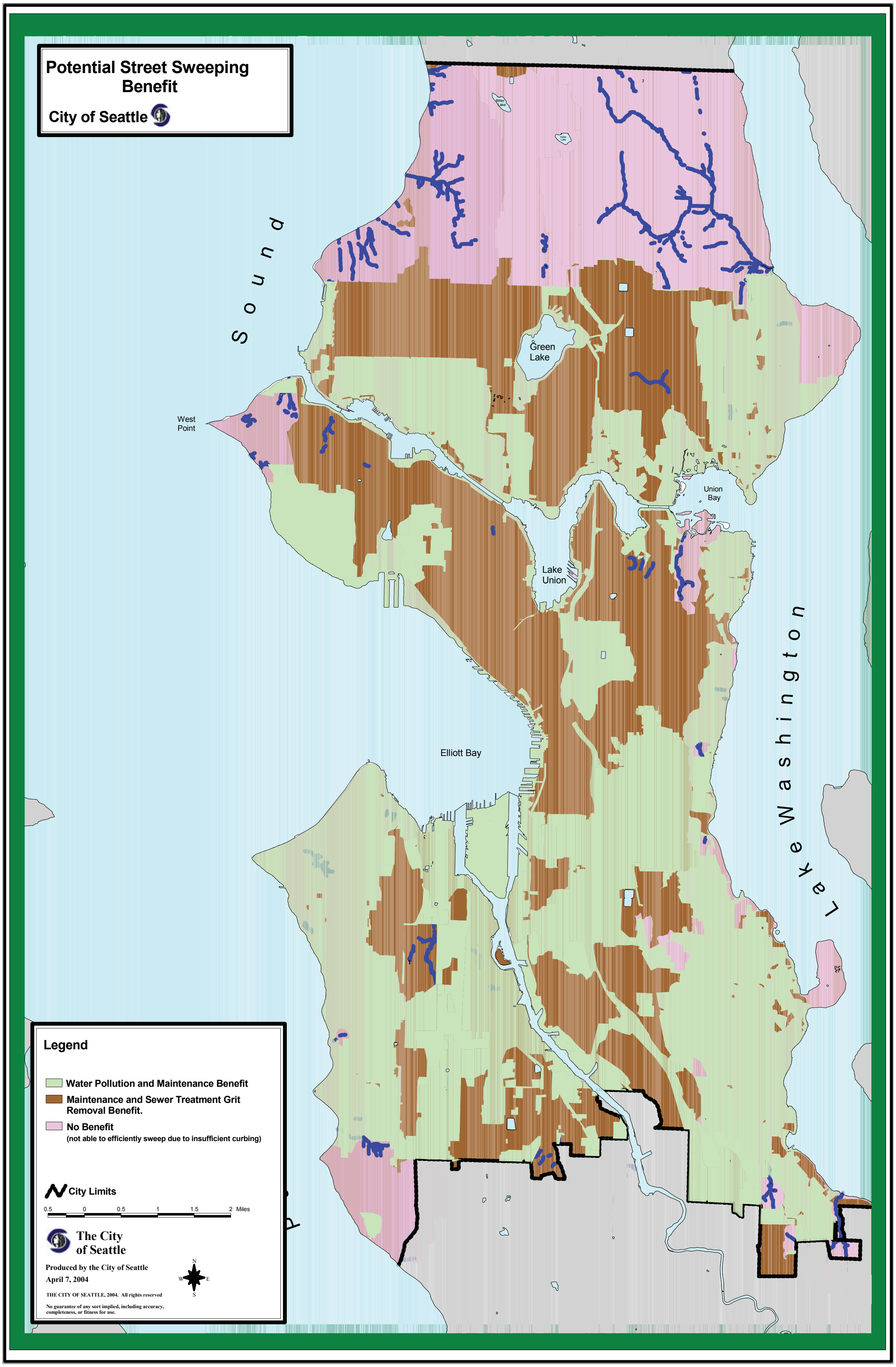


Figure 3. Seattle drainage basins and those areas benefiting from street sweeping.

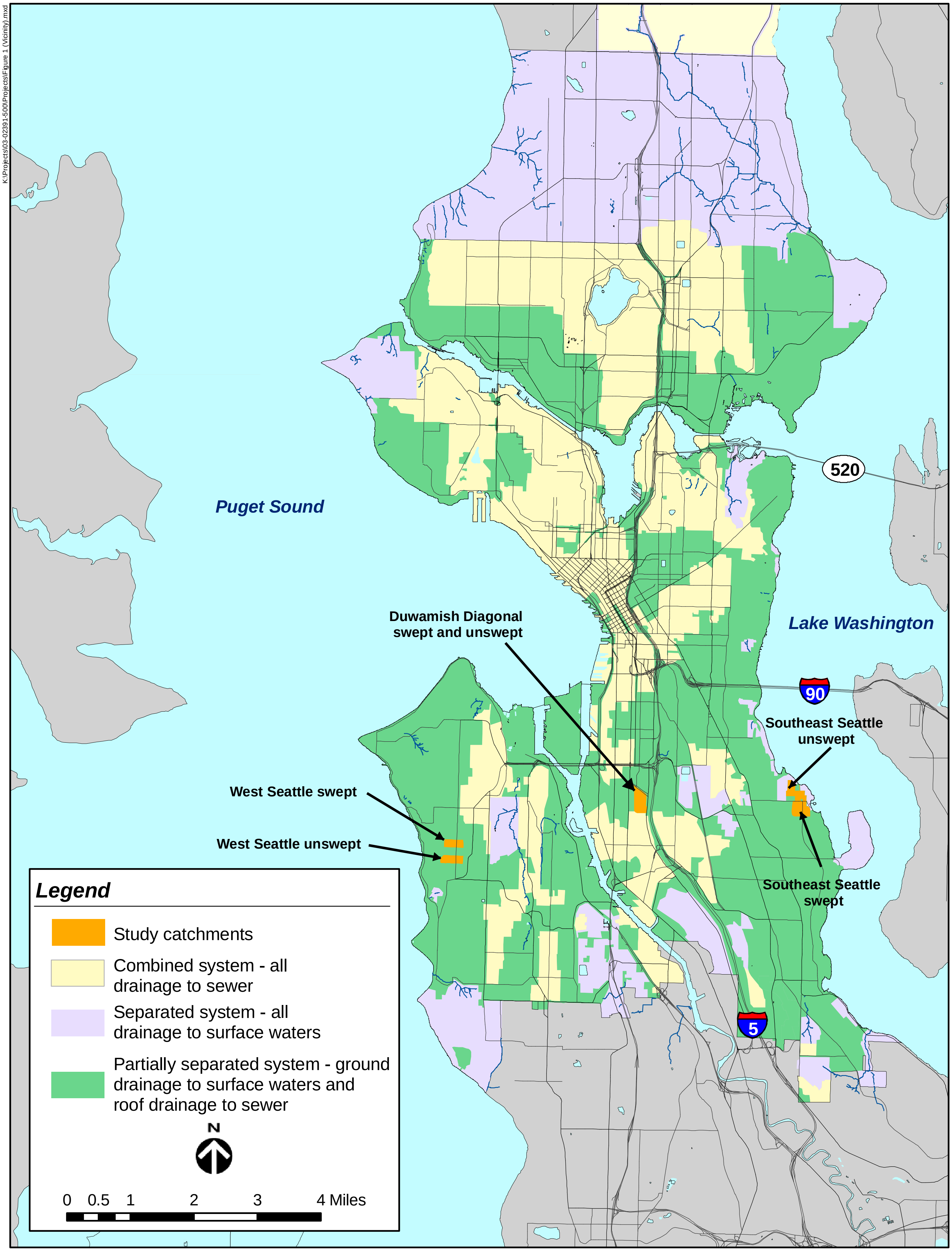


Figure 4. Study area locations and drainage areas for the Seattle Street Sweeping Pilot Study.

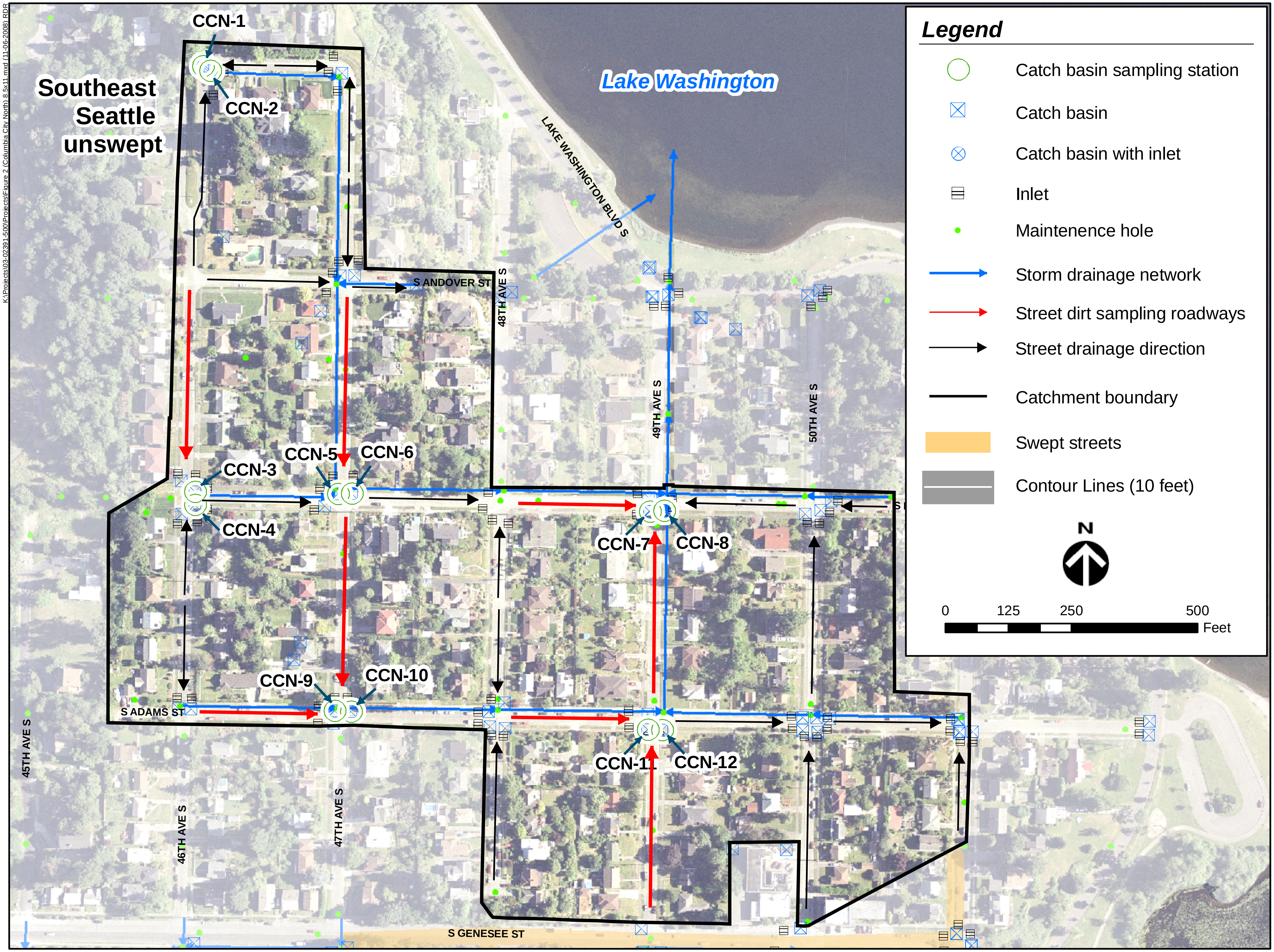


Figure 5. Catch basin sampling stations in the Southeast Seattle unswept site for the Seattle Street Sweeping Pilot Study.

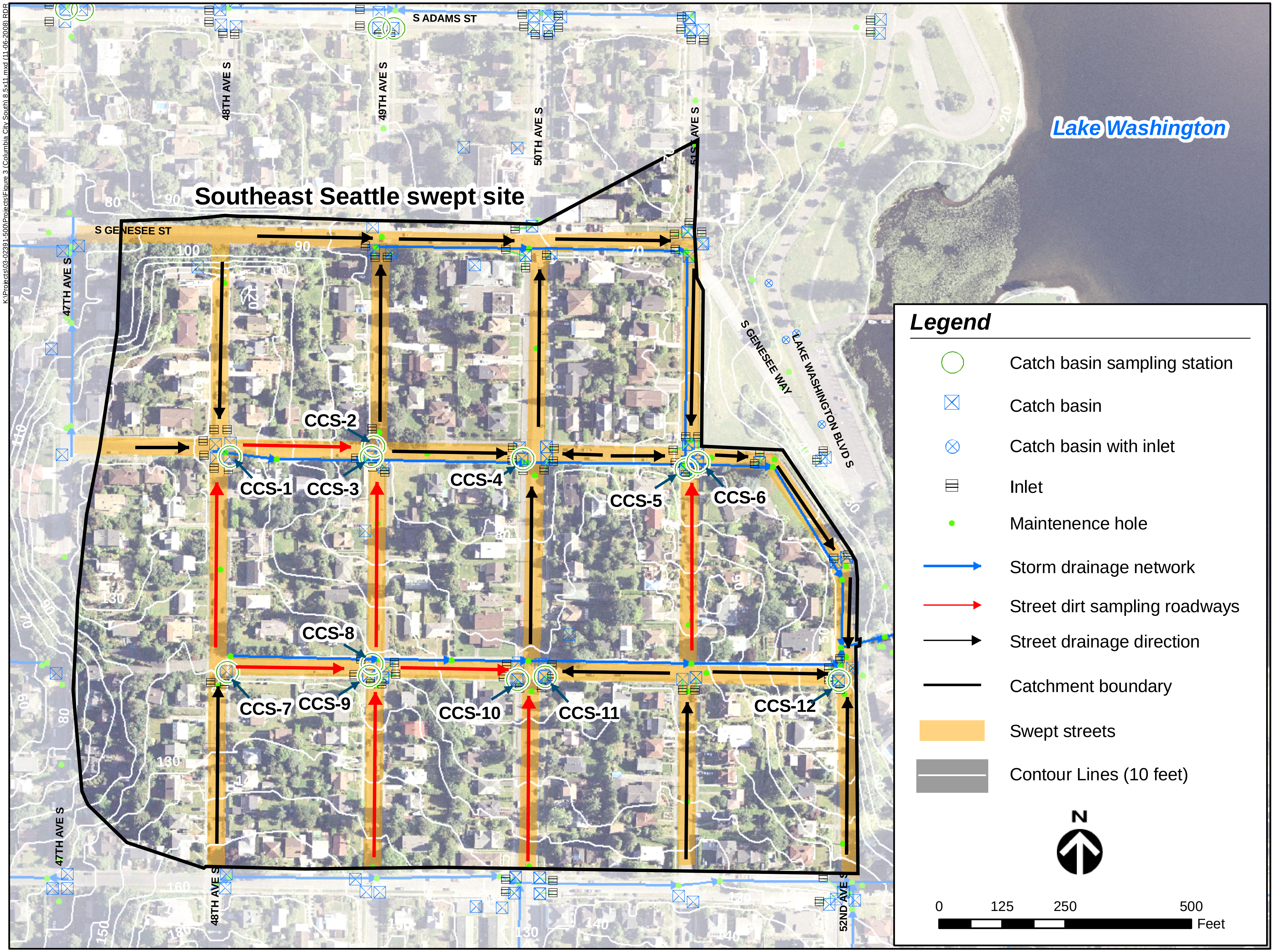


Figure 6. Catch basin sampling stations in the Southeast Seattle swept site for the Seattle Street Sweeping Pilot Study.

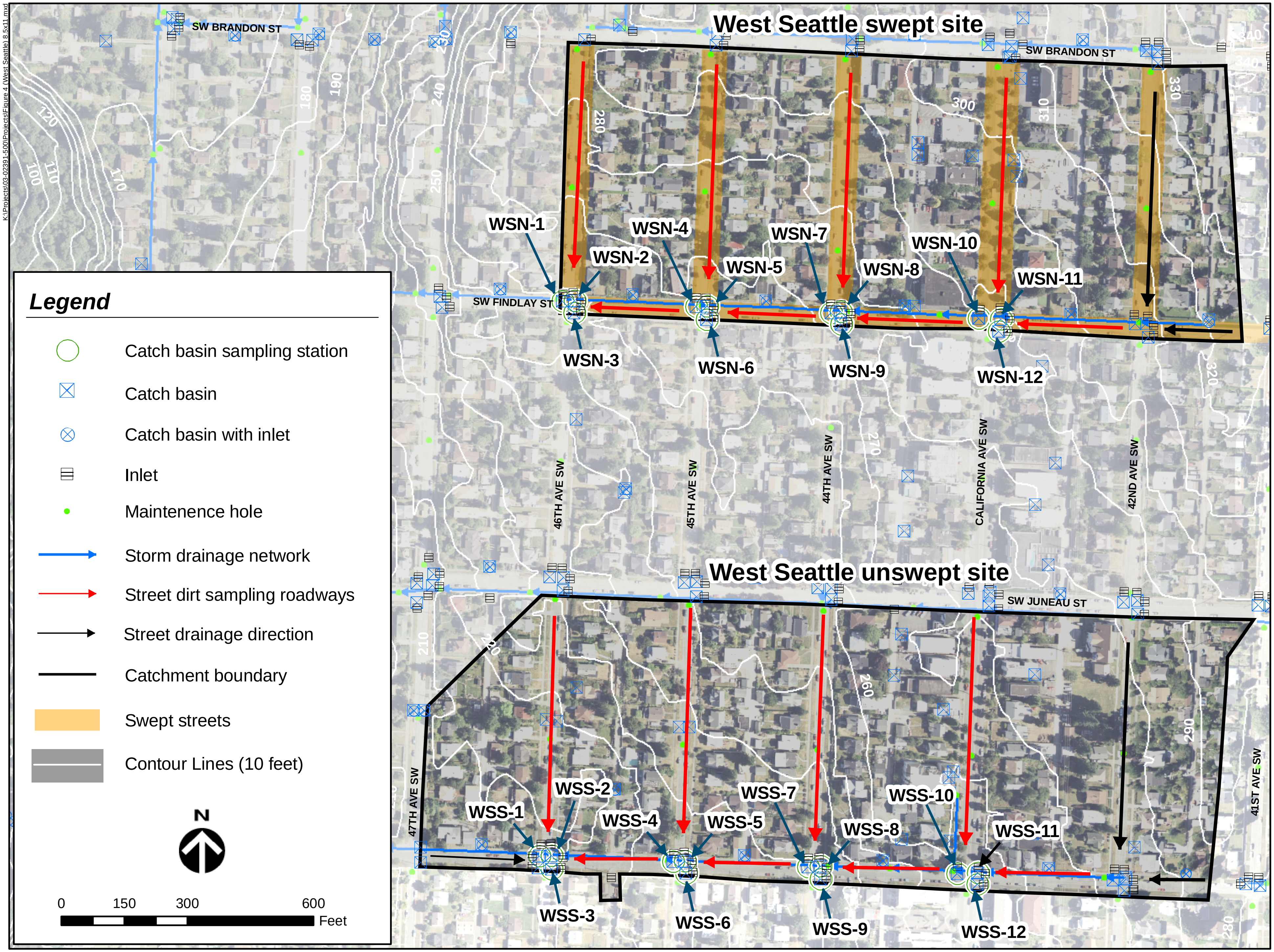


Figure 7. Catch basin sampling stations in the West Seattle swept and unswept sites for the Seattle Street Sweeping Pilot Study.

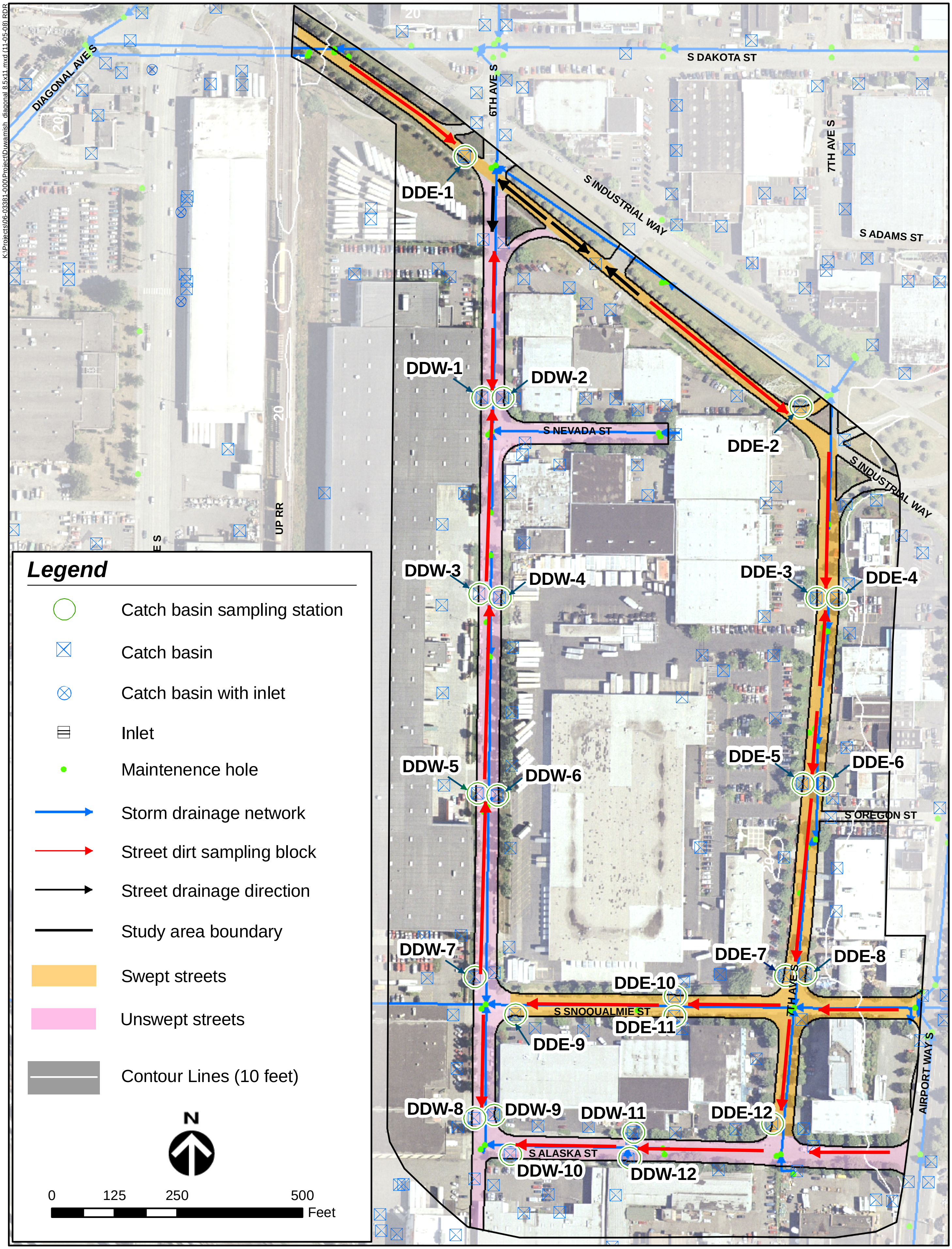
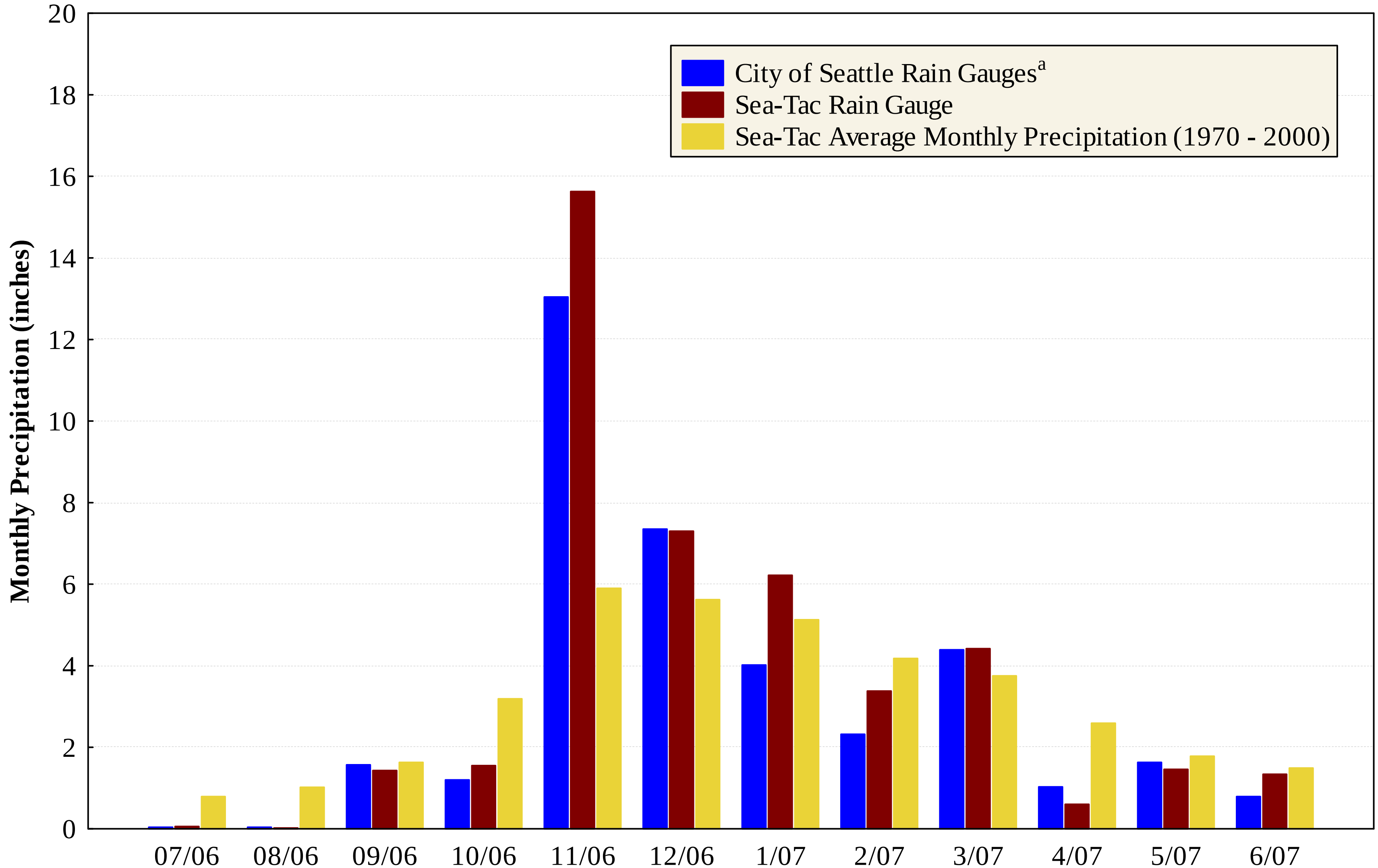


Figure 8. Catch basin sampling stations in the Duwamish Diagonal swept and unswept sites for the Seattle Street Sweeping Pilot Study.

Figure 9. Photographs of the Schwarze A8000 regenerative air sweeper used for the Seattle Street Sweeping Study.



[a]Precipitation data from 6/1/06 – 3/11/07 is from rain gauge RG16 which is located in the approximate geographic center of the three monitored catchments. Precipitation data from 3/12/07 – 6/17/07 is from rain gauge RG18 located near the Southeast Seattle

Figure 10. Monthly precipitation measured at rain gauges located in the approximate vicinity of the study sites compared to average monthly precipitation data measured at Seattle-Tacoma International Airport.

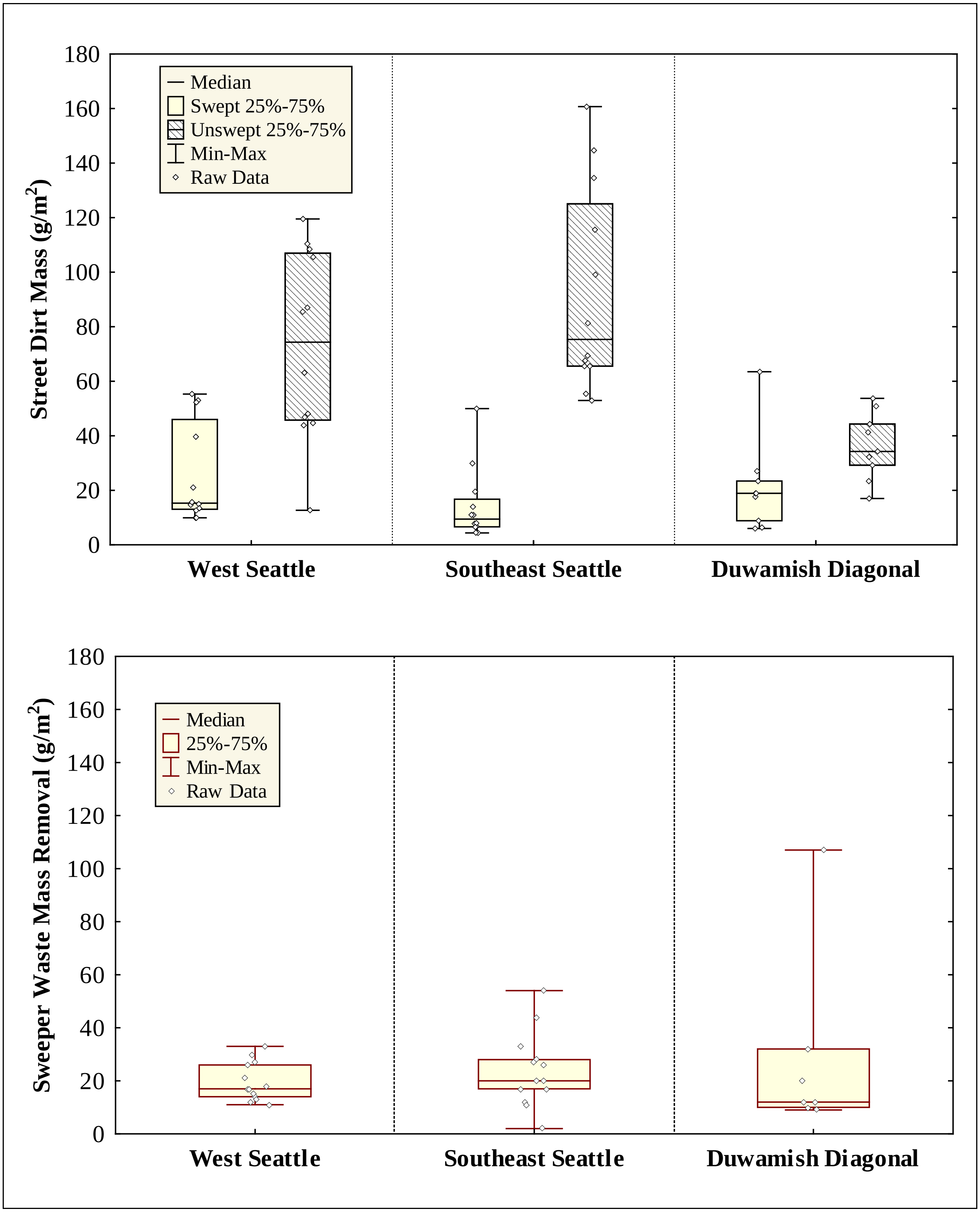


Figure 11. Box plots of street dirt mass and sweeper waste mass in the three paired sites for the Seattle Street Sweeping Pilot Study.

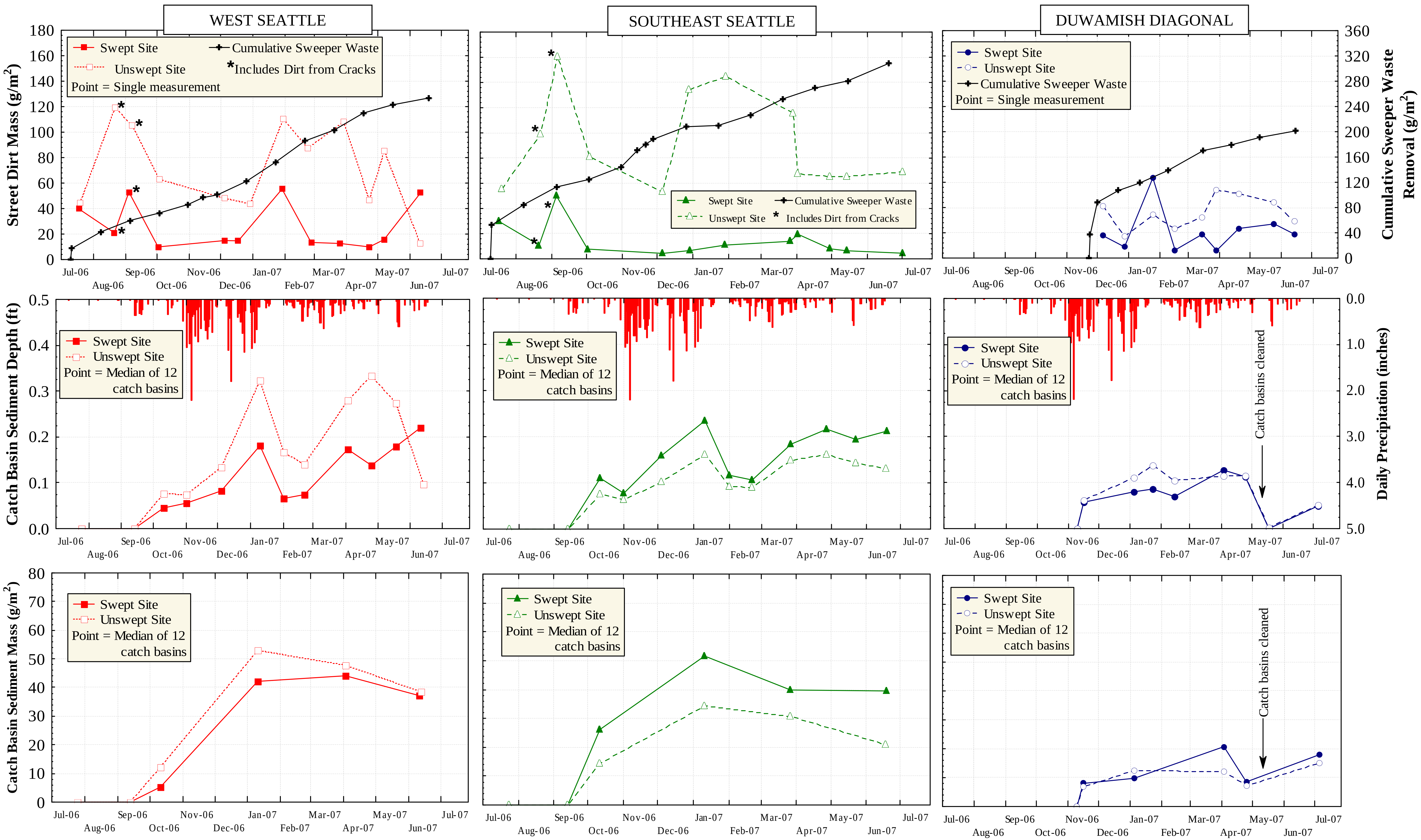


Figure 12. Chronological plots of 1) street dirt mass including cumulative sweeper waste mass removal, 2) catch basin sediment depth and daily precipitation amount, and 3) catch basin sediment mass measured over time in the three paired sites for the Seattle Street Sweeping Pilot Study.

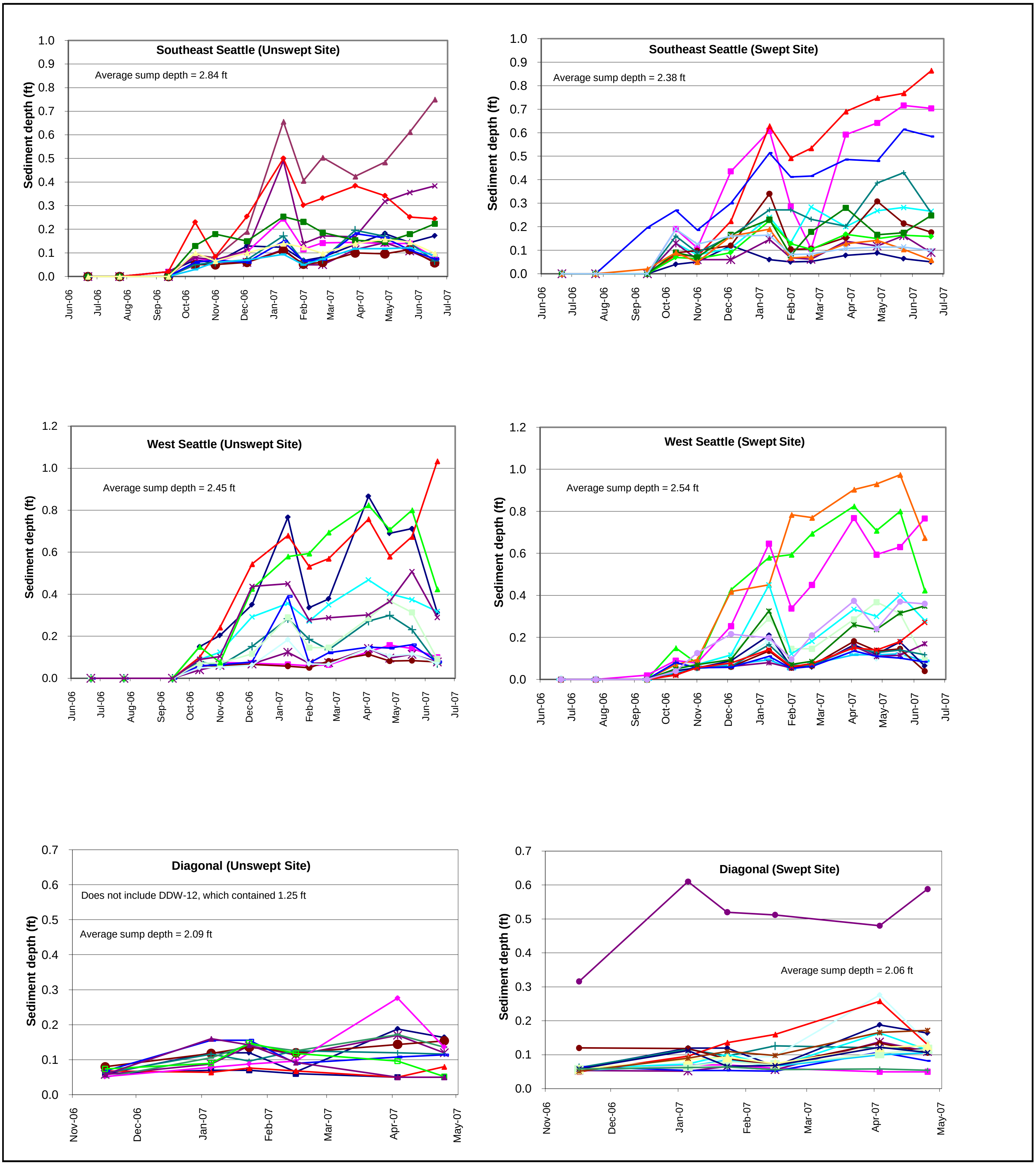
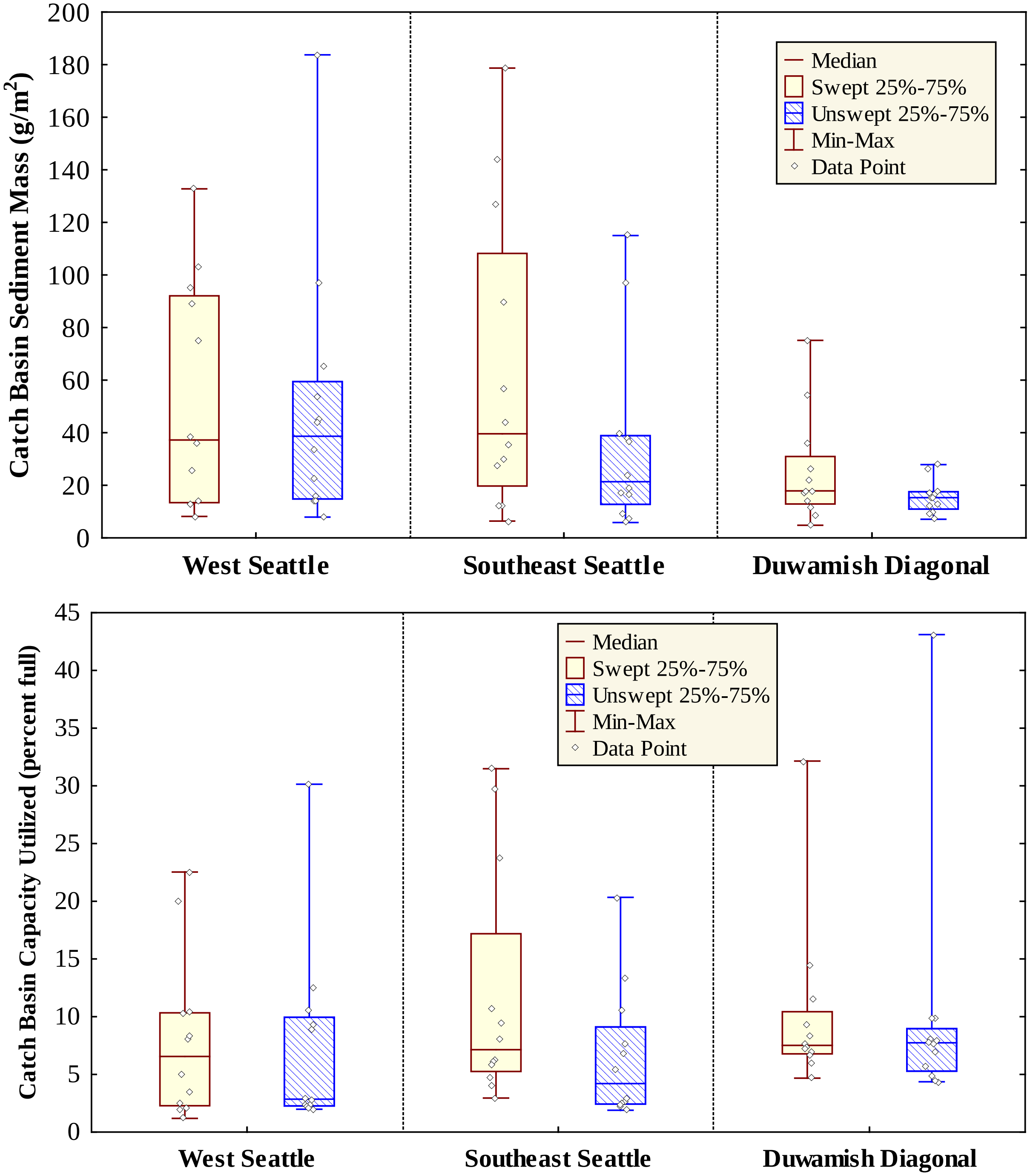


Figure 13: Measured sediment depth in the monitored catch basins during the study period.



Final measurement dates: 6/11/07 West Seattle, 6/18/07 Southeast Seattle, 7/6/07 Duwamish Diagonal (sum of measurements on 4/25/07 and 7/6/07).

Figure 14. Box plots of catch basin sediment mass and capacity utilization (percent full) at the end of the study period in the three paired sites for the Seattle Street Sweeping Pilot Study.

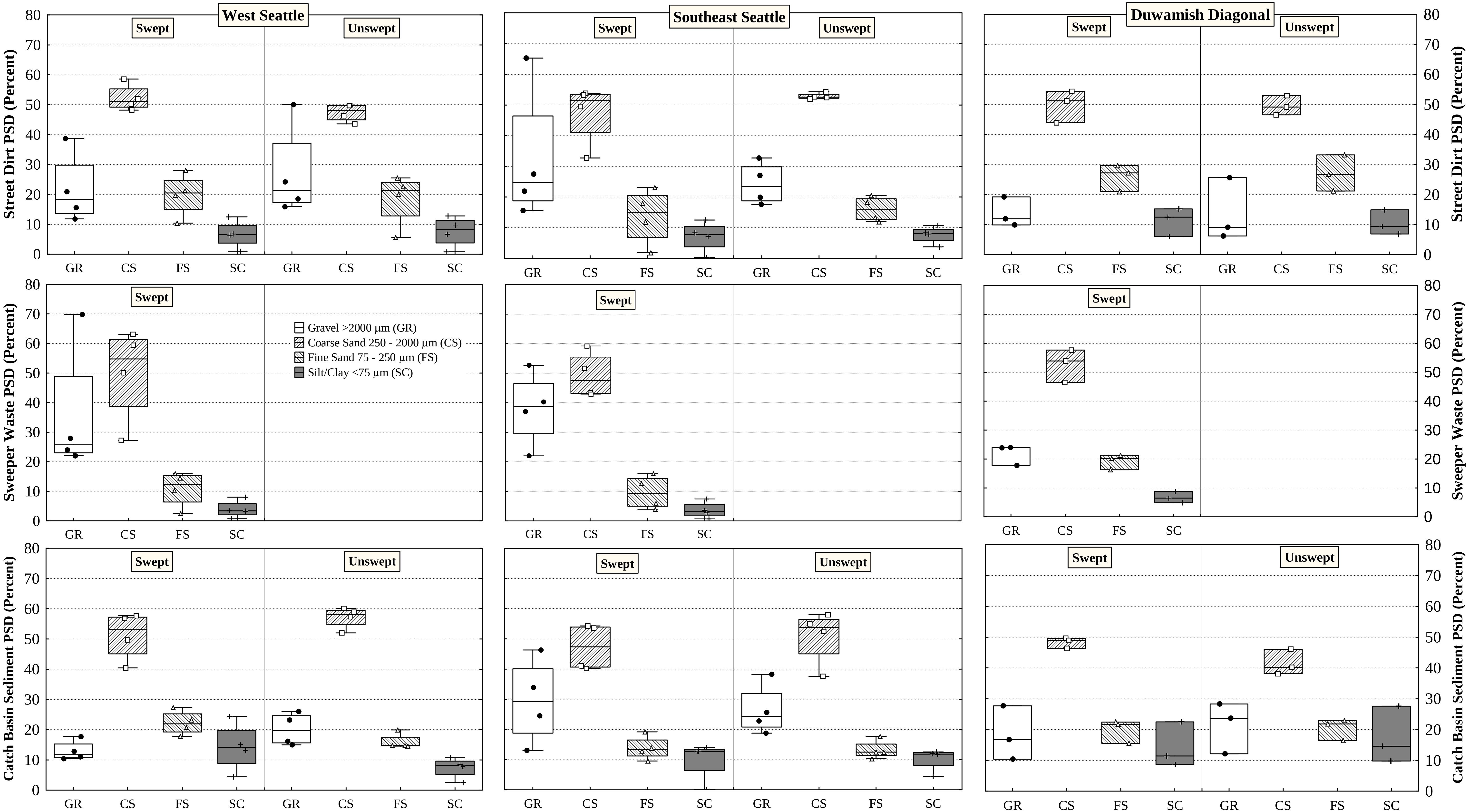


Figure 15. Particle size distribution for street dirt (top), sweeper waste (middle), and catch basin sediment (bottom) samples in the three paired catchments for the Seattle Street Sweeping Pilot Study.

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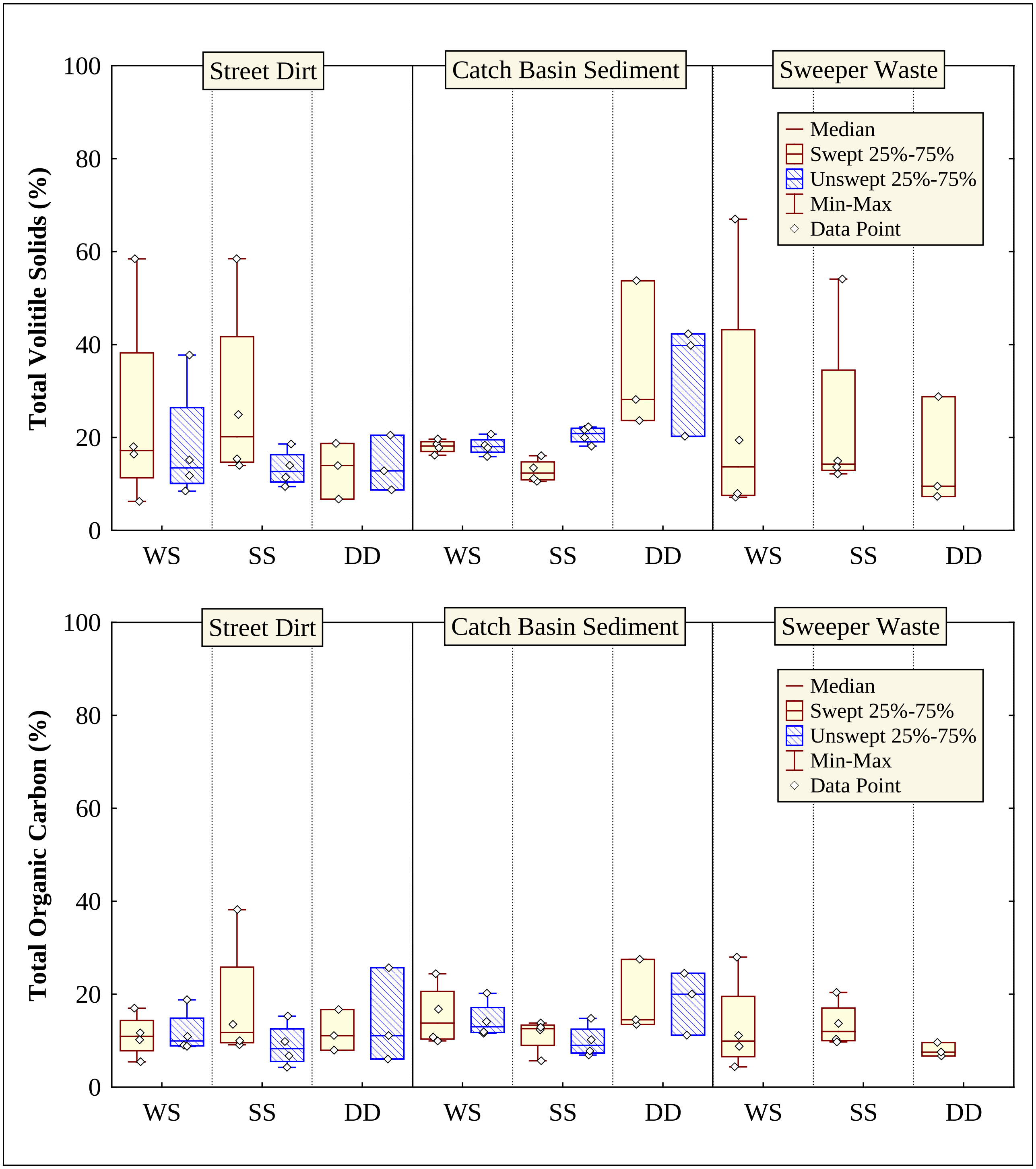

Figure 16. Total volatile solids and total organic carbon percentage for street dirt, sweeper waste, and catch basin sediment in the three paired sites (WS = West Seattle, SS = Southeast Seattle, and DD = Duwamish Diagonal) for the Seattle Street Sweeping Pilot Study.

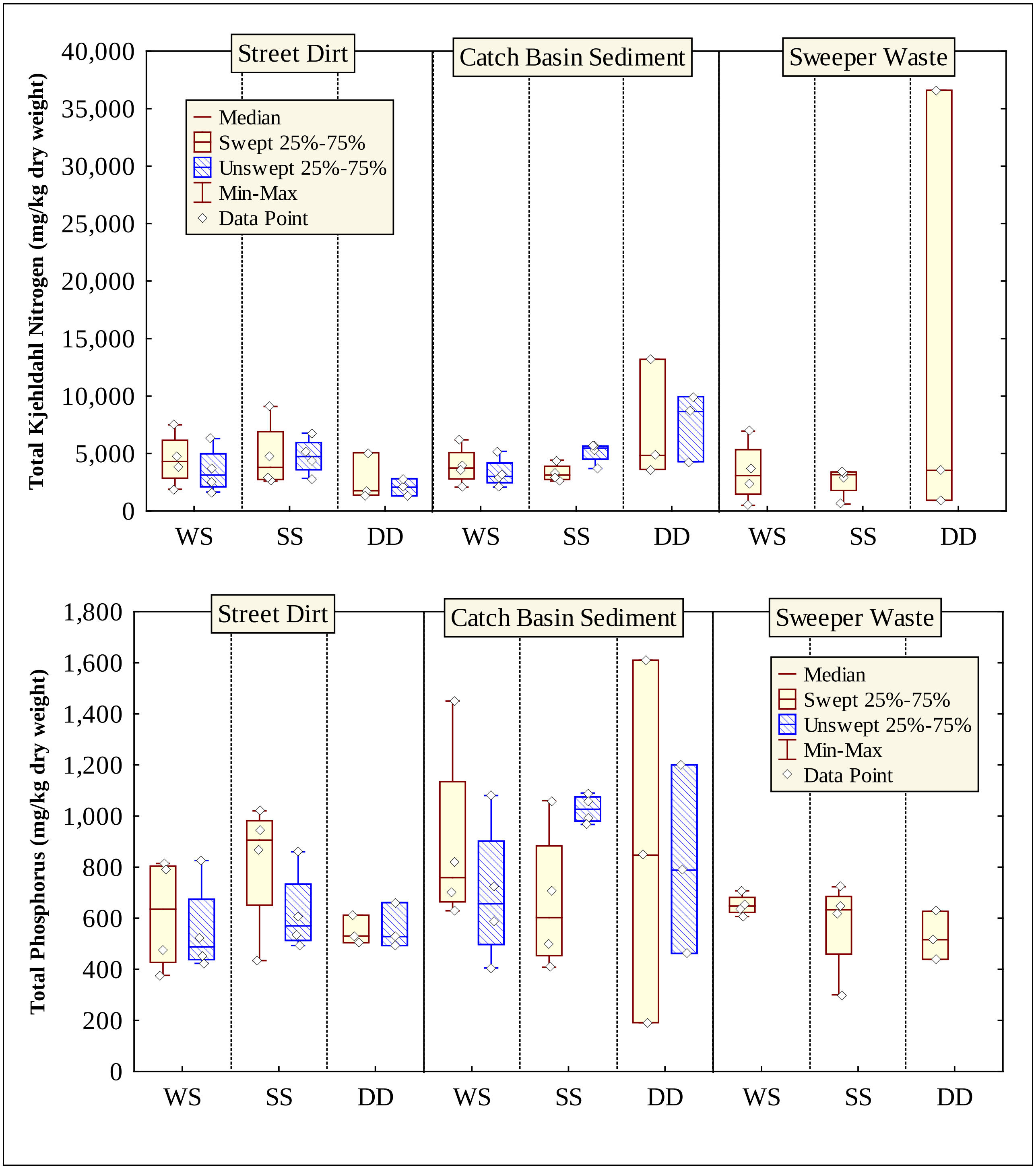

Figure 17. Total Kjeldahl nitrogen and total phosphorus concentrations for street dirt, sweeper waste, and catch basin sediment in the three paired sites (WS = West Seattle, SS = Southeast Seattle, and DD = Duwamish Diagonal) for the Seattle Street Sweeping Pilot Study.

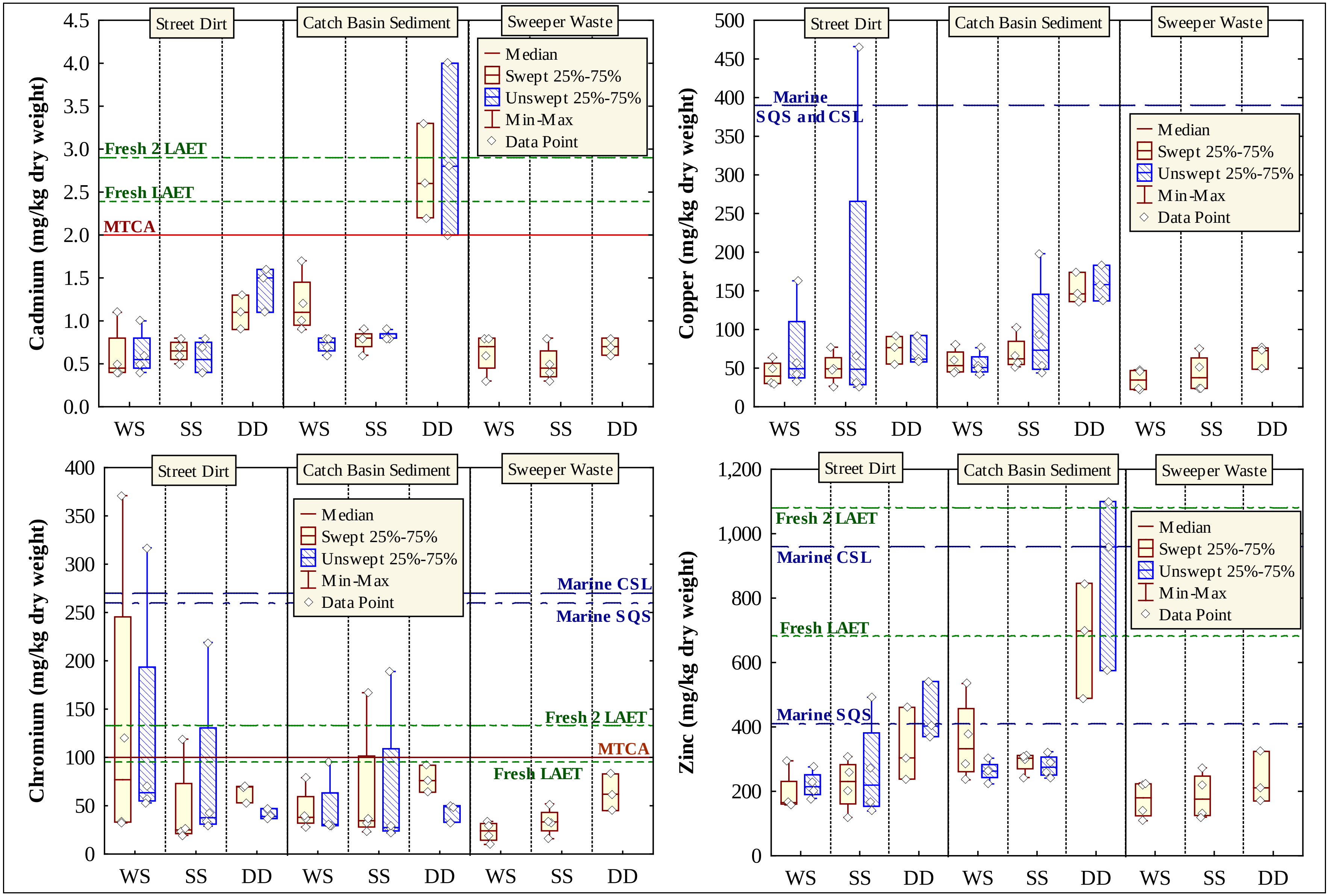

Figure 18. Cadmium, chromium, copper, and zinc concentrations found in street dirt, sweeper waste, and catch basin sediment in the three paired sites for the Seattle Street Sweeping Pilot Study (WS = West Seattle, SS = Southeast Seattle, and DD = Duwamish Diagonal).

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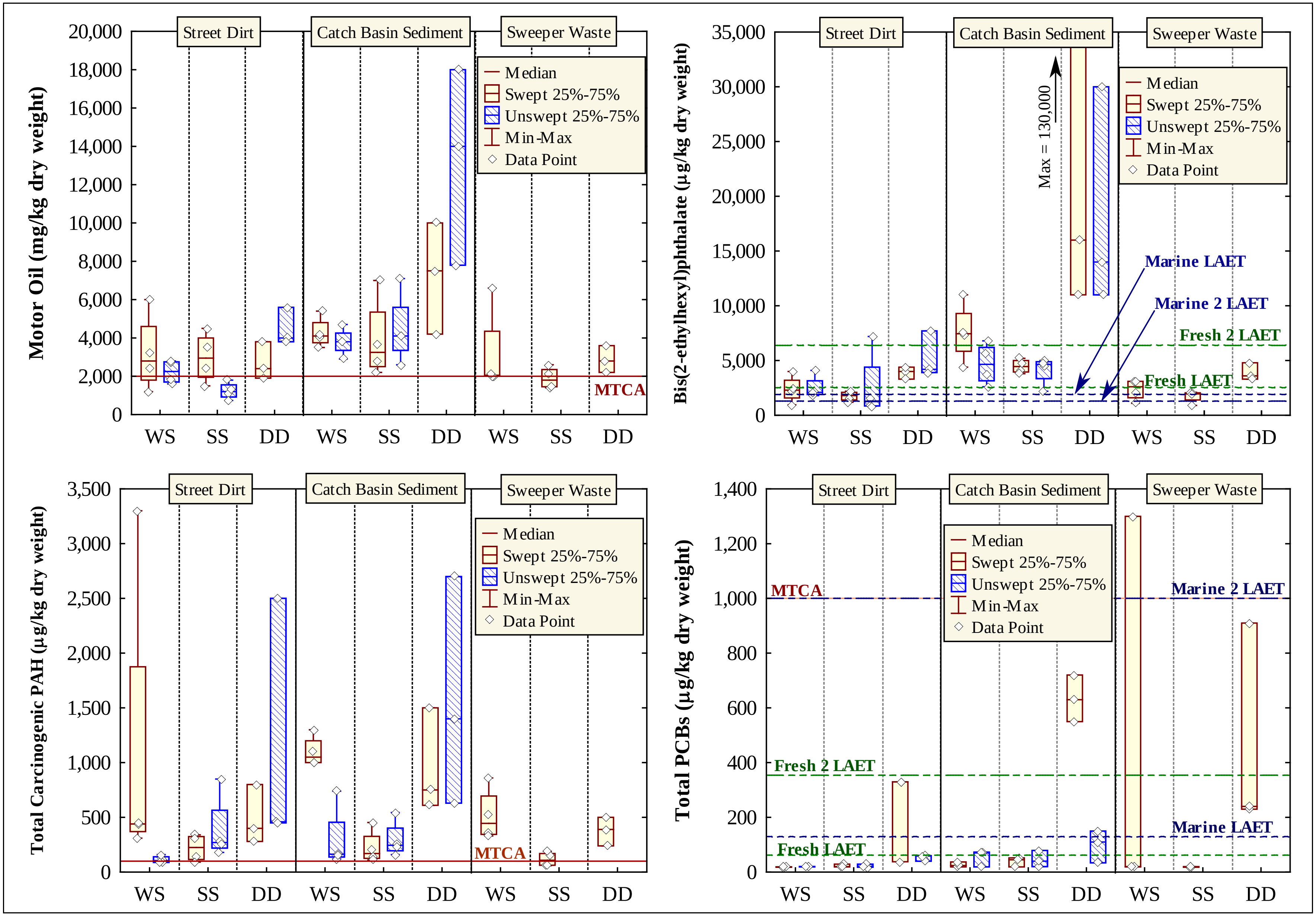

Figure 19. Concentrations of motor oil, total carcinogenic polycyclic aromatic hydrocarbons (PAHs), bis(2-ethylhexyl)phthalate, and total polychlorinated biphenyls (PCBs) observed in street dirt, sweeper waste, and catch basin sediment in the three paired sites for the Seattle Street Sweeping Pilot Study (WS = West Seattle, SS = Southeast Seattle, and DD = Duwamish Diagonal).

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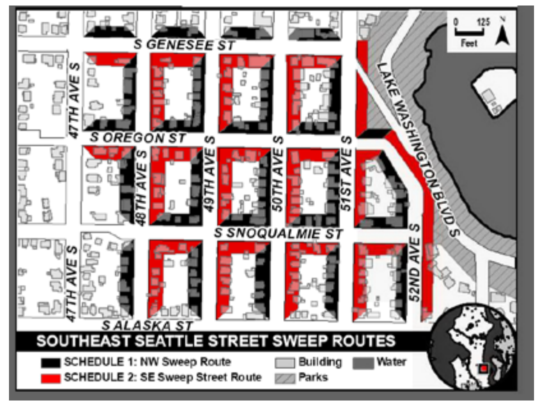
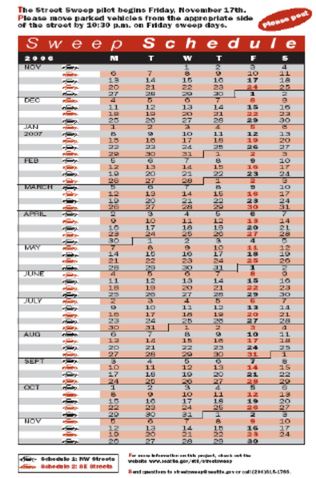
Street Sweeping Sign



Steet Sweep Route



Street Sweep Schedule

Figure 20. Examples of signs, routing information, and schedules used in the Seattle Street Sweeping Pilot Study.

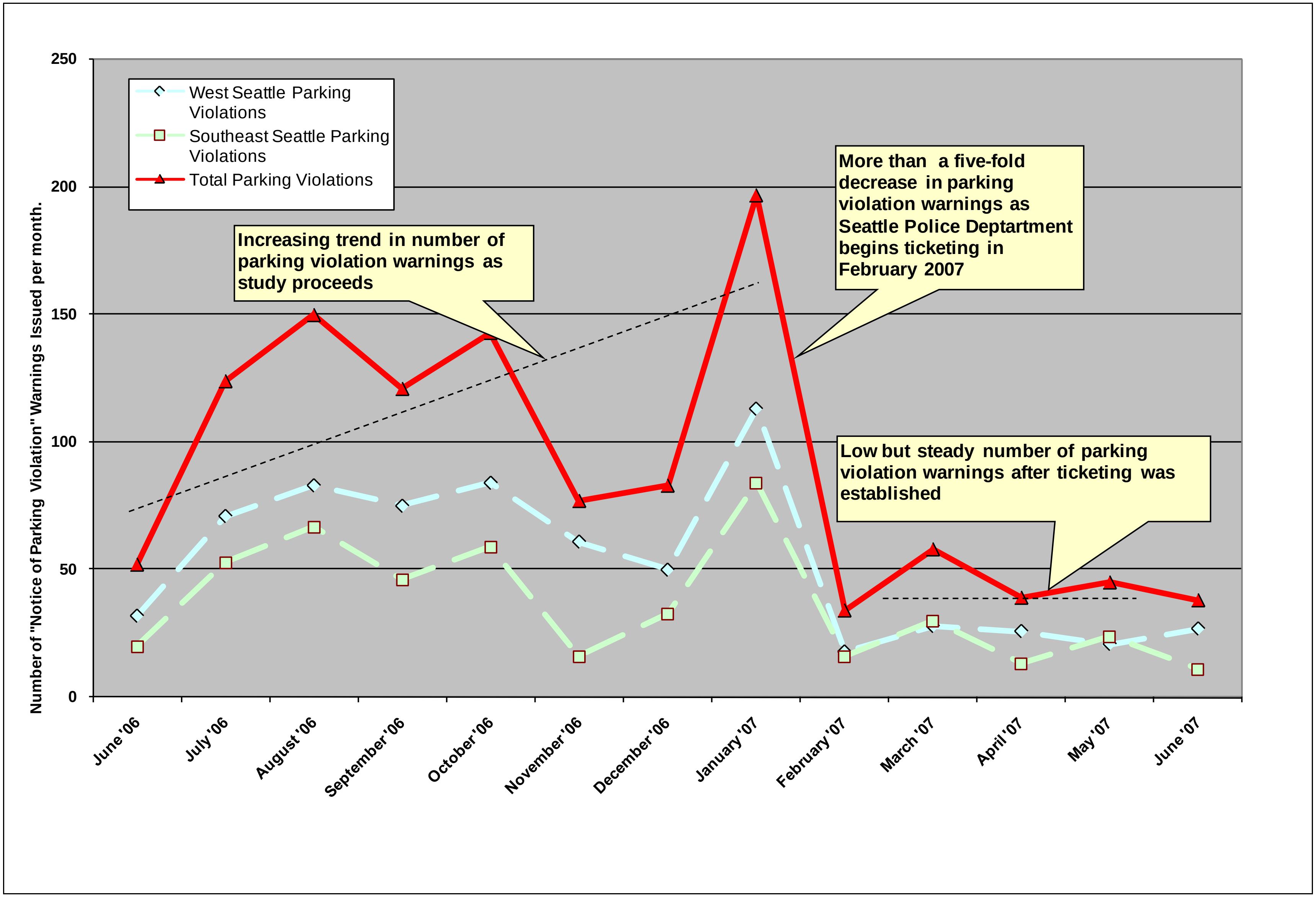


Figure 21. Parking violation warnings issued each month in the Southeast Seattle and West Seattle study area for the Seattle Street Sweeping Pilot Study

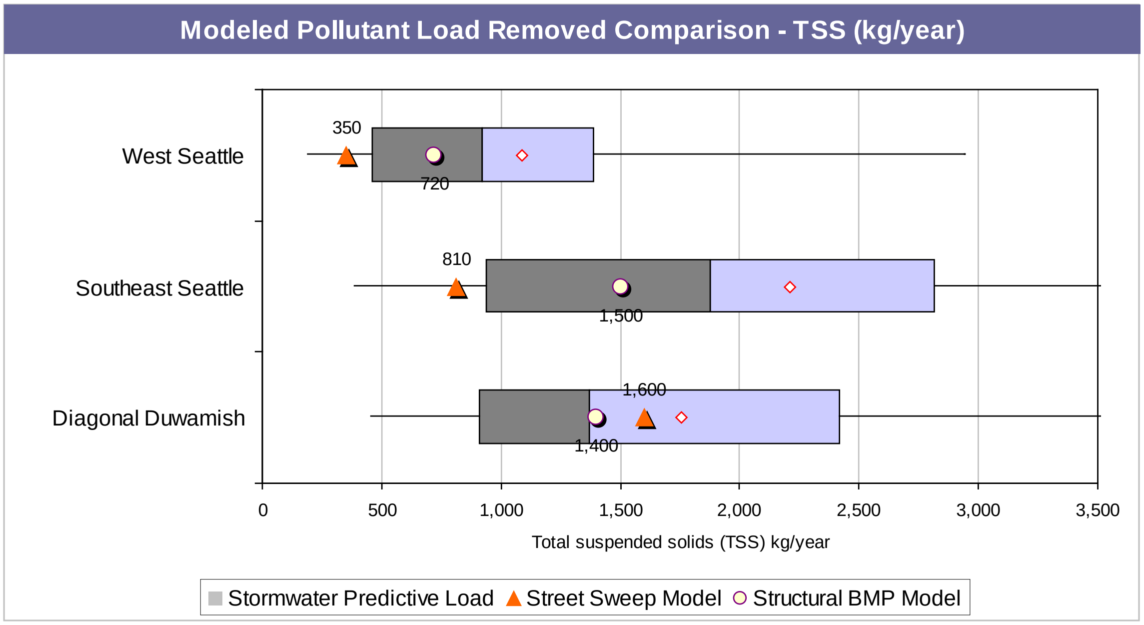


Figure 22. Total suspended solids load (kg/year) removed by street sweeping and structural BMPs compared to predicted load (vertical line = median, diamond = mean, box = 25th to 75th percentiles, whiskers = range).

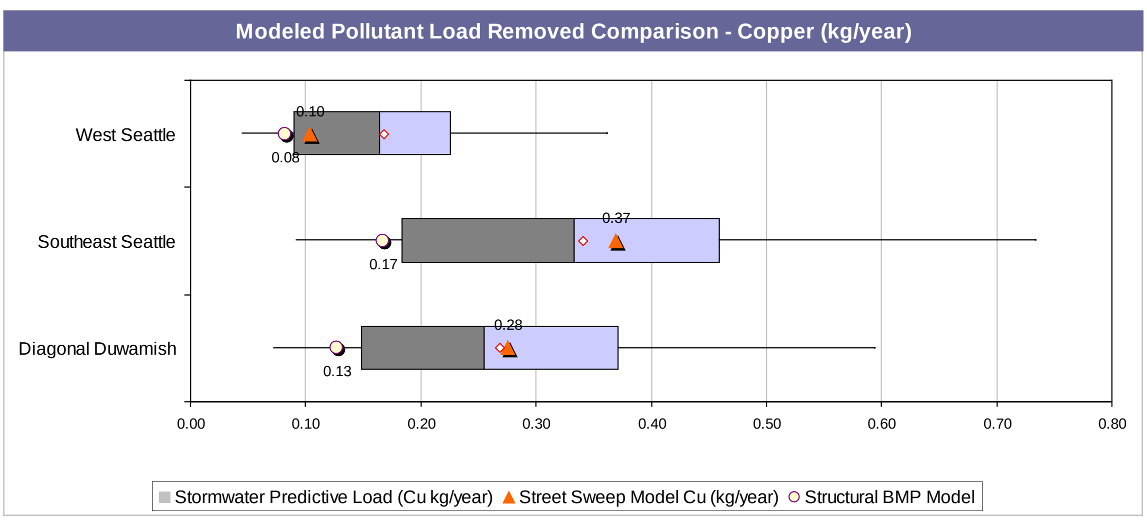


Figure 23. Total copper load (kg/year) removed by street sweeping and structural BMP compared to the stormwater predicted load (vertical line = median, diamond = mean, box = 25th to 75th percentiles, whiskers = range).