BASMAA

Tracking California's Trash (TCT) Project

Literature Review

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1. INTRODUCTION

This literature review was conducted as part of the Tracking California's Trash (TCT) project to evaluate the existing knowledge of monitoring methods for: 1) assessing the performance of street sweeping with and without partial capture devices in removing trash from public right-of-ways; 2) conducting on-land visual assessments to evaluate the effectiveness of trash control measures; and 3) conducting receiving water monitoring to quantify the concentrations and loads of trash transported via creeks, rivers and channels to bays, estuaries and oceans. This review also informed the TCT's Sampling and Analysis Plan (SAP) development. Conceptual monitoring program designs were previously included as part of the TCT Draft Monitoring Plan submitted to the California State Water Resources Control Board (State Board) on April 15, 2014.

1.1. Background

The State Board has placed a high priority on the development and adoption of Total Maximum Daily Loads (TMDLs), National Pollutant Discharge Elimination System (NDPES) permit requirements and other policies designed to significantly reduce trash in freshwater creeks, rivers, lakes, bays and estuaries in California. Prioritization has spawned the development of baseline trash loading studies from stormwater and the implementation of enhanced best management practices (BMPs) in the Los Angeles and San Francisco Bay regions. Information on the costs and benefits of these BMPs, however, is limited and monitoring methodologies needed to accurately measure progress towards TMDL and NPDES permit reduction goals have not been developed.

The TCT project will improve the collective knowledge of municipal stormwater program agencies and regulators regarding California's trash problems and the actions regulators, public agencies, and the concerned public can take to effectively resolve these problems. Project outputs include the development of rigorous and repeatable trash monitoring methods, an assessment of effectiveness and cost/benefits of specific trash reduction strategies, and development of a web-based portal that disseminates related information and recommendations to the public.

Specifically, the TCT project consists of three major tasks:

1. Developing Trash Trends Monitoring Methods:
    a. Receiving Water Trash Flux Monitoring Methods
    b. Stormwater Conveyance System Monitoring Methods
2. Evaluating the Effectiveness and Costs of Trash Control Measures
3. Developing a Web-based Portal to Disseminate Related Information

This literature review addresses TCT project tasks 1 and 2. The data users for the trash assessment and characterization methods developed through this study will be stormwater municipal program agencies, citizen monitoring groups, and regulators including the State Board and the Regional Water Quality Control Boards (Regional Boards).

The conceptual monitoring program design was previously included submitted on April 15, 2014. The detailed monitoring study design will be included in the Sampling and Analysis Plan (SAP). The SAP is based on a review of worldwide literature discussing methods previously used by researchers to measure trash in stormwater conveyances and receiving waters, and evaluate the performance of stormwater BMPs. The literature review is one of the Grant-required project tasks.

1.2. Literature Review Objectives

The objective of the literature review was to evaluate the existing knowledge of three aspects of the monitoring program:

- Street sweeping both with and without partial trash capture devices;
- On-land visual trash assessments; and,
- Receiving water monitoring for trash.

The following sections present summaries of the applicable studies identified and reviewed as part of the literature review. A summary of methodologies, pertinent findings and data gaps is included in the last section of this report.

2. Street Sweeping

Numerous scientific studies designed to quantify the effectiveness of street sweeping at removing various pollutants have been performed over the last 30 years. The majority of street sweeping studies have focused on the effectiveness of removal of sediments and the pollutants – such as PCBs, metals (i.e., mercury, copper, lead, zinc, etc.), petroleum products, chlorinated and organophosphate pesticides, and polybrominated diphenyl ethers (PBDEs) – associated with those sediments. However, some have focused on trash or gross pollutants. Additional knowledge may be obtained from studies that assessed the removal of gross solids or large particles, which act as a surrogate for trash, though there is a considerable difference in density.

The effectiveness of street sweeping at removing trash and other pollutants depends on the following four factors:

- The type and condition of street sweeper;
- Sweeping frequency and timing in relation to rainfall events;
- Operator attentiveness and speed; and
- The presence of obstructions (e.g., parked cars) which hinder the ability of the street sweeper to reach the curb.

Street sweeping studies have shown that under ideal conditions, street-dirt removal rates can be up to 99 or 100 percent for trash and particles in the coarse size range (Sutherland 2011, Sartor et al. 1974). However, the relationship between street trash/dirt removal and improvement in stormwater runoff quality has not been decisively described. Early studies in the 1970s conducted with the National Urban Runoff Program (NURP) concluded that street sweeping was not effective in reducing stormwater pollutants measured by end-of-pipe runoff concentrations (Sartor and Garbory 1984). Improvements in sweeping equipment and practices have greatly improved experimental outcomes (Sutherland and Jelen 1997, Sartor and Garbory 1984, Pitt 2004a) thus making this original conclusion refutable. Because early studies primarily focused on fine sediments and related pollutants, their findings are not necessarily applicable to the removal of trash. Further study is needed to determine the effectiveness of street sweeping as a control measure for trash pollution in stormwater conveyance systems. It should be noted that the effects of sweeping on water quality may be limited since roads are only one of several pathways in which trash may be transported to receiving waters.

Studies summarized below that specifically focus on trash include the following:

- New York City Floatables Control (Newman et al. 1996);
- City of Cape Town and Rainfall (Marais and Armitage 2004);
- Caltrans Litter Management Pilot Study (Lippner et al. 2001);
- Broom Sweeper Pickup Ability (Lippner and Moeller 2000);
- Cape Town Case Study (Marais et al. 2004); and
- New York City Computer Model (Riccio and Litke 1986).

2.1. Street Sweeper Type and Condition

Original research conducted in the early 1980s involved mostly mechanical broom sweepers. In the last decade or so, there have been technological changes in street sweepers with the introduction of advanced street sweeping equipment that includes regenerative air sweepers and vacuum assisted sweepers.

Vacuum assisted sweepers use a combination of mechanical brooms and brushes to dislodge dust and dirt and vacuum it up and into the hopper. A filter is also used to prevent dust and dirt from leaving the hopper.

Regenerative air sweepers use air in a closed loop system that blasts air under pressure in the form of jets to dislodge dust and dirt, and applies vacuum suction to lift the dust and dirt into a collection hopper. Air containing the fine road dust is cleaned (or regenerated) by filtering and is then directed under pressure to the road surface. Gutter brushes are used that extend out to the side of the sweeper to direct material in the gutter into the vacuum area.

Regenerative air and vacuum assisted sweepers have been found to be more effective at removing fine sediment (and associated pollutants) (Sutherland 2011), but there is not decisive evidence of their advantages in removing trash. Three studies found that the removal efficiency for coarse material was the same or higher when using vacuum or regenerative air sweepers compared to conventional mechanical broom sweepers (Breault et al. 2005, Sutherland 2011, and Sutherland and Jelen 1997). One trash-focused study reported that larger items can clog the vacuums in these systems (Lippner and Moeller 2000).

In addition to comparing sweeper type, many studies assess sweeper efficiency across particulate size ranges or across varied levels of initial street dirt or trash loading. Further descriptions of street sweeper types and practices are shown in Table 1.

Table 1. Descriptions of different street sweeper types and practices (Schilling 2005).

Type	Description
Mechanical Sweepers	This is most common type of street sweeper. Rotating gutter brooms remove particles from street gutters. Material is then swept onto a conveyor belt and into a storage hopper. Water spray is used to control dust.
Vacuum-assisted Sweepers	A gutter broom pushes particles from the street into the path of a vacuum intake that transports the dirt to the hopper. The transported dirt can be saturated with water.
Regenerative Air Sweepers	Regenerative air sweepers use re-circulated air to blast the pavement, dislodging litter before it is swept by rotating brushes towards a vacuum for pick-up. This sweeper also uses water sprays for dust suppression.
Scrubbers and Captive Hydrology (High Efficiency) Sweepers	These sweepers, mainly used in Britain, include brooms directed into pick-up heads with a high-pressure washer system followed by intensive vacuum pressure. Water is recycled within the machine.
Tandem Sweeping	One sweeper immediately follows another. Usually, a less efficient sweeper (e.g. mechanical) is followed by a more efficient type (e.g. vacuum-assisted or regenerative air)

The most important measure of effectiveness is the improvement of runoff water quality and loads to receiving waters. This is measured by monitoring the runoff at some location downstream of the road segment during swept and unswept periods. Although few studies of sweeper performance include runoff measurements, this was one criteria used in selecting literature sources to review.

Water Pollution Aspects of Street Surface Pollutants (Sartor and Boyd 1972)

Sartor and Boyd (1972) conducted one of the first comprehensive studies to characterize pollutants on street surfaces and to evaluate the effectiveness of street sweepers. Sampling was conducted in various cities throughout the United States, including San Jose, Phoenix, Milwaukee, Baltimore, Seattle, and Atlanta. Sartor and Boyd found that a disproportionate amount of some pollutants were associated with the solids finer than 248 microns (µm). For example, fine particles less than 246 µm constituted about 37% of the mass of solids on the street surface.

In-situ street sweeper tests were limited to mechanical broom sweepers and were conducted in Milwaukee, Baltimore, Scottsdale, Phoenix, Atlanta, and Tulsa. Effectiveness was determined by measuring the accumulated dust and dirt (using hand sweeping and flushing with water) before and following the passage of the sweeper. The test results indicated that broom sweepers removed on average approximately 50% of the dust and dirt per pass of sweeper, but 70% of the material removed was particle sizes greater than 246 µm.

A set of controlled street sweeper tests were conducted in San Jose where a prescribed amount of a synthetic material (with representative size distribution) was spread evenly over a previously clean road segment. Six tests were conducted and the removal effectiveness per single pass of sweeper ranged from 26% to 77% depending on the sweeper type and sweeper speed (higher effectiveness for slower speeds).

The study also provides an excellent discussion of the factors that affect street sweeper efficiency including loading factors (mass level, particle size, and uniformity), road surface condition (type and condition), sweeper type, and sweeper operation (speed, frequency of sweeping, and availability of gutter broom), and operator skill. Climatic conditions, including rainfall amounts, intensity and pattern also are important.

Street Sweeping can be an Effective BMP (Sutherland and Jelen 1997)

Sutherland and Jelen (1997) evaluated the abilities of three different sweeping technologies to remove accumulated sediment of various sizes using a computer model to simulate interactions of sediment accumulation, washoff, and street sweeper pickup over a period of time, calibrated from real data. The studies used in development of the model showed that sweeping removes little, if any, material below a certain base residual. The amount of sediment removed by sweeping is linearly related to the initial accumulation (i.e. street dirt loading) and also depends on the base residual and sweeping efficiency. The modeled relationship is as follows, for any loading greater than the base residual:

*Amount Removed = Street Sweeping Efficiency * (initial accumulation – base residual)*

The calibrated base residual is shown in

Table 2 and calibrated sweeper efficiencies are shown in Table 3. According to Table 3, the mechanical sweeper and tandem operation leave behind more particles at most size ranges than the regenerative air or vacuum sweepers.

Table 3 and 3 show clear improvement from older sweeping equipment.

Table 2. Sweeper base residual (lbs/paved acre) by particle size ranges (Sutherland and Jelen 1997).

Size Range (microns)	1978 Mobil Mechanical	1988 Mobil Mechanical	Tandem Sweeping*	Elgin Crosswind Regenerative Air	Enviro-Whirl Vacuum
<63	9.0	5.8	2.0	0.0	0.0
63-125	12.0	5.8	2.0	0.0	0.0
125-250	18.0	5.3	2.3	0.9	0.0
260-600	18.0	2.5	2.3	1.9	0.0
600-1000	12.0	0.4	0.8	0.7	0.0
1000-2000	4.2	0.5	0.6	0.7	0.0
2000-6370	3.6	0.3	0.5	0.0	0.0
>6370	1.8	0.0	0.0	0.0	0.0

*** Mobil mechanical broom sweeper followed by TYMCO vacuum-assisted sweeper**

Table 3. Sweeper efficiencies by particle size ranges (% removal rate for initial accumulation greater than the base residual) (Sutherland and Jelen 1997).

Size Range (microns)	Mechanical (1978)	Mechanical (1988)	Tandem Sweeping	Regenerative Air	Vacuum
<63	44	100	93	32	70
63-125	52	100	95	71	77
125-250	47	92	93	94	84
260-600	50	57	89	100	88
600-1000	55	48	84	100	90
1000-2000	60	59	88	100	91
2000-6370	78	81	98	94	92
>6370	79	70	87	92	96

Pickup of High Efficiency Sweepers (Kidwell-Ross 2000)

Another form of advanced equipment is a high-efficiency sweeper, such as the Schwarze Model EV2 sweeper. When a high-efficiency sweeper (Schwarze Model EV2) was operated in tandem behind a mechanical broom sweeper (Schwarze M5000), the EV2 picked up 141 percent more than the mechanical broom. Similarly, the EV2 was operated in tandem behind a regenerative air sweeper (Schwarze A7000) and picked up 44 percent more than the regenerative air sweeper. The debris removed by the high-efficiency sweeper is likely composed primarily of smaller particles.

The Role of Street Cleaning in Stormwater Management (Pitt 2004a)

The authors present a review article that summarizes research conducted by them and others, including data on street sweeping effectiveness in several locations including Castro Valley, California, Bellevue Washington, and Milwaukee Wisconsin. Early street sweeping tests using mechanical sweepers indicated that street dirt removal was higher for the coarser fraction and for dirtier streets. If the loadings of the 500-1000 µm fraction were less than 75 kg/curb-km (about 100 lbs/curb mile) conventional sweeping was not effective. For higher loading, the removal performance could be in the range of 25-50%. The Milwaukee data indicated a 40% reduction in solids concentrations at the outfall at the 80% confidence level, one of the first statistically reliable documentation of stormwater quality being improved due to street sweeping.

New technology sweepers such as regenerative air sweepers showed improved performance for removing finer particles, especially in areas with intermediate street loadings. A hypothesis presented is that the higher loadings of large particles may armor or cover the smaller particles, making them more difficult to remove.

Test results using advanced street sweeping technology (Schwarze Industries Enviro Whirl I) for a freeway segment in Milwaukee, Wisconsin indicated a 25% reduction in street dirt while the dust and dirt load at the unswept control site increased 160%. Data indicates that the Enviro Whirl I removed about 50% of the street dirt when the loading was about 500 lbs/curb mile. Removal was zero when the street loading was about 100 lb/curb/mile. This performance is similar to the regenerative air sweeping results achieved in Bellevue, Washington, and is much better than mechanical street cleaning performance tested in some of the earlier programs.

Review of Historical Dust and Dirt Accumulation and Washoff Data (Pitt et al. 2004b)

The authors review and discuss the empirical data available to properly characterize the dust and dirt buildup washoff routines in mathematical models and provide a summary of studies conducted as of the publication date (Pitt et al. 2004b).

The paper summarizes much of the data on initial and ultimate street dirt loading and deposition rates collected by the authors and others, including data from San Jose and Castro Valley, California. Initial (or residual) loadings following intensive street cleaning ranged from 35-85 gm/curb-meter (140-340 lbs/curb mile) for smooth and intermediate textured streets, and from 220 to 510 gm/curb-m (880 – 2000 lbs/curb mile) for rough textured streets (the upper end of the range corresponds to what is referred to as an “oil on screens” overlay applied to asphalt roadways in need of repair. The residual load is the load that remains on the roadway even after intensive sweeping and typical rain events.

The ultimate load on the road is the maximum that would be obtained during dry conditions and no sweeping. The maximum observed loading in grams per curb meter (g/curb-m) varied from 140 – 230 g/curb-m (560 – 920 lbs/curb mile) for smooth and intermediate textured conditions, to 430 -710 g/curb-m (1720 - 2840 lbs/curb mile) for rough textured streets with again the high end of the range corresponding to “oil and screens”. The time required to reach these levels was inversely related to road condition and varied from 30 days for very poor conditions to 50-70 days for fair or good conditions. Accumulation of dust and dirt on roadways is not a linear process and much of the ultimate load is achieved within 1-3 weeks following the initial loading state.

Of particular interest is the discussion of washoff data that is generally less available in the literature, and refers to tests using simulated rainfall to examine the characteristics of the particles mobilized in the tests. A key finding is that typical rain events ranging from 10-30 mm (approximately 0.5-1 inch) tend to mobilize primarily the finer fraction (<63µm) of dust and dirt, and the organic coarse material that is lighter in density. The median particle size of dust and dirt in the washoff tests ranged between15-50 µm. This fine fraction may only account for 10-20% of the dust and dirt mass on the roadway, and typical storms may remove about 50% of the total fine fraction, or 5-10% of the total loading. These estimates are for typical rains on smooth roads. For low intensity rains on poor condition streets the amount removed is less.

The majority of the coarse fraction of dust and dirt remains on the roadway following typical rainfall events. This fraction is then preferentially removed by mechanical and other types of street cleaning equipment, or very intense rainfall events. Data indicates that washoff loads tend to increase only when rainfall intensities reach about 15 mm/hr (approximately 0.6 in/hr).

Residential Street-Dirt Accumulation Rates and Chemical Composition, and Removal Efficiencies by Mechanical-, and Vacuum-Type Sweepers (Breault et al. 2005)

The authors report on a street sweeper study conducted on two streets in New Bedford, Massachusetts in 2003 and 2004. Street dirt collected by the city using hand-held vacuums, and street-dirt hopper samples were analyzed for particle size distribution, elements, and organic compounds.

The study evaluated the effectiveness of two types of sweepers (mechanical and vacuum assisted) by applying a known mass of dirt to a street and measuring the mass of dirt picked up by each sweeper type. The know mass of dirt consisted of gravel (22%), coarse sand (44%), fine sand (22%), very fine sand (9%), and silt and clay (about 6 %). Overall, street sweeper efficiencies ranged from about 21-31% for the mechanical sweeper and 60-92% for the vacuum sweeper. The vacuum sweeper efficiency was higher for all particle size classes from gravel to silt/clay.

Evaluation of Street Sweeping as a Stormwater-Quality Management Tool in Three Residential Basins in Madison, Wisconsin (Selbig and Bannerman 2007)

Selbig and Bannerman (2007) conducted an extensive street sweeping study in Madison, Wisconsin using a paired basin approach to compare relationships between street sweeping, street dirt removal, and stormwater quality. Three street sweeper types were evaluated in the study (vacuum, regenerative air, and mechanical) at a frequency of once per week. For assessment of street dirt removal using mechanical brooms only, two frequencies were tested (once per week and once per month).

Selbig and Bannerman describe the paired basin method as follows:

"The basis of a paired basin approach is that the relation between paired street-dirt and water-quality loads for the control and test basin is valid until a major change is made at one of the basins. At that time, a new relation will develop. Changes in either street-dirt and/or water quality as a result of street sweeping could then be quantified by use of statistical tests."

Street dirt samples were collected before and after each weekly sweep by vacuuming several narrow strips across the street width (sampling vacuum is described in detail in the report). Each vacuumed strip began at one curb edge and stretched across the street to the other curb edge. The study also included a test to examine the reproducibility of street-dirt sampling procedures. The average rate for sampling collection vacuuming was about 1 foot per second. However, care was taken to move the vacuum nozzle more slowly over rougher, pitted street surfaces in order to collect all material in the sample. Basins were equipped with monitoring stations to measure stormwater runoff water quality data (dissolved solids, metals, and nutrients). Particle size analysis was conducted on street dirt samples and runoff samples.

The effectiveness of street sweeping can be expressed in terms of pickup efficiency, reduction in overall street dirt yield (accumulation), or water quality improvements. Pick up efficiency is the % of material removed per sweeping, whereas the reduction in overall dust and dirt accumulation (expressed as lbs/curb mile) is a measure of the cumulative effect of sweeping at, in this case, the weekly frequency. Selbig and Bannerman analyzed pickup efficiency as a function of particle size and found that mechanical broom pickup efficiency ranged from a high of approximately 20% for large (>2000µm) to negative values for small (<63 µm) particles, which indicated to the authors that the mechanical broom sweepers could potentially be grinding up larger particles and thereby increasing the mass of finer particles. The pickup efficiency for regenerative air sweepers varied from about 30% for larger particles to negative values for smaller particles. Vacuum assisted sweepers showed positive efficiencies over the range of particle sizes from about 10% for smaller particles to about 50% for larger particles. The average pickup efficiencies for each sweeper were 5% for mechanical broom, 25% for regenerative air, and 30% for vacuum assisted.

The study indicated that all sweepers reduced the accumulation of dust and dirt (street dirt yield) on the swept streets when compared to the unswept control. The reductions were on average 20 % for the mechanical broom, 76% for the regenerative air, and 63 % for the vacuum assisted. (The 20% effectiveness for the broom sweeper was primarily associated with removing larger particles associated with winter application of friction materials and might not apply to Bay Area conditions.) Statistical analysis indicated that these reductions were statistically significant at the 5% significance level. Statistical analysis of event mean concentrations and loads of pollutants in the runoff failed to show a difference, which the authors attributed to the variability in the runoff data, and the inadequate number of samples in the data set.

Seattle Street Sweeping Pilot Study (Herrera 2009)

This study applied a mass balance approach to determine the amount of materials and associated pollutants on streets and in catch basins (with a sump), and how that balance might be affected by street and catch basin cleaning. The mass balance is calculated based on the following components of street dirt and sediment:

- Dirt remaining on street (i.e., street dirt)
- Dirt removed by street sweeper (i.e., sweeping debris)
- Dirt that accumulates in storm drain inlets (i.e., storm drain inlet sediment)
- Dirt exported from the site in urban runoff (estimated through mass balance).

The mass balance approach was selected after it was concluded from a power analysis that a runoff monitoring study sufficiently robust to evaluate the benefits of sweeping on water quality was too expensive. The studies were conducted at three sites representing residential and industrial land uses that had an area consisting of 4-15 blocks. Each site was divided into swept (test) and unswept (control) portions consisting of similar land uses, topography and number of storm drain inlets. The test sweeping involved sweeping either side of the street weekly, so the frequency of sweeping each side of the street was once every two weeks. The sweeper used was a Schwarze Industries Model A8000 regenerative air sweeper. 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 mass of street dirt, sweeper waste, and catch basin sediment was measured approximately every four weeks. Street dirt samples were obtained using a hand-held industrial vacuum on swept and unswept road segments one to two days prior to sweeping. Sweeping debris was collected and stored in separate dumpsters assigned to each test site. Debris greater than 2 centimeters in diameter was removed and weighed separately to determine the proportion of debris in the swept material. Material accumulated in catch basins was also collected from 12 inlets among test and control sites.

Study results indicated that sweeping at the biweekly frequency with this type of sweeper reduced the amount street dirt on the road (referred to as street dirt yield) in all three sites by 48, 74, and 90 percent compared to the controls. The lowest effectiveness was associated with the industrial site. Test results indicated that street sweeping removed at least 80 percent more material than catch basin cleaning, but the results did not indicate that sweeping affected the amount or rate of sediment accumulation in the test area catch basins.

The study concluded that street sweeping, with an estimated life cycle cost for removal is approximately $5 per kilogram dry TSS is cost effective compared to regional-scale treatment where the cost is estimated at $10 - $30/kg.

Herrera also evaluated the effects of street sweeping once every two weeks on accumulation of materials in catch basins with the intent of determining if street sweeping might affect the need for or frequency of catch basin cleaning. The evaluation was based on monitoring the accumulation of sediments in 12 catch basins located in each of the three test areas that were subject to a period of sweeping and a period of non-sweeping. The duration of the study was one year for two of the test sites, and eight months for the third test area.

Test results did not show that street sweeping every other week affected the rate of sediment accumulation in the test area catch basins, which indicates that sweeping may not reduce the frequency at which catch basins would need to be cleaned. The tests indicated that during the testing periods, the actual accumulations in the catch basin during the swept periods either remained the same or actually increased somewhat, although not statistically. The authors point out that the accumulation rates in the catch basin were such that the catch basins were less that 10 percent full, and the short study period as well as monitoring by measuring down to the surface of the sediment was subject to some uncertainty.

One interesting result is that the amount of sediment removed from street sweeping was higher by as much as a factor of five to the amount of sediment accumulated in catch basins. For both sites (total of 12.7 ac) on an annualized basis, sweeping is estimated to have removed approximately 33,800 lbs (15,400 kg) of dry sediment, while annual cleaning of catch basins in the area is estimated to have removed about 6,200 lbs (2,800 kg) dry sediment.

Thus, street sweeping carried out on a bi-weekly schedule at these test sites is much more effective in terms of sediment removed than annual catch basin cleaning.

Estimated life cycle costs for a full-scale street sweeping program ($0.34 per wet kilogram of material removed and $0.62 per dry kilogram of material removed) are generally lower than the costs for the SPU city-wide catch basin cleaning program ($0.42 per wet kilogram and $0.74 per dry kilogram). Inspection, cleaning, material handling, and disposal costs were included in the estimate. Catch basin cleaning costs vary widely on a dry weight basis ($0.47 - $1.36 per dry kilogram of material) depending on the estimated moisture content.

Real World Street Cleaning Pickup Performance Testing (Sutherland 2011)

Street dirt pickup performance tests for five different Elgin sweeper models was conducted over three days on a curbed test track under a tent within a parking lot. While trash was not considered in this study, the particles collected were separated into seven (7) different size ranges from smaller than 63 microns to 6370 microns (6.37 mm). Often, trash can fall into the coarsest size range. To conduct the study, a known quantity of street dirt was applied to the test area and after a pass by the sweeper, the remaining dirt on the street is removed with a shop-vac and sampled for analysis.

The pickup performance efficiencies by particle size range for the five sweepers are shown in Table 4. The regenerative air and vacuum sweepers are comparable, and both types are more efficient than the mechanical broom sweeper. However, as particle size increases (and becomes more representative of trash), the difference in efficiency between the equipment types is reduced. For the mechanical broom sweeper (Eagle with water), the use of water spray to control dust reduces the sweeper's ability to pick up particulate material.

Table 4. Sweeper pickup performance efficiency (%) by particle size range. (Sutherland 2011)

Size Range (microns)	Crosswind (NX) Regenerative	Crosswind Regenerative	Whirlwind (MV) Vacuum	Eagle (FW) Mechanical	Eagle (FW) w/water Mechanical
2000-6370	99.4	99.4	99.3	95.9	95.8
1000-2000	98.5	98.7	98.2	93.3	91.2
600-1000	97.8	98.1	96.3	93.1	88.3
250-600	97.9	97.6	93.5	93.4	84.2
125-250	97.7	95.7	89.6	91.1	72
63-125	97	93	86.5	89.9	68.7
<63	90.8	89.4	93.5	78.1	68.2

2.2. Street Sweeping Frequency and Timing

There are two factors which affect the efficiency and effectiveness of street sweeping schedules. Increasing sweeping frequency decreases the load of solids that enter storm drains. This is apparent as the rate of street sweeping becomes more frequent than rainfall events, which can transport trash and other solids to storm drain inlets (Marais and Armitage 2004). However, as the load of dirt or solids on roads decreases, the efficiency (percent solids removal) of the sweeper decreases (Pitt 2004a, Pitt and Shawley 1981). This suggests that diminishing returns are likely as street sweeping frequency is increased past a certain point (i.e. at higher frequencies, the marginal increase of sweeping will produce lower gains in efficiency) (Newman et al. 1996). Optimal frequency will depend on the level of effectiveness required and the resources available for the sweeping program.

San Francisco Bay Area Nationwide Urban Runoff Program, A Demonstration of Non-Point Source Pollution Management on Castro Valley Creek (Pitt and Shawley 1981)

Pitt and Shawley (1981) conducted a two year study of the effectiveness of street sweeping at sites located within the Castro Valley Creek watershed. In partnership with the Alameda County Flood Control District and the USGS, Pitt and Shawley monitored street sweeping effectiveness (as measured before and after sweeping by mechanical or regenerative air sweepers), street surface pollutant accumulation, precipitation, and runoff quantity and quality.

Tests were conducted using mechanical and regenerative air sweepers working either side of a road segment and alternating sides to ensure comparable initial (pre sweeping) loadings. Most of the street cleaning tests used modern, mechanical, four-wheel brush-type cleaner. Cleaning frequency varied during the first year, and then in the second year the frequency was 5 times/week for one month, followed by two months of no sweeping. The sweepers were operated about every 3 or 4 days for the first part of December 1979 for a total of 24 test runs for each sweeper type. Total solids, lead, arsenic, chemical oxygen demand, and phosphorus were measured by sampling before and after each sweeping pass.

The regenerative air sweeper was found to be slightly more effective than the broom sweepers but effectiveness was dependent on the initial loadings. If the initial loading was approximately 400 lbs/curb mile, the regenerative air sweeper effectiveness was approximately 61% compared to the broom sweeper effectiveness of 53%. If initial loading was 850 lbs/curb mile, the regenerative air sweeper effectiveness was estimated at 69% compared to 64% for the mechanical broom sweeper.

Sweeping could not reduce the surface loadings to below 200 lbs/curb mile irrespective of sweeping frequency. The authors suggest that to realize the maximum benefit of street sweeping for water quality improvement, streets should be cleaned more frequently prior to and during the wet season (between adjacent storm periods).

Findings showed that three passes per week was the point at which diminishing returns were observed. As frequency surpassed three time a week, the marginal gains from sweeping (measured by reduction of total solids in runoff) were reduced. After four times per week, gains were minimal. While increasing sweeping beyond three times a week produced smaller returns in water quality, increasing from weekly to twice weekly more than doubled total pollutant removal. By comparing the watershed loads during runoff events with the initial road surface loadings in the watershed, the authors indicate that a maximum of 20% of the total solids could have been removed from the runoff if twice weekly sweeping were conducted.

A survey of street cleaning practices in Alameda County indicated that commercial areas received the most frequent cleaning (estimated on average as every other day) with industrial areas being cleaned on average once per week. The study recommended that more frequent cleaning of industrial areas with less frequent cleaning of commercial areas could result in water quality benefits.

Review of Street Sweeping Knowledge (Sartor and Gaboury 1984)

In the late 1970s, street sweeper effectiveness began to be measured in terms of reduction in end-of-pipe runoff concentrations and loads rather than street dirt removed by specific equipment. However, it was concluded that sweeping was not effective in reducing end-of-pipe loads of stormwater contaminants. Some early studies were conducted in San Jose and within the San Francisco Bay area. The authors also determined that under favorable conditions, a 30% percent reduction could be expected in end-of-pipe contaminant loads. Typical street sweeping performance would likely reduce loads by 10 to 30% but certain constituents (e.g., lead) where street surfaces are overwhelming sources could result in load reductions up to 50%. Given the advances in sweeper technology and the relatively large size of trash in comparison to contaminants initially studied, it is plausible that current trash load reductions from street sweeping could be much higher.

The following factors influencing street sweeping effectiveness:

- **The amount of particulates accumulated on street surfaces,** which is in turn affected by:
    - Local meteorology – the frequency and intensity of rainfall, storms, and wind

    - Uses of streets and adjacent areas – land use, traffic patterns, and parking
    - Street surface conditions – type and age of pavement, gutters and curbs (e.g. cracks in pavement can store dirt and trash not easily moved by rain, wind, or sweeping)
- **Sweeping operations**
    - Sweeper type, operational speed, and operator skills
- **Sweeping program**
    - Sweeping frequency, effectiveness of parking restrictions, and number of passes made by sweeper

It was also noted that removal efficiency increased with increasing particle size, which supports the idea that trash removal efficiencies would have been higher than fine sediment or dissolved material removal efficiencies.

Time intervals are dominant influences on sweeping effectiveness, specifically inter-storm and sweeping intervals. If the average time between runoff events is much less than the sweeping interval, street contaminants would be routinely washed away. For sweeping to be "efficient" (approximately 30 %), sweeping intervals must be at most two times the inter-storm period. To achieve higher removal rates (greater than 50%), the sweeping interval must be ½ to 1 times the inter-storm period.

New York City Floatables Control (Newman et al. 1996)

The impact manual trash removal has on floatable trash loads was studied on a 15-blockface area in New York City. For one month, the test area received one of the following degrees of cleaning:

1. Baseline – current street sweeping practices that entail two mechanical sweeps per week.
2. Level 1 – augments baseline with four manual sweeps per week. Each blockface is swept once a day for six days.
3. Level 2 – augments baseline with 10 manual sweeps per week. Each blockface is swept twice per day for six days.

Samples were collected once a week with a broom and did not include vegetation, sediment, and other items under parked vehicles. The collected material was weighed, sorted into 13 categories and evaluated as floatable. Item counts, total weights, wetness, and loose pack density were also measured. Overall, there was a much greater difference in trash reduction from the baseline to Level 1 than from Level 1 to 2. The incremental percent reduction in baseline street floatables by item count, surface area, and weight for different land use types is provided in Table 5.

Table 5. Incremental percent reduction in baseline street floatables by items count, surface area and weight for different land use types.

Predominant Land Use Type	# Blockfaces	Incremental % Reduction in Baseline Street Floatables					
		Item counts		Surface Area		Weight	
		Level 1[a]	Level 2[b]	Level 1	Level 2	Level 1	Level 2
Low Density Residential	2	3	47	10	36	48	11
High Density Residential	3	46	10	51	10	54	23
Commercial	4	42	0	47	0	69	-8
Industrial	2	64	2	70	2	78	-15
Vacant/Parking Lots	1	72	12	66	18	83	9
Parks/Institution	1	58	-9	88	-20	95	-5

[a] (Baseline-Level 1)/Baseline*100
[b](Level 1-Level 2)/Baseline*100

On average, there was at least a 50% reduction in floatables when blockfaces were swept six times per week (Level 1) to blockfaces swept twice per week (Baseline). The incremental increase from Level 1 (six times per week) to Level 2 (12 times per week) was at most 10%. Levels 1 and 2 had little impact on low density residential areas (with very low loads) and had the most impact on streets near vacant lots where the highest loads were observed. Several blockfaces in Business Improvement Districts (BIDs) were included in the study. It was found that those blocks had a 75 percent reduction in item counts (at the Baseline level) compared to those without BIDs.

Effectiveness of Street Sweeping for Stormwater Pollution Control (Walker and Wong 1999)

The objective of this study was to examine the effectiveness of street sweeping for controlling gross pollutants (all solids greater than 5 mm in diameter, including trash) and sediment (and associated pollutants). The authors interpreted Australian and other field data on street sweeping and gross pollutants. A survey of Melbourne, Australia municipalities found that residential areas are swept every two weeks to every six weeks; commercial areas are swept daily to every two weeks; and shopping and commercial are swept once or twice a day in busy areas and once or twice a week in less popular areas.

The authors define street sweeping effectiveness as the reduction in the end-of-pipe runoff pollution concentrations and loads, and not the effectiveness of specific equipment. Street sweeping effectiveness is more dependent on land use activities, inter-event dry period, street sweeping frequency and timing, access to source areas, and sweeper operation than the actual street sweeping mechanism efficiency.

The authors illustrated the relationship between gross pollutant loads in stormwater conveyance systems and the magnitude of storm events (**Error! Reference source not found.**). It is a monotonically increasing logarithmic function and indicates a possible upper limit. This upper limit may represent the deposited load available to be transported to the stormwater conveyance system. Enhancing street sweeping frequency or effectiveness could potentially reduce this upper limit value and thereby alter the shape of the gross pollutant export curve.

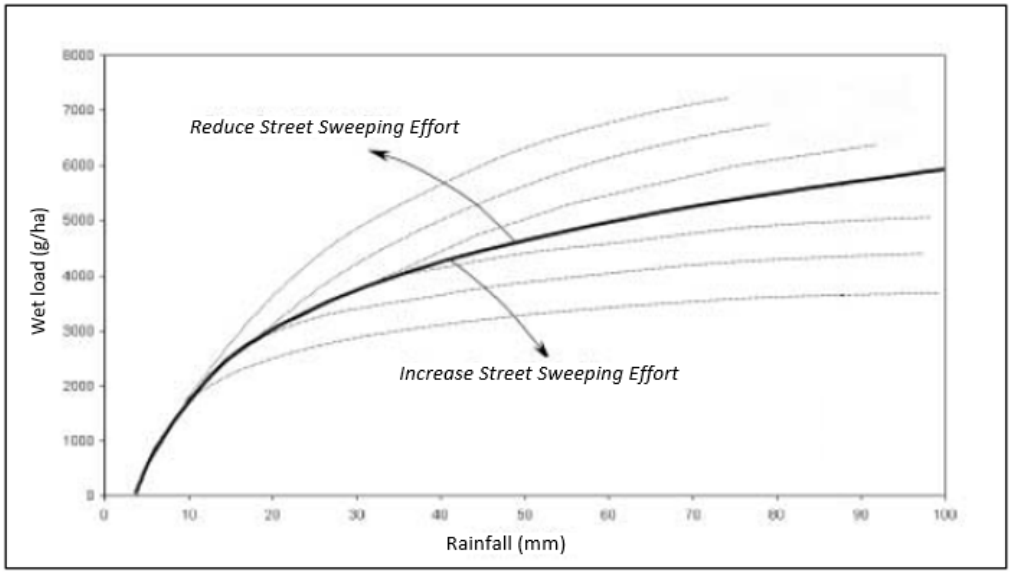

Figure 1. Hypothetical Gross Pollutant Load and Street Sweeping Effort (Walker and Wong 1999, initial curve based on data from Allison et al. 1998)

Other pertinent findings include the following:

- There is a minimum threshold load of sediment on the street surface before mechanical and regenerative air sweepers become effective. The threshold can be three times higher for mechanical sweepers;
- The performance of regenerative air sweepers is better than mechanical sweepers;
- Significant amounts of gross pollutants are mobilized into stormwater conveyance systems during bursts of rain and/or wind;
- The fraction imperviousness of a catchment area influences runoff, thereby affecting the available energy for mobilization of gross pollutants;
- Street sweeping effectiveness increases with particle size and can be up to almost 80 percent for particles greater than 2mm under ideal conditions (when sweeping is more frequent than rainfall occurrence and parking restrictions are in place);
- If sweeping occurs at longer intervals than inter-event dry periods, there is a higher likelihood that pollutants will be flushed into stormwater conveyance systems before being collected by sweepers;
- Gross pollutant wash off becomes significant for storm events larger than 3.7 mm in rainfall and 0.70 mm of runoff;
- The limiting mechanism affecting the amount of gross pollutants entering the stormwater conveyance system is dependent on rainfall (for re-mobilization and transport) not on source loading;
- Commercial areas produce twice the gross pollutants of residential areas and three times more than light industrial areas, despite higher sweeping frequencies.

Analysis of Street Sweeping Data for Alameda Countywide Clean Water Program (EOA 1999)

Alameda Countywide Clean Water Program member agencies document monthly sweeping and submit the data as part of their Annual Report. Agencies included Alameda, Alameda County, Berkeley, Hayward, Livermore, Newark, Oakland, San Leandro, and Union City. The data for all the agencies were combined except for Oakland, which was analyzed separately as it represents approximately 50% of the miles swept in the county.

Agencies use a standard form to record the volume of material (cubic yards) and miles swept (curb-miles) for residential, commercial, industrial and other areas by sweeper type. The distance swept is measured by broom odometer or by tracking mileage when sweeping. The volume collected is determined by visually estimating the cubic yards of material in the sweeper hopper. Cities who measure weight of material (Albany, Dublin, Fremont, and Pleasanton) obtain weight tags from landfills or transfer stations where the material is disposed.

Study data was compiled for dry months (May – September) in order to minimize the influence of rainfall wash-off effects on conclusions about accumulation and removal rates. This study found that increasing sweeping frequencies to twice a month did not affect material removal rates (assumed once per month initial rate). Therefore, the findings suggest that the maximum accumulation period of material is less than two weeks.

For the agencies other than Oakland, the estimated total annual removal rates varied from about 0.28 to 0.36 cubic yards per curb mile (yd^3/curb mile). Estimates for the dry season only ranged from 0.25 to 0.30 yd^3/curb mile. Removals in commercial areas (0.26-0.30 yd^3/curb mile) were comparable to removals in industrial areas (0.24-0.35 yd^3/curb mile). The data reported were highly variable and statistical analysis of the annual data before and after changes in street sweeping frequency and other factors such as the issuance of parking citations indicated only limited differences.

For the City of Oakland, the total annual removal rates ranged from 0.33 to 0.42 yd^3/curb mile depending on the year, with the lowest removal rates in commercial areas (0.21 to 0.29 yd^3/curb mile), and highest removal rates in industrial areas (0.36 to 0.77 yd^3/curb mile). Dry season data indicated high removal rates in industrial areas during FY 92/93 (2.3 yd^3/curb mile) and FY 93/94 (1.08 yd^3/curb mile).

The data were converted to lbs/curb mile by multiplying by 6.43 lbs/gallon which was an average density measured in the City of San Mateo. Using this conversion factor, the overall removal rate for the county ranged from about 260 to 520 lbs/curb mile. The data reported included trash and vegetative debris, so the estimate of mass removed could be biased high.

Broom Sweeper Pickup Ability (Lippner and Moeller 2000)

This study was conducted to evaluate the reduction potential of a mechanical broom sweeper on highway trash using a triplicate paired watershed approach. The authors did not choose a regenerative-air sweeper because during field tests, large material often became lodged in the air intake hose of air sweepers. When air sweepers become clogged, other material is pushed along the street (causing a 'snow plow' effect) until it passes over and is deposited into a storm drain. This effect is reduced when sweepers are run in tandem. Instead, a Mobil model M-8A broom sweeper swept three watersheds monthly and the other three were swept weekly. A comparison of the end-of-pipe discharge was made using mesh bags (with one-quarter inch openings) attached to outfalls for two rainy seasons and 21 storms (October 1998 to April 2000).

The study found that most trash collected was less than 1.5 inches (38 mm) in size, the same size as the drain inlet grate spacing. These results indicate that the grates were effective at preventing larger trash from entering storm drains. The total end-of-pipe load was 60 to 90 percent vegetation by weight and volume. Cardboard, paper, plastic and Styrofoam™ made up 50% of the trash by weight and volume. The most numerous item, cigarette butts, accounted for 35% by count. Weekly sweeping was considered effective if the reduction of trash (by volume, weight and count) was statistically significant at the 95% level. However, the analysis determined that the reduction of litter was not statistically significant. There were instances where weekly sweeping elevated the litter discharged to the storm drain.

Caltrans Litter Management Pilot Study (Lippner et al. 2001)

The Caltrans Litter Management Pilot Study (LMPS) was conducted in Los Angeles, California to test the performance of five best management practices (BMPs) at reducing trash in highway storm drains. Two of the five BMPs tested were increased street sweeping (from monthly to weekly) and increased manual pick-up (monthly to weekly). The study used a paired watershed approach with one watershed receiving the weekly sweeping or manual pick up paired with a control watershed receiving monthly sweeping. Mesh bags were installed to outfalls before each storm event with a 70% probability of more than 0.2" of rainfall. After each storm event, the wet and dry weight and volume of the collected material were measured and items were counted.

Effectiveness was defined as the difference between treatment and control for dry weight, volume, and count expressed as a percentage of the control. Hypothesis testing was done using the Wilcoxon Rank-Sum Test. While increased manual pick-up resulted in apparent improvement based on all measurement types (weight, volume, and count – 30 to 45% reductions), the authors concluded that increased street sweeping was not more effective in this study. By weight and count, swept watersheds actually appeared worse; dry weight was 29 to 59% higher in treatment watersheds and count was 5 to 25% higher. By volume, swept watersheds were marginally better with 3 to 5% lower volumes of trash than unswept watersheds. However, the null hypothesis (the treatment amount was equal to the control amount) could not be rejected. It should be noted that this study measures street sweeping on highways, which do not have curbs. Since curb accessibility is an important factor in litter removal by street sweeping, results may differ from commercial, residential, and industrial area streets.

Cape Town, South Africa and Rainfall (Marais and Armitage 2004a)

This study proposes guidelines for reducing trash in stormwater conveyance systems by focusing on source control of urban trash. The authors reviewed international and local practices and drew from the results of a study performed in Cape Town, South Africa. The most relevant finding was that the efficiency of street sweeping is less than 50% once the interval of days between street sweeping is greater than the number of dry days between rainfall events. The relationship between street sweeping efficiency and antecedent dry days is shown in Figure 2.

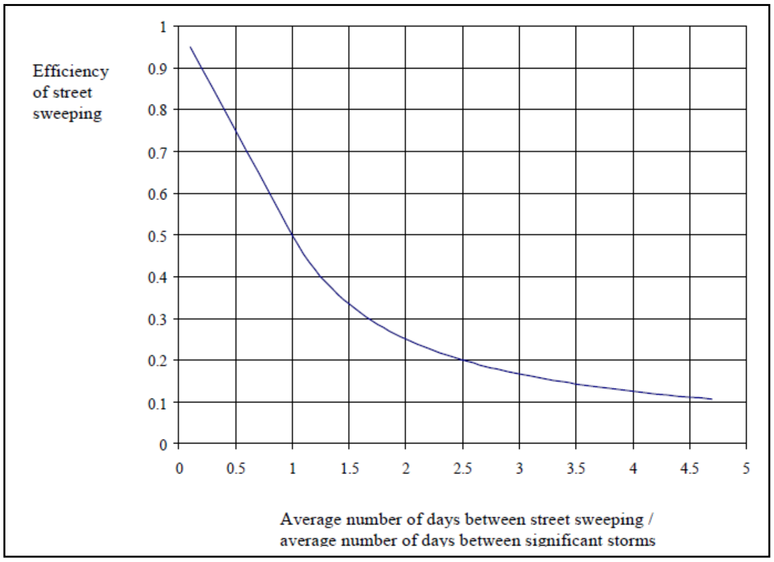

Figure 2. Maximum expected efficiency of street sweeping (Marais and Armitage 2004a).

<u>Cape Town, South Africa Case Study (Marais et al. 2004b)</u>

Over a two-year long period, trash in storm drain inlets was quantified and profiled in nine different catchments in Cape Town, South Africa with different demographics and land uses. While trash in waterways was the focus of this study, the effectiveness of street sweeping in three Central Business District (CBD) catchments was determined from measurements taken from six catch basins and annualized. The catch basin measurements were made by collecting trash from litter traps placed in the basins for this study. Streets were swept by hand two to three times per day on weekdays in the morning and afternoon. In high litter areas, streets were swept mechanically late at night or very early in the morning.

The study emphasized the importance of street sweeping and trash collection from public bins in the Central Business Districts. In the districts studied, litter measured from catch basins was about one to three percent (by mass) of the amount intercepted by street sweeping and bins. Another study in Springs, South Africa by the same authors found that 83% of trash was removed when streets were swept once a day (Armitage 1998 in Marais et al 2004) as compared to 99% of trash removed from sweeping two to three times a day in Cape Town (Marais and Armitage 2004).

<u>City of San Diego Targeted Aggressive Street Sweeping Pilot Study – Phase I and II (Weston 2010)</u>

The City of San Diego conducted a pilot study in 2008 and 2009 to compare three sweeper types and two sweeping frequencies and their impacts on debris and metals removed from roadways. For the two frequencies tested, diminishing returns were not observed for vacuum sweepers, but were observed for mechanical and regenerative air sweepers.

Study methods consisted of collecting and weighing all trash, dirt, and debris swept by each sweeper type. The collected debris was then sampled to evaluate presence of constituents of concern and debris particle sizes. Each sweeper type was assigned specific sweeping frequencies. All three sweeper types were assigned routes in the Chollas Creek study area (route 3J) and mechanical and vacuum sweepers were assigned routes in the La Jolla Shores study area (routes 103 and 1C).

The results of the sweeper frequency assessment indicate that the amount of material collected by the vacuum sweepers per pass (approximately 80 lbs/curb mile) does not go down if the sweeper frequency is increased from once to twice per week. Therefore, the amount of material collected is doubled if the frequency is doubled. By contrast, the amount of material collected using the mechanical sweeper once per week was approximately 50 lbs/curb mile. This amount was reduced to approximately 30 lbs/curb mile if sweeping was conducted twice per week.

Debris removal rates (lbs/curb mile) varied between routes and temporally within each route, but were higher with vacuum assisted sweepers. Vacuum assisted and regenerative air sweepers were more effective in removing fine material than mechanical sweepers on flat, even surfaces (Route 3J). Less difference was observed in steeper routes (Routes 1C, 103).

City of San Diego Targeted Aggressive Street Sweeping Pilot Study – Phase III (MWH and URS 2010)

Phase III of the City of San Diego's Targeted Aggressive Street Sweeping Pilot Study was conducted between February and May 2010, and evaluated the water quality benefits of sweeping medians adjacent to high-trafficked roadways. The study involved sweeping both sides of the median on four routes in different watershed management zones with a mechanical broom sweeper. Routes were swept at three week intervals for three months at six to 12 miles per hour. Median type ranged from barrier type medians, to raised medians, to flat painted medians. The initial sweeping event served as a baseline, and street sediment was analyzed for metals, general chemistry, and hydrocarbons. This baseline was compared to the material removed during the tri-weekly sweeping events. In addition, one square yard of undisturbed area on a raised median was swept and analyzed for the same analytes. All samples were sifted using a No. 4 sieve to remove gross solids including trash. The study found that the initial baseline sweeping event collected three to five times more debris than the subsequent tri-weekly sweeping events. In addition, results indicate that periodic manual sweeping of raised medians removes more street debris than sweeping alone.

2.3. Operational Practices

In addition to sweeper type and sweeping frequency, the way in which sweeping is conducted can affect removal efficiencies. Operational speed, attention, and ability to reach the curb can affect the success of street sweeping programs (Sartor et al. 1974, Sutherland 2011, Riccio and Litke 1986).

Water Pollution Aspects of Street Surface Contaminants (Sartor et al. 1974)

Although the parameters of concern in this study were primarily water pollution constituents, not street litter, conclusions from the study regarding the importance of street cleaning operational practices are relevant. Methods included field measurements, sample collection, sample analysis, experimental studies, literature reviews and questionnaire surveys. The three main objectives of the study were to (1) determine amounts and types of material commonly collected on streets; (2) determine the effectiveness of conventional public works practices in preventing this material from polluting receiving waters, and (3) evaluate the significance of this source of water pollution when compared with other sources.

The study found that most street dirt and debris accumulates close to the curb, as illustrated by **Error! Reference source not found.**. They also found that effectiveness was higher at slower speeds. They recommended that sweepers should be driven at maximum 5 miles per hour. High-speed arterials, requiring faster sweeping speeds, should be swept more frequently. The authors also noted parked cars as "one of the most serious street sweeping problems" and promoted city planning strategies (signs, campaigns, etc.) to address the issue.

Table 6. Typical Solids Loading Intensity (Sartor et al. 1974).

Street Location (in. from curb)	Solids Loading Intensity (% of total)
0–6	78
6–12	10
12–40	9
40–96	1
96 to center line	2

The authors recommend that operators not only be trained in best practices (e.g. vehicle speed, broom speed, and broom position), but also educated as to what material needs to be removed and where it is likely located. For example, street sweeping may be more effective if operators understand that removal of fine dirt closest to the curb is important in protecting water quality.

The removal effectiveness of litter and debris was 95 to 100%. The study also supported findings that efficiency increased with particle size. In addition, the rate at which rainfall washes loose particles from street surfaces depends on rainfall intensity, street surface characteristics and particle size. Factors affecting loading intensity include land use, elapsed time since streets were last swept, local traffic volume and character, street surface type and condition, public works practices and season.

Demonstration of Nonpoint Abatement through Improved Street Cleaning Practices (Pitt 1979)

This study assessed the effectiveness of street sweeping at five sites at three locations (Downtown, Keyes, and Tropicana) in San Jose, California. All sites were classified as having good asphalt road surfaces except for one oil/screens site not discussed here. Sweeping was conducted daily or weekly and was sustained for about four to six weeks. Equipment consisted of three varieties of mechanical street sweepers: 4-wheel mechanical street cleaner, state-of-the-art 4-wheel mechanical street cleaner, and 4-wheel vacuum-assisted mechanical street cleaner. Median particle size before sweeping ranged from 150 - 330 µm, but the median size decreased with street sweeping which was more effective at removing larger particles. Pitt points out that street conditions (especially dust/dirt loading) were more important in terms of determining effectiveness than the type of equipment which included broom and vacuum type sweepers. In other words, the most effective equipment was that which was cleaning the dirtier streets, and which was cleaning most frequently.

Pitt found that road condition played an important role in effectiveness. Percent reductions in overall dust/dirt loading for sites with good asphalt varied on average from 33-43% with removals ranging from 83-130 lbs sediment/curb mile. For sites classified as poor asphalt, the removals was 40%, not much different from the other sites, however the load reduction was 540 lbss/curb mile. The reason for this large difference is that the loading on the poor condition asphalt was 1400 lbss/curb mile, compared to 200-400 lbss/curb mile on the good asphalt roads. In other words, the dust and dirt on a poor asphalt road may be 3 to 7 times more than that on a good asphalt road.

Pitt also examined how effectiveness varied with particle size. For example, the downtown site with good asphalt had dust/dirt load reductions which ranged from about 20% for fine particles (<45 µm) to about 40% for coarser fractions (850-2000 µm). On good asphalt road, over 80% of the dust and dirt was within 5 feet of the curb and therefore parking restrictions were important for effective street sweeping.

On the basis of limited monitoring of runoff quality (three storms), Pitt concluded that water quality improvements in runoff of about 50% reduction in solids and metals could only be achieved with very frequent (e.g. daily or twice daily) sweeping. Pitt also indicated that street sweeping was not generally effective for nutrients whose sources he attributed to runoff from areas surrounding roads (e.g., parkways between streets and sidewalks) and not the roads themselves.

New York City Computer Model (Riccio and Litke 1986)

The objective of this study was to determine the increase in sweeping effectiveness resulting from a reduction in the number of illegally parked cars on a street block. The authors expected parked car obstacles to be an important factor in street sweeping effectiveness given that "95% of all street litter accumulates within 18 inches of the curb" (Fleming 1978, as cited by Riccio and Litke 1986). Using a computer model, litter (pieces and piles) and cars were randomly placed on a block. Litter was "measured" using a scoring system from 1.0 (no litter) to 3.0 (continuous litter) where 1.5 was acceptably clean. Previous studies found that street sweeping removes 90 to 98% of all trash when there are no obstacles (e.g., parked cars), and the sweeper is traveling at the standard operating speed. The model was run at a constant 90% effectiveness. Table 7 shows the increase in probability that a street will be made acceptably clean (score of 1.5) after street sweeping from a one car reduction.

Table 7. Increase in the probability that a street will be made acceptably clean after street sweeping from a one car reduction (Riccio and Litke 1986).

Initial # Cars	Remaining # Cars	Initial Dirtiness				
		1.6	1.7	1.8	1.9	2.0
4	**3**	0	3	11	27	28
5	**4**	4	8	21	24	12
6	**5**	7	15	25	16	4
7	**6**	10	22	17	6	1
8	**7**	15	14	12	4	0
9	**8**	13	16	5	2	1
10	**9**	14	9	4	0	0

Reducing one parked car per block, from four to three can increase the probability that a street will be made acceptably clean by 28% (when the initial street dirtiness is 2.0). A one-car reduction had the greatest impact on the dirtiest streets when few cars were parked.

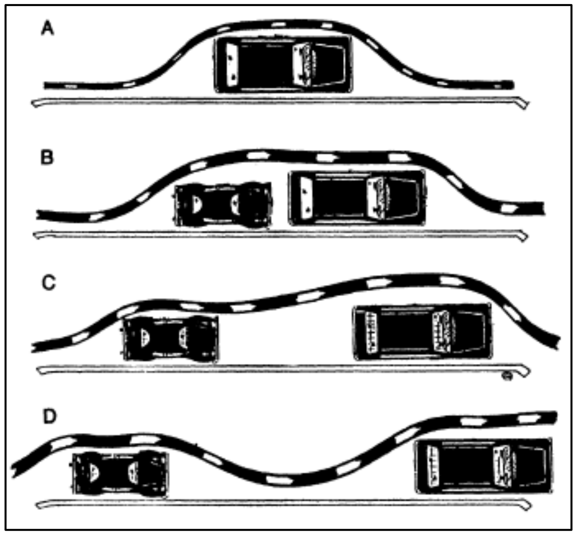

Figure 3. Effect of illegally parked cars on street sweeping. (Riccio and Litke 1986).

<u>City of Palo Alto (Teresi 2008)</u>

In the City of Palo Alto, residential areas are swept weekly and business districts are swept three times a week using five regenerative-air sweepers and three broom sweepers. However, the residential areas next to the business districts are a problematic due to the presence of parked cars on sweeping days. Originally, temporary "No Parking" signs were posted every five weeks to prohibit parking on one side of the street. Because temporary signs were determined to be ineffective and costly, the City conducted a trial signage program in 2004. The program involved posting signage on trees which restricted parking for two hours per week within a 10 square block area (40 acres). After three months, the time was reduced to one hour. The trial signage program led to an additional 40 cubic yards of debris collected over a six-month period. In early 2005, one permanent "No Parking" sign was posted per block restricted parking for one hour, alternating sides of the street each week. In 2006, the area was expanded to 145 acres. Approximately 3.5 hours of police staff time is spent each sweeping day, at an annual cost of $6,500. However, parking enforcement has resulted in an additional $120,000 in annual revenue from more than 3,000 violations issued. Due to permanent signage, an additional 350 cubic yards of street sweeping debris has been collected annually within the 145-acre area.

<u>City of San Diego Targeted Aggressive Street Sweeping Pilot Study – Phase IV (URS 2011)</u>

The fourth phase of the City of San Diego's Targeted Aggressive Street Sweeping Pilot Study assessed sweeper speed efficiency. The study compared the pollutant removal efficiency of mechanical sweepers at the City's typical operating speed, 6-12 miles per hour, with the efficiency of the sweepers at the manufacturers' recommended operating speed, 3-6 miles per hour. During the study, two routes were monitored four times. During each monitoring event, each route was partially swept at each speed and the sweeper material was weighed. In addition, randomly selected 10 by 12-foot areas were vacuumed prior-to and after each sweeper event and analyzed for metals, nutrients and hydrocarbons. The study found that the weight of the material collected by the sweeper and pollutant removal capability did not depend of sweeper operational speed. There was high variability in both total sweeper material weight and chemical composition of the pre and post event samples.

3. Trash Partial Capture Device Case Studies

Partial-capture devices are treatment devices that have not been approved as full capture (i.e., trap all particles retained by a 5 mm mesh screen, and has a treatment capacity that exceeds the peak flow rate resulting from a one-year, one-hour storm in the subdrainage area) by the Los Angeles Regional Water Quality Control Board or San Francisco Bay Regional Water Quality Control Board, but capture trash at a known level of performance. Partial-capture devices may be similar to full capture devices, but do not meet the full-capture definition due to engineering challenges; or they may be completely different types of devices. Case studies that attempted to assess the effectiveness of partial-capture devices are described below.

3.1. Curb Inlet Screens

Curb inlet screens are perforated screens or evenly spaced bars that are designed to fit outside or immediately within the storm drain curb opening. Inlet screens may be fixed or retractable. Retractable screens open either manually or hydraulically when a storm flow/volume is detected. Since curb inlet screens block trash and debris from entering the storm drain inlet or storm drain, trash remains in the street and is removed by regular street sweeping.

Based on an evaluation of existing storm drain infrastructure and installed full-capture devices within the City of Los Angeles, the Watershed Protection Division (WPD) of the City of Los Angeles Department of Public Works, Bureau of Sanitation decided that the most practical and cost-effective approach for achieving TMDL compliance is the installation of connector pipe screens and curb inlet screens.

City of Los Angles (City of Los Angeles 2006b)

The WPD conducted a study to determine the trash capture effectiveness of storm drain inlet opening screen covers during a typical calendar year. The study location was as high trash generation area in the Westlake neighborhood, west of downtown Los Angeles and has a drainage area of approximately 55 acres. To determine effectiveness, a total of twenty-four (24) storm drain inlets were retrofitted with opening screen covers having diamond shape opening measuring one inch in the longitudinal direction by ¾ inch in the vertical direction. Covers remain in the closed position and release when runoff builds up to approximately 60 percent of the curb height (City of Los Angeles 2006b). Once the flow diminishes, the covers close into the locked position. The study location also included one CDS unit. Field measurements from all storm drain inlets and the CDS unit were obtained during the FY 2005-2006 wet season after every storm greater than 0.25 inches. Measurements only occurred for storm events occurring ten or more days apart.

The overall trash capture effectiveness of the storm drain inlet opening screen covers was determined by visual observations and field measurements. The effectiveness determination considered the sum of historical data (i.e., trash collected from the CDS unit and those storm drain inlets which drained into the CDS unit); and current data (i.e. trash collected from the CDS unit and those storm drain inlets retrofitted with opening screen covers which drained into the CDS unit). The overall trash capture effectiveness of the opening screen covers ($SC_{effectiveness}$ %) was determined by visual observations and field measurements using the following equation (City of Los Angeles 2006b):

$$SC_{effectiveness}\ \% = (TH_{tCDS+CBs} - TC_{tCDS+CBst} / TH_{tCDS+CBs}) \times 100$$

$$\begin{aligned} TH_{CDS+CBs} &= Trash\ Historical_{tCDS+CBs} \\ &= 860\ lbs\ \text{(based on average 2003/2004 wet season cleaning)} \\ TC_{CDS+CBs} &= Trash\ Current_{CDS+CBs} \end{aligned}$$

The effectiveness of opening screen covers in deflecting trash during a storm greater than 0.25 inches was determined to be 58 to 79 percent (City of Los Angeles 2006b). During dry days, the trash deflection effectiveness of the opening screen covers is considered to be 85 percent since the screens remained in the closed position and only trash smaller than one inch entered the storm drain inlet (City of Los Angeles 2006b). A typical year experiences approximately 25 wet days and 340 dry days (City of Los Angeles 2006b). Using a 1:9.3 weighted average over the course of the entire calendar year, storm drain inlet opening screen covers were determined to have an 86 percent effectiveness rate (City of Los Angeles 2006b). However, the historical CDS data and current CDS data from this study only included the removal of floatable trash while settleable trash in the sump was not collected and measured. Similar to the storm drain inlet insert study performed by WPD, effectiveness was recalculated and determined to be 83.2 to 84.6 percent.

In early 2010, the WPD installed approximately 710 storm drain inlet opening screen covers within the City of Los Angeles (Sedrak, M. pers. comm. 2010).[1]

3.2. Litter Booms and Curtains

Litter booms are floatation structures with suspended curtains used to collect floating trash. They are placed downstream of one or more outfalls usually in slow moving waters. Trash and debris collects in the area with the highest water flow velocity (i.e., middle of the boom). Litter booms have been shown to trap large quantities of floatable materials. However, a significant portion of trash in urban runoff is likely not caught since booms are designed to capture floatable trash (Gordon and Zamist 2006). Study results and antidotal information regarding the performance and/or effectiveness of litter booms is described below.

Melbourne, Australia (McKay and Marshall 1993)

A Melbourne, Australia study released tagged litter items upstream of litter booms to determine floating boom performance. The results varied from 12 percent to 50 percent recapture. These values were considered preliminary due to the low number of items released in the boom catchments. In addition, the items released in the study were highly floatable and do not represent the complete range of items found in urban runoff. It is expected that the figures determined by McKay and Marshall (1993) are higher than those expected for the total trash and debris load (i.e., including submerged material) (Allison et al 1998a). Other Australian studies have reported capture rates of 24 to 71 kilograms per hectare from four booms in Sydney (Gamtron 1992).

[1] Morad Sedrak. City of Los Angeles, Department of Public Works, Watershed Protection Division. March 2010.

Queens, New York (USEPA 1999b)

A four-boom containment system was tested in Jamaica Bay (Queens, New York) during a two-year pilot study. Floatables were contained by booms and collected with a skimmer vessel. Boom effectiveness was determined by measuring the quantities of floatable materials present in the water and on the shorelines before and after boom installations. Results showed substantial improvements from pre-boom installations with booms collecting approximately 75 percent of floatables. During the two-year test period, approximately 44.8 tons of trash was removed from the containment area (USEPA 1999b).

County of Los Angeles (2003)

The County of Los Angeles Department of Public Works tested a litter boom at the mouth of the Los Angeles River between 2000 and 2003. During the first two years of the testing, the litter boom trapped approximately 150 tons of trash and debris (County of Los Angeles 2003). County of Los Angeles staff estimates that litter boom performance is approximately 80 percent. Historical trash collection data indicates a large variation in the volume of trash harvested after each storm event. Approximately 90 percent of trash harvested from the first storm is vegetation. The remaining 10 percent is mostly Styrofoam™ and plastics (Teren, E. pers. comm. 2007).[2]

Albuquerque, New Mexico (Ho 2005)

A study performed in Albuquerque, New Mexico (Ho 2005) evaluated the hydraulic performance of various boom designs in an experimental flume. Researchers found that a 30° boom barrier approach angle works better than a 45° approach angle because the smaller angle makes a longer and better performing screening area. In addition, when bending the pier 15° from vertical to the flow direction, the boom is able to move easier (Ho 2005). As a result, the angle and manner that a boom is attached to the shore can have an impact on its overall performance. The researchers also recommended a high buoyancy boom for easy floating but cautioned that turbulent flows make boom movement unstable, reducing debris-collection capacity.

City of Oakland (2006)

A sea curtain/trash boom was installed on the Oakland Slough in 1999. The City of Oakland Public Works Department removes debris an average of eighteen times per year. This frequency was higher in the early years of installation. The average amount of debris removed per cleaning is approximately 16 cubic yards (Bavinger, M. pers. comm. 2007).[3]

Litter booms are also installed in Lake Merritt. Staff and volunteers of the Lake Merritt Institute routinely remove trash from the litter booms. According to Dr. Richard Bailey, Executive Director of the Lake Merritt Institute, litter booms:

- Only allow floating trash to be easily removed (some trash becomes waterlogged and sinks where it is hard to remove);
- Can be overtopped by high flows, especially if the barrier is too small for the outfall;
- Allow some material to flow underneath;

[2] Ed Teren. County of Los Angeles, Department of Public Works, Flood Maintenance Division. May 2007.
[3] M. Bavinger. City of Oakland, Environmental Services Division. April 2007.

- Leak at the sides where they are attached. This is especially true because water level rises and falls. If the barrier at the attachment point does not rise and fall with the water, it will be submerged and trash will flow out; and

- Sometimes break and needs to be repaired or replaced (Bailey, R. pers. comm. 2007).[4]

3.3. Pump Station Trash Racks

Stormwater pump stations transport stormwater from areas where gravity drainage is impossible or impractical (USDOT 2001). However, stormwater pumps are designed to pass solids up to 2 to 3 inches (SCVURPPP 2009) and cannot pass large debris which may be suspended in stormwater flows. Trash racks located at the intake to the pump station or inside the wet well are installed to protect pumps and prevent fish from entering pump stations. Trash racks consist of steel bars spaced 4 to 10 centimeters (1.57 to 3.94 inches) apart (Allison et al. 1998b) and provide a physical barrier to floating and submerged pollutants. Trash racks can remove 80 to 100 percent of large, hard trash and 40 to 100 percent of soft, deformable trash, such as plastic bags (Nielsen and Carleton 1989 in Fletcher et al. 2004). For floatables, the removal effectiveness is suggested to be 5 to 14 percent (McKay and Marshall 1993 in Allison et al 1998b).

The United States Department of Transportation (USDOT) states that trash racks are “essential” since they screens out large objects capable of damaging pumps (USDOT 1982).

[4] Dr. Richard Bailey. Executive Director, Lake Merritt Institute. January 2007.

4. On-Land Trash Assessment Protocols

Several methods have been developed and performed at the local and regional levels to assess the level of litter on-land. Some studies have focused on quick surveys of overall litter conditions, while others include detailed counts and characterization of littered items. Studies are generally carried out along roadways (e.g., streets or highways). Summaries of the major studies that are most applicable to developing visual on-land trash assessment methods are included in this section.

The important considerations in choosing and developing an assessment protocol include:

1) Accuracy and precision
2) Repeatability and objectivity
3) Ability to extrapolate data temporally or account for variability
4) Ability to extrapolate or interpolate data spatially
5) Ability to detect changes over time (i.e., as a result of control measures)
6) Time and resources required to complete assessments

This review focuses on methods for assessing on-land, accumulated trash that is capable of entering stormwater conveyance systems. Surveys focused on littering behavior and the magnitude and extent of litter in receiving waters are included in Section 5.

4.1. Qualitative Visual Surveys

The following qualitative visual surveys use trained observers to assign a score reflecting litter conditions at a site, based on a defined scale.

Keep America Beautiful – KAB Litter Index (KAB 2000)

Keep America Beautiful (KAB) is a national organization formed in 1953 with the goal of reducing litter and promoting clean communities. Each year, it hosts many trash reduction, recycling, litter-abatement, and community clean-up programs. KAB also performs and supports several litter surveys, some of which are qualitative visual assessments of litter levels, and others which are quantitative including the characterization of littered items by size, material, and product type.

The KAB Litter Index, developed in 1998, uses a four-point scale to assess the visual impact of litter. A score of 1 indicates "no litter", 2 represents "slightly littered", 3 "littered", and 4 "extremely littered." Full descriptions are included in

Table 8. A “scorer” is trained in categorizing areas into these four levels by reviewing example photographs and the associated scores. Field training is also provided at several sample sites. After viewing and scoring the sites, scorers collectively review the assigned scores to develop a consensus around the conditions that reflect the four index levels. The KAB Litter Index can be performed from a moving vehicle.

Table 8. Descriptions of KAB Litter Index scores (KAB 2000).

Score	Description
1 **"No litter"**	Virtually no litter in the sub area is present. The scorer has to look hard to see any litter, perhaps a very occasional litter item or two in a city block, or equivalent. Any litter seen could be quickly collected by one individual. The entire area has a generally neat and tidy appearance—nothing grabs the eye as being littered or messy.
2 **"Slightly littered"**	A small amount of litter is obvious to the scorer upon careful inspection. The litter in the sub area could be collected by one or two individuals in a short period of time. While the sub area has a small amount of litter, the eye is not continually "grabbed" by litter items.
3 **"Littered"**	Visible litter throughout the sub area, or several piles of litter, likely requiring an organized effort for removal. One can see considerable litter without much visual effort. The area is "littered" and clearly needs to be dealt with.
4 **"Extremely littered"**	The litter level is one of the first things noticed about the sub area. Litter is almost totally continuous throughout the sub area. Major dumps may be in the sub area, requiring equipment/and or manpower for removal. There is an impression of lack of concern about litter in the sub area.

The overall monitored area is divided into areas (e.g., neighborhood or land use area) and sub-areas (or sites). Survey results are used by KAB and affiliates to determine which areas within the City have severe litter problems. It is also used to assess yearly litter trends.

To determine the reliability of the KAB Litter Index, KAB compared assessment results with the previously used method: the Photometric Index. After both methods were performed at the same 50 sites in Houston, Texas, assessments using both protocols were also performed in the following locations: Norfolk, Virginia; Beatrice, Nebraska; Colorado Springs, Colorado; Stamford, Connecticut; and Gwinnett County, Georgia. The consulting agency that reviewed the data from these six locations determined that "inter-rater reliability was very high" (KAB 2000).

In Houston, Texas, assessment results indicated that "95% of all scores were within one point of the average score for an area" and that "inconsistent scoring was more common toward the upper (more littered) end of the scale" (KAB 2000). Reviewers also noted that seating location on the bus was found to impact field of vision. Subsequently, KAB has instructed scorers to use a large vehicle (i.e., van) to avoid limitations on field of vision.

Keep Britain Tidy – Grades of Cleanliness (KBT 2013)

Keep Britain Tidy is an independent environmental charity founded in 1954 to reduce litter and to maintain clean streets, parks, and beaches throughout Britain. Their work today includes public education, waste reduction, recycling, and continued litter reduction efforts. In 2001, the organization developed an annual Local Environmental Quality Survey of England (LEQSE) for the Department for Environment, Food and Rural Affairs. This survey's primary focus is on street cleanliness, which is assessed on a defined grade scale by personnel trained in the survey method and technique. In addition to monitoring litter levels, the survey also assessed detritus and graffiti. The survey was developed with assistance from the Office of National Statistics and the Audit Commission based on a representative sample of sites from different regions with varying land uses and socio-economic indicator levels.

The Grades of Cleanliness used by Keep Britain Tidy are taken from the UK Code of Practice on Littering and Refuse. They consist of four letter grades ranging from no litter (A) to heavily littered (D) and are described in Table 9. Grade A is defined as completely free of litter (i.e., zero pieces of litter are present in the survey area). In addition, grades of B+, C+, and C- are also used for conditions reflecting a level between the definitions provided (UK DEFRA 2006). Through experience, Keep Britain Tidy has determined that the use of intermediate grades improves accuracy and gives a more refined view of litter conditions within the local environment (KBT 2012).

Table 9. Descriptions of Keep Britain Tidy Litter Grades (KBT 2012).

Grade	Description
Grade A	No litter or refuse
Grade B	Predominately free of litter and refuse apart from some small items
Grade C	Widespread distribution of litter and/or refuse with minor accumulations
Grade D	Heavily affected by litter and/or refuse with significant accumulations

The LESQE has been performed in Britain for 12 years. In annual report cycle 2012-2013 (April 2012-March 2013), a total of 10,682 sites were evaluated in 54 local authority areas. Up to 200 sites were evaluated in each local authority area and surveys were collected throughout the annual cycle. Data from the surveys has been used to assess trends in national litter rates over time, across land use types or regions, and to compare litter issues against other LESQE-monitored environmental quality issues such as detritus, graffiti, or excessive sign posting.

4.2. Quantitative Visual Surveys

The following quantitative visual surveys include the counting and characterization of trash items within surveyed sites.

New Jersey Litter Survey – Visible Litter Survey (VLS) methodology (NJLS 2004)

The New Jersey Litter Survey was conducted for the New Jersey Clean Communities Council using the Visible Litter Survey Methodology with some notable differences in technique. Concerns regarding visual impacts (e.g., community perception) of litter are the motivation of this study. The purpose of this survey was to collect accurate and comprehensive data reflecting overall litter levels, distribution, and composition in the state of New Jersey (NJLS 2004). One of the goals of the study was to determine a statewide litter-level baseline to use in developing a statewide litter reduction goal.

In the study, 94 sites were surveyed. Instead of using a fixed site length, the site length was dependent on the site and number of items counted. In an effort to select sites most capable of showing significant reductions in future surveys, the site continued from a beginning point until an acceptable distance and/or number of items was counted. An identifiable point or "milestone" was chosen for the site starting point and endpoint. The sites averaged 689 feet in length with only four sites under 300 feet. Sites had an average item count of 84 and a minimum item count of 20, except for a few cleaner urban sites. Methods for this study otherwise followed the same process as in the Northeast Litter Survey.

Georgia Visible Litter Survey - Visible Litter Survey (VLS) methodology (GVLS 2007)

This survey was conducted in 2006 for Keep America Beautiful and the Georgia Department of Community Affairs. The survey was designed to provide data that would assist the State's Litter Initiative in developing litter prevention and abatement programs. A total of 96 roadway sites were sampled using the same VLS methodology described above.

In addition to performing the meandering visible litter count, assessors also scored the site using the KAB Litter Index scale of 1 to 4. Assessors were instructed to use half values (1.5, 2.5, or 3.5) as needed. These qualitative scores were compared with litter counts to gain an understanding of the relationship between the qualitative and quantitative methods. The researchers found that KAB Litter Index scores are positively correlated with litter counts reported in units of Meandering Pedestrian Visible Items for Mile (M-PVIM). The count obtained from a meandering path was used to most closely align with a density-per-area estimate, which is representative of the visual assessment used in the KAB Litter Index. The two measures are highly related. Although a linear correlation was observed, analysis indicated that a non-linear relationship was more representative.

Analysis also showed that road types influenced the relationship between KAB Litter Index scores and M-PVIM values. Based on regression analysis of the collected data, mean M-PVIM values were estimated for each KAB Litter Score. The results are depicted in Error! Reference source not found.. If a KAB Litter Index score was not available for a specific road type, extrapolation was used in forming the estimate; for instance, no 4's were observed on rural freeways/toll roads. Using this tool, M-PVIM litter density can be estimated based on KAB Litter Index scores.

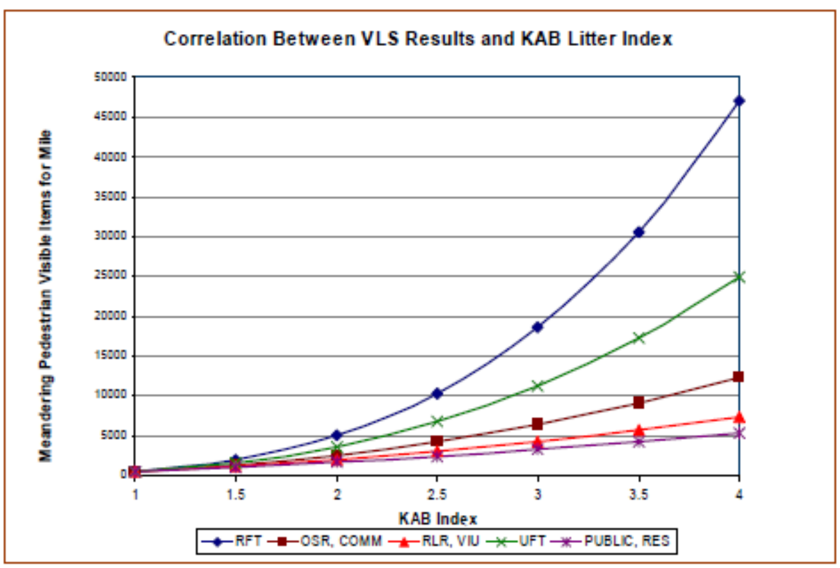

Figure 4. Mean estimates of Meandering Pedestrian Visible Items for Mile (M-PVIM) for each KAB Litter Index score (GVLS 2007). RFT – Rural Freeways / Toll Roads; OSR – Other State / Rural Highway; COMM – Commercial Street; RLR – Rural Local Roads; VIU – Vacant, Industrial or Unmaintained Street; UFT – Urban Freeways / Toll Roads; PUBLIC – Public Facility Street; RES – Residential Street

It was also determined that for site observations scoring on the more littered end of the KAB Litter Index, there was a larger range of associated M-PVIM values. This corroborates findings from initial 1999 scoring of the KAB Litter Index, which showed that assessors were more variable in scoring at the higher end of the scale.

However, the analysis did not explain the extent of training in the KAB Litter Index approach given to assessors, nor did the report note whether the assessors assigned a KAB score before or after performing the litter count.

MGM Management – Street Litter Audits (2009, 2008): San Francisco and San Jose

This street litter audit method was designed by MGM Management, a Canadian environmental consulting company with experience in litter assessment. The method has been applied in several cities including Edmonton, Toronto, San Francisco, and San Jose.

This detailed visual assessment of street litter was performed for the City of San Jose Environmental Services Department in August of 2008. The purpose of the study was to quantify and characterize a baseline trash level for the city. Audit data was collected to inform San Jose staff of litter sources and trends. The survey was also intended to provide data for evaluation of litter abatement programs and trash management plans. Visual surveys were conducted at 124 randomly selected sites throughout the city (SJSLA 2008).

The same method was applied for San Francisco's Street Litter Audits conducted in 2007, 2008 and 2009. The average and total litter count across all sites is compared for each year's audit in Table 10. The 105 randomly selected sites originally assessed in 2007 were again sampled in 2008 and 2009 with 25 additional sites added in 2008 and two additional sites added in 2009 (SFSLA 2009). Trained two-person field teams were able to complete between 7 and 10 sites per day using this assessment method (SFSLA 2008).

Table 10. Comparison of San Francisco Litter Audit Results from 2007 – 2009 (HDR and MGM 2009 and 2008 reports).

Year		2009	2008	2007
# Sites		132	130	105
Large Items	Total	4,488	3,973	3,812
	items/site	34	30	36
Small Items	Total	3,370	2,335	2,393
	items/site	26	18	23

Sites were 200 feet long and up to 18 feet wide. Detailed information was collected about the sites including grass height, proximity to fast food restaurants or traffic lights, and number of road lanes. Trash was classified as large litter if it was greater than 4 square inches in size, or small litter if less than 4 square inches. Large litter was classified into 84 categories, small litter into 16 categories (SJSLA 2008).

A detailed process was followed to survey small litter. A frame constructed with ½ inch PVC plastic tubing was used to distinguish a survey area. The frame was placed on the ground and small litter items were counted within the frame. The frame was placed once at the beginning of the site, at the middle, and at the end. At each location, it was flipped three times along the width of the site as depicted in Figure 5, thus using nine frames in total.

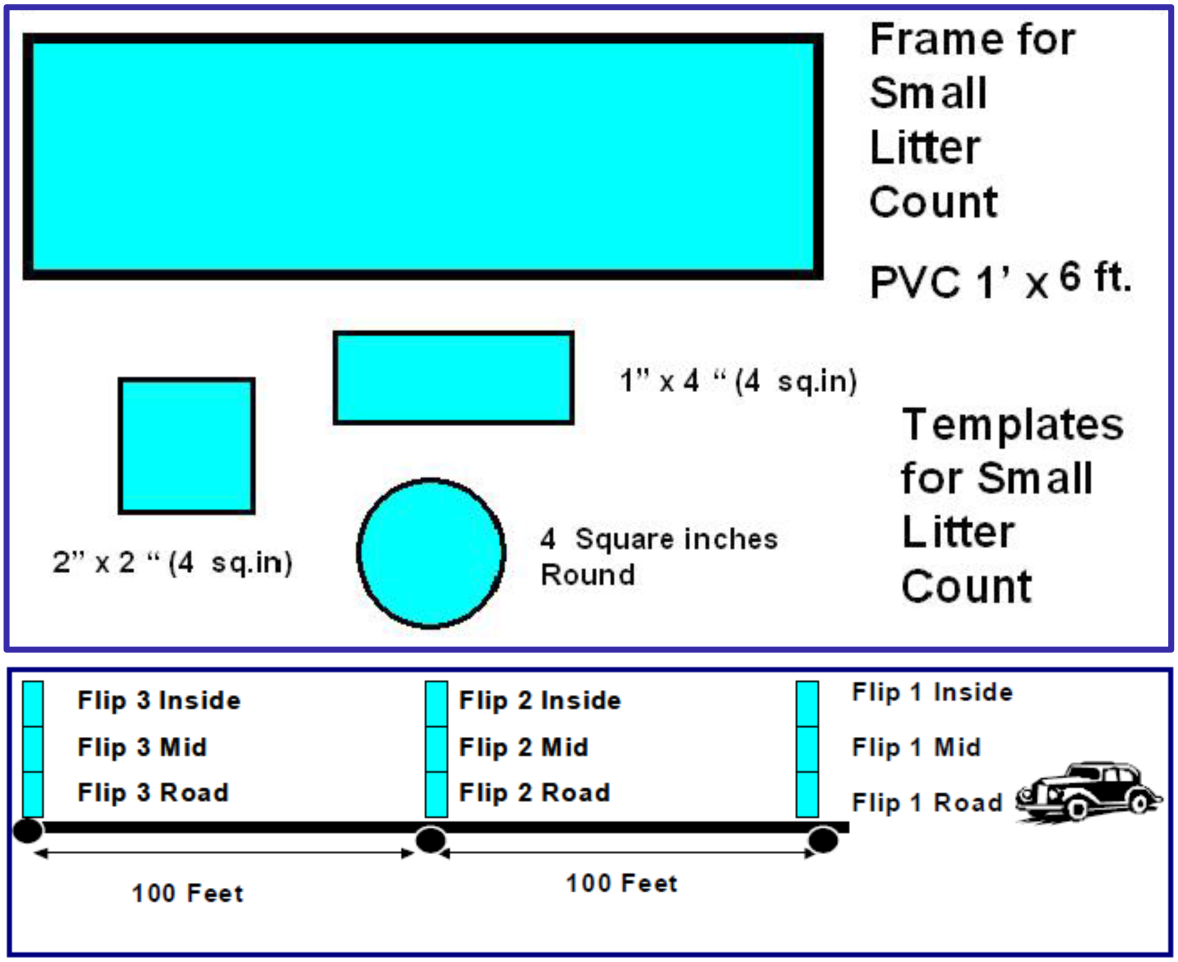

Figure 5. Illustration of method used to frame specific areas for counting small trash at each transect along the 200 ft. site length (SJSLA 2008).

Digital photographs were taken at each site. The survey was recorded using a digital tape-recorder. The assessor dictated detailed information including site number, date, start time, land use type, roadway type, etc. A visual litter rating was also recorded on a subjective basis following the common visual rating scale of 1 to 4, in which 1 represents no litter and 4 represents a heavily littered area. However, no subjective score results were included in this report (SJSLA 2008).

The assessor walks along the site and records observations of large litter into the tape-recorder including item descriptions and product /material classifications, noting when the midpoint and end point of the site are reached, completing pass one. The process is repeated in the opposite direction.

Results of the two passes are averaged. Observations were recorded before leaving the site (SJSLA 2008).

The San Jose audit observed a total of 6,121 littered items, comprised of 3,928 large items (average of 31.7 per site) and 2,172 small items (averaging 17.5 per site) (SJSLA 2008). The most common types of small litter were gum, glass pieces, paper pieces, and cigarette butts. Analysis showed that the majority of litter was observed from a minority of sites. Therefore, the authors noted, litter abatement targeted at specific locations may be plausible (SJSLA 2008).

As shown in Table 10, San Francisco litter counts (average per site) were lower than the baseline (2007) counts for both large and small litter in 2008 and for large litter in 2009. Small litter average per site was higher in 2009 than 2007. Overall, small litter occurrence in San Francisco was low as compared to other cities audited using the same methodology (SFSLA 2009). Initial large litter counts were relatively high compared to previous litter audits in other regions (e.g. Florida, Toronto) (SFSLA 2009).

<u>Keep America Beautiful – National Visible Litter Survey (KAB 2009)</u>

This quantitative study was commissioned by Keep America Beautiful to update and advance the research foundation for the benefit of litter prevention programs. Visual counts were conducted by field crews, one of which would walk in a meandering path (i.e., 300 feet long by 15 feet wide along a street/roadway) and perform a count of large items (i.e., greater than 4 square inches in size). A second assessor would count small items at a cross section of the site.

The study included a discussion on seasonal effects on litter rates. Prior research indicated that litter generation is highest during the summer and least in the winter in most areas. This would indicate that to identify real trends from annually collected data, surveying should be conducted in the same seasonal period.

The survey also included non-roadway site sampling of construction sites, loading docks, recreational areas, storm drains, retail shopping areas, and transitional points (e.g., bus stops, movie theatre entrances, and other places) where someone consuming a food or tobacco products are required to discard the product before entering.

Storm drains were surveyed and found to include mostly small litter (i.e., less than 4 square inches). Of the small items observed, which comprised 83 percent of the total count, cigarette butts were the most common followed by confection litter. Various types of plastics, which comprised 20 percent of all material (large and small) found in storm drains.

<u>Northeast Litter Survey – Visible Litter Survey (VLS) methodology (NELS 2010)</u>

The Northeast Litter Survey was conducted for the American Beverage Association. The survey assessed baseline litter conditions at 288 street and highway locations in Maine, New Hampshire, and Vermont. The method has been used in more than 70 statewide litter surveys. One goal of the study was to compare the source and degree of litter between the three states surveyed and against other states surveyed using the same method.

With this method, litter counts are performed along roadways 500 feet in length and 15 feet wide. A field crew walks at a steady pace along the side of the street/road and counts all visible litter items greater than 1 inch in diameter. Authors of the study indicate that previous litter studies show more reliable and reproducible litter counts if small items are excluded. The authors also stated that this exclusion "does not inhibit the ability to track reductions in cigarette or container litter, since experience has shown that the reductions of cigarette packages as well as whole bottles or cans is usually accompanied by a similar reduction in cigarette butts and container fragments" (NELS 2010).

During a second pass, while walking more slowly, the crew categorizes the littered items by type (e.g., soft drink container, water bottle, etc.) and material (e.g., glass, plastic, etc.). At the site, crews also recorded data on a number of factors influencing litter including traffic, rainfall, population size, and average income level.

4.3. Semi-Quantitative Visual Surveys

The following semi-quantitative visual surveys may include some form of item counts, but do not include characterization of trash items within surveyed sites.

Keep America Beautiful – Photometric Index (1974)

A Photometric Index was the initial method used by KAB for assessing litter until the development of the KAB Litter Index in 1998. This method involved taking photographs within a sample area (e.g., streets or parking lots within randomly selected land use categories) and projecting them on a 96-square grid and counting the number of littered squares within the grid. The Photometric Index is then obtained by adding all the littered squares in a set of categories and dividing by the total number of pictures. Sites with higher litter counts in photographic analysis have more severe litter problems (KAB 2000).

Keep Holland Tidy – Measuring System for Beach Litter (MSBL 2006)

Keep Holland Tidy is a part of the NederlandSchoon organization formed by business, government, and interest groups with the aim of preventing litter across the Netherlands. In cooperation with the Royal Dutch Touring Club ANWB, Keep Holland Tidy developed a standard method for evaluating beach litter in 2006. Litter was counted per 100 square meters for bulky litter or per one square meter for fine litter. Bulky litter was characterized by height, breadth, length, and/or diameter greater than 10 cm but less than 50 liters in volume. Fine litter was characterized by height, breadth, length, and/or diameter less than 10 cm but greater than 1 cm, but excluding chewing gum (MSBL 2006). This method has since been used by the Blue Flag Program, which monitors beaches in several countries around the world for environmental quality (BFP 2009).

This measuring system uses a scale similar to the KAB Litter Index (Table 11). The measuring system is semi-quantitative in that it uses both the descriptive method used by KAB Litter Index with accompanying illustrative photographs for scorer training and also item counts corresponding to each descriptive category. Authors cite that combining a qualitative and quantitative method for assessment brings the benefits of reduced labor costs from qualitative methods and specificity of quantitative measures. The report suggests that counts should only be used in cases when it is unclear which photographs most closely matches the litter conditions at an assessment site.

Table 11. Keeping Holland Tidy measuring system for beach litter (BFP 2009).

Score	Item Count	Description
A+ Very Clean	0	No visible litter
A Clean	1 - 3	At first glance no litter, but can sometimes be detected when looking closely
B Moderately Clean	4 - 10	Several items of litter spread here and there on the beach.
C Dirty	11 - 25	A significant part of the beach contains litter
D Very Dirty	> 25	Litter nearly everywhere in all shapes and sizes

San Francisco – Street and Sidewalk Maintenance Standards (SF CSA 2010)

As a result of a City Charter mandate resulting from an amendment passed by San Francisco voters in 2003, the City of San Francisco Services Auditor and the Controller's Office worked with the Department of Public Works to develop measurable standards for street and sidewalk maintenance. These standards include a litter ranking scale (Table 12), designed to provide an objective and measurable standard in regards to street maintenance. The results from assessments of litter conditions, as well as other street environment conditions (i.e., graffiti, landscaping, and condition of trash receptacles) are used in compliance reporting. Results from assessments conducted by City inspectors are also included a public annual report.

A final average rating of less than 2 must be attained to meet the standard for the route (SF CSA 2010). Inspection scores were analyzed to find an average of all sites assessed in the fiscal year (FY). For FY 2009 – 2010, 383 sites were assessed with an average score of 1.97, which was noted as an improvement in comparison to the previous year, which had a 2.37 average cite score (for 428 sites).

Table 12. San Francisco Street and Sidewalk Maintenance Standards for Street Cleanliness.

Score	Description
1	Acceptably clean, less than 5 pieces of litter per 100 curb feet examined
2	Not acceptably clean, 5 - 15 pieces of litter per 100 curb feet examined
3	Very Dirty, over 15 pieces of litter per 100 curb feet examined

5. TECHNIQUES TO MONITOR TRASH IN RECEIVING WATERS

Agencies throughout the U.S. have attempted to evaluate the concentrations and loads of pollutants discharged from stormwater and receiving waters. With regard to trash, different methods and equipment have been used to varying degrees of success. As a result of the worldwide literature, methods previously used by researchers to measure trash flux in stormwater conveyances and receiving waters are documented and summarized below.

5.1. Freshwater Trash Monitoring

Characterization of water quality in Los Angeles River (Ackerman et al. 2001)

The goal of the Ackerman et al. (2001) study was to identify sources of potential pollutants and characterize water quality along the Los Angeles River during dry weather. Grab sampling was conducted along eight points in the main stretch of the Los Angeles River, along with at the head of each of the seven tributaries, at three different times within 40 minutes. The samples were analyzed for bacteria, metals and nutrients, along with visual documentation of trash. The sampling locations may be applicable to the upcoming Tracking California's Trash Project.

Anacostia Watershed Trash Reduction Plan (Anacostia Watershed Society 2008)

Trash levels in the Anacostia River in Maryland were a severe problem that was monitored for years. Trash was monitored in the Anacostia River, Kingman Lake, and surrounding tributaries to understand the levels of trash in the area. Shoreline monitoring was used to monitor trash levels over time. This was done by establishing specific transects along the shoreline where the amount and types of trash and debris were documented. No debris floating in the water bodies were evaluated.

Guideline for Monitoring Stormwater Gross Solids (Environmental and Water Resources Institute (U.S.) Gross Solids Technical Committee 2010)

Gross solids are litter, trash, leaves, and large coarse sediments that travel, either as floating debris or bed loads, in stormwater conveyance systems. Traditional monitoring programs, which were designed to determine the effectiveness of Best Management Practices (BMPs) for reducing stormwater pollution, have relied on autosamplers that ineffectively sample gross solids. These large pollutants can have a harmful impact on the environment. The goal of Guideline for Monitoring Stormwater Gross Solids is to standardize data collection procedures and laboratory protocols used in evaluating the removal of gross solids. Three levels of monitoring procedures are analyzed throughout this report: screening evaluation, performance evaluation, and research and design.

Assessment of Efficient Sampling Designs for Urban Stormwater Monitoring (Leecaster et al. 2002)

The technical document describes guidelines for estimating marine debris concentration on shorelines, in surface waters, during visual surveys at sea, and in the benthos. Survey design, required equipment, survey techniques, and study implementation considerations are discussed. Surface water methods described include techniques used since 1971, including mainly plankton tows and nueston nets. Sea Education Association research is documented as the longest stating data set collected using a neuston net towed by a sailing vessel, used to create a 22-year data set. The manta trawl is described as the favored technique, and the details to develop a solid research plan are described. Bethic sampling is also described, though there is less research to reference for guidelines. Dive surveys, along with equipment options are compared and described.

Optimizing Sampling Methods for Pollutant Loads and Trends in San Francisco Bay Urban Stormwater Monitoring (Melwani et al. 2010)

The report summarizes efforts to evaluate sampling methods for pollutant loads and trend monitoring in the Guadalupe River and Zone 4 Line A. Technical evaluation of sampling methods, load estimators and strategies are described. The project partnered with the US Geological Survey to understand sediment loads in the monitored areas. Sampling points and information included in this report may be helpful to understand the water bodies in the Bay Area.

Working Our Way Upstream: A Snapshot of Land-based Contributions of Plastic and Other Trash in Coastal Waters and Beaches of Southern California (Moore et al. 2005)

The paper summarizes plastic pollution levels in the Los Angeles and San Gabriel Rivers, through collecting samples at three locations on Coyote Creek, San Gabriel River and the Los Angeles River in 2004 and 2005. Each site was analyzed during dry and wet periods over a six-month period. Samples were collected using a hand net to analyze the surface waters at the end of the water bodies, manta trawl to analyze the surface waters in the middle of the water bodies, steambed sampler to sample the bottom section of the water column, and rectangular net to sample the middle subsurface of the water column. Each device used a mesh size of 0.333mm except the handnets had a mesh size of 0.800 and 0.500 mm. Samples were taken to the lab and Tyler sieved were used to separate each sample into size fractions and then the sample type was analyzed (fragments, foam, pellets, line, films, etc.). Trash TMDLs in the Los Angeles region are required to reduce plastic debris greater than 5mm; however, this project determined that plastic particles less than 5 mm were more abundant. The report summarizes the average county by class in 24 hours, average weight density by size in 24 hours, average county by type in 24 hours, and average weight by type in 24 hours. The Los Angeles River has higher levels in all categories.

Quantity and Type of Plastic Debris Flowing from Two Urban Rivers to Coastal Waters and Beaches of Southern California (Moore et al. 2011)

Plastic pollution levels in the Los Angeles and San Gabriel Rivers (including Coyote Creek) were analyzed using several different monitoring techniques in 2004 and 2005, including the handnet, streambed sampler, manta trawl, and rectangular net (same project as Moore et al, 2005 reference). The data suggests that plastic pieces smaller than 5mm are of concern, showing particles less than 5mm in size to be 16 times more abundant than those greater than 5mm. Plastic fragments was the most common type of plastic found in Coyote Creek, while foamed plastic was the most abundance in the San Gabriel and Los Angeles Rivers. The Coyote Creek/San Gabriel River complex had a greater density of whole objects, while the Los Angeles River had the greatest density of pre-production plastic pellets. Small plastics, 1 to 4.75 mm, were most common in both river systems, making up 81% of all plastics sampled. The data can be extrapolated to understand 72-hour total abundance estimations. Also, each sample taken can be used to understand g/m3 for each size and type class.

<u>Personal communications with Gijsbert Tweehuysen, President of Waste Free Waters Foundation, The Netherlands (Tweehuysen 2014)</u>

Gijsbert Tweehuysen, President of the Waste Free Waters Foundation, described the methods that he is developing to sample litter in riverine conditions. Tweehuysen will be sampling four rivers, including Rhine (North Sea), Oder (Baltic Sea), Po (Mediterranean Sea) and Danube (Black Sea) for litter and microplastics. Tweehuysen conducted tests in the Meuse River and discussed the details with Marcus Eriksen and Carolynn Box. Tweehuysen samples the rivers at a depth of 20 to 70 cm, because this is where the density of litter is expected to be the highest, based on water flow speeds. Tweehuysen states that deeper levels are difficult to monitor because of the high water flows. The Meuse river tests were conducted during low discharges, and showed that during low water speeds, plastic litter (< 1 cm) were at the surface (tested using surface nets) and only a small portion of the plastic litter was found suspended in the water column. Tweehuysen believes that micro plastics are difficult to analyze in the water column because other litter can case mesh to clog.

<u>Personal Communications with Wilco Urgent, Graduate Student in the Department of Natural Sciences at Open Universiteit, The Netherlands (Urgent 2014)</u>

Wilco Urgent, a graduate student at Open Universiteit in The Netherlands, has been carrying out research in the Meuse and Rhine to evaluate microplastics between 125 microns and 5mm. The method that Urgent used evaluates microplastics sieves by pumping water through soil sieves. At three stationary water quality monitoring stations (two floating pontoons and one laboratory behind a dike); water is pumped from a depth of 80-100 cm below the surface. The inlet pipe's dimension is about 10-15 cm and the flow rate is 30 m3/h. About 700-1000 liters per hour runs through the stack of sieves with diameters at 1mm, 0.25 mm and 0.125 mm. A 5 mm prefilter is used on the water pumped to eliminate larger materials. Tests have been run on these methods that prove the presence of microplastics in the Rhine and Meuse rivers. Microplastics from a wide range of specific gravity have been found. Most particles are solid and compact and smaller than 1 mm. Films and sheets can measure up to 3mm. Expanded plastics have also been found.

5.2. Trash Monitoring in Marine Ecosystems

<u>The Role of the Rıo de la Plata Bottom Salinity Front in Accumulating Debris (Acha et al. 2003)</u>

Bottom trawls and costal sampling were conducted to describe the distribution, types, and amount of debris found in the bottom and shoreline across the salinity front of the South American estuary environment around the Rio de la Plata that drains the Buenos Aires watershed. Plastics and plastic bags were the main debris types in both areas. Research was conducted on six fisher-research cruises between 1996 and 2001 to sample the freshwater, estuarine, and marine environments. A bottom trawl, using a 200 mm mesh in the winds and 102 mm mesh at the cod ends and towed at a speed of four knots for 15-30 minutes, was used to estimate the concentration of marine debris on the bottom of the riverbed. Trawling stations were selected and sampled multiple times. Debris retained in the trawl net was counted and density was estimated. Concentrations of total debris upriver of the front were always significantly higher than downriver the front showing that the front acts as a barrier accumulating debris. The marine debris data was compared to the salinity profile; however no correlations were made. Shoreline surveys were also conducted to analyze trash inputs from the shorelines.

UNEP/IOC Guidelines on Survey and Monitoring of Marine Litter (Cheshire et al. 2009)

The report aims to summarize existing efforts to analyze trash through shoreline surveys, floating trash surveys, and benthic trash surveys. The floating and benthic trash surveys use visual observations made by researchers on a vessel or by SCUBA, and trawls to collect information. The report gives details for projects in water bodies near rivers, however, no details on how to measure rivers is documented. The techniques and project design aspects can be applied to river analyses.

Microplastic Pollution in the Surface Waters of the Laurentian Great Lakes (Eriksen et al. 2013)

Neuston samples were collected at 21 stations during a ~700 nautical mile (~1300 km) expedition in July 2012 in the Laurentian Great Lakes of the United States using a 333 µm mesh manta trawl and analyzed for plastic debris. Although the average abundance was approximately 43,000 microplastic particles/km^2, station 20, downstream from two major cities, contained over 466,000 particles/km^2, greater than all other stations combined. SEM analysis determined nearly 20% of particles less than 1 mm, which was initially identified as microplastic by visual observation, was aluminum silicate from coal ash. Many microplastic particles were multi-colored spheres, which were compared to, and are suspected to be, microbeads from consumer products containing microplastic particles of similar size, shape, texture and composition. The presence of microplastics and coal ash in these surface samples, which were most abundant where lake currents converge, are likely from nearby urban effluent and coal burning power plants.

Litter on the Sea Floor along European Coasts (Galgani et al. 2000)

The distribution and abundance of large marine debris were investigated on the continental shelves and slopes along the Baltic Sea, North Sea, Celtic Sea, Bay of Biscar and different areas in the north-western basin of the Mediterranean Sea and the Adriatic Sea. The study included 27 oceanographic cruises between 1992 and 1998 that documented marine debris on the seafloor using nets with otter boards, with 20 mm mesh and towed for 20 to 150 minutes, and pole trawls, with a 20 mm mesh and towed for 5 to 30 minutes. Submersibles were also used to document density of trash on the seafloor during some of the cruises, resulting in data that estimated pieces per km. The data found higher concentrations of plastic (average 70%) in the samples.

Microplastics in the Marine Environment: A Review of the Methods Used for Identification and Quantification (Hidalgo-Ruz et al. 2012)

68 studies to monitor microplastics in coastal and marine environments were explored and compared in the document. Different sampling strategies were identified to analyze sediment on beaches and seawater. Specifically, equipment and methods used to sample of suspended microplastics in sea water were compared in 33 studies. Of these studies, the majority (28) used neuston nets to collect sea surface samples, while bongo nets and zooplankton nets were used in five studies to collect water column samples, a continuous plankton recorder, an epibenthic sled, and a rotating drum sampler were used in three studies for water column sampling. The mesh sizes used in the equipment ranged from 0.053 to 3 mm, with most samples collected using mesh between 0.30 to 0.39 mm. The bongo nets and the epibenthic sled used nets that were 3-meters and 1-meter long, while the neuston nets had nets that varied between 1.0 to 8.5-meters. Laboratory processing and sorting of microplastics were explored, and include four main steps: density separation, filtration, sieving, and visual sorting. Visual sorting was one of the most commonly used methods for the identification of microplastics (using type, shape, degradation stage, and color as criteria). Chemical and physical characteristics (e.g., specific

density) were also used. The most reliable method to identify the chemical composition of microplastics is by infrared spectroscopy.

Three Easy to Ship and Easy to Use Aluminum Neuston Trawls Designed and Fabricated for use on Different Vessels of Opportunity. Results of Field Tests and Preliminary Intercalibration Efforts (Eriksen et al. 2011)

Three different neuston trawls were described and compared for use in different environments and towed at different speeds. The design parameters of each trawl are discussed and described.

Concentrations of Marine Microplastics in Puget Sound and Chesapeake Bay (LaRocque et al. 2013)

Samples of floating microplastic were collected from the upper 0.5 water column using a custom-fabricated manta net, with 0.33 mm plankton net, and towed at 0.7 to 4.5 m/s for 5-15 minutes. The research was done by University of Washington Tacoma, where they have multiple programs dedicated to understanding plastic pollution along the region's shorelines and waters.
http://www.urbanwaters.org/sources-and-distribution-marine-microplastics

A comparison of Neustonic Plastic and Zooplankton at Different Depths near the Southern California Shore (Lattin et al. 2004)

Trash at two Santa Monica Bay sites offshore from Ballona Creek, which drains downtown Los Angeles, were evaluated by conducing trawl surveys before and after a 20 mm rain event. All debris and zooplankton density were measured at three depths at each site. One site was located approximately 0.8 km offshore (15 m deep) and the other was approximately 4.5 km offshore (30 m deep). Samples were taken on the surface, in the water column (5 m depth), and near the bottom. Surface samples were collected with a manta trawl, mid-depth samples with paired 61 cm diameter bongo nets, and bottom samples with an epibenthic sled, using 0.333mm mesh nets. All trawls were completed parallel to shore for 10 minutes, with varying speed between 1.0 to 2.3 m/s (measured with a B&G paddlewheel sensor). Flowmeters were mounted across the net mouths at all times to estimate water volumes. Samples were preserved and taken back to the laboratory for analyses. Samples were placed in fresh water and floating plastic was removed. A dissecting microscope was used to remove remaining debris and plankton. Debris was sorted by category and size. Density of debris was greatest near the bottom and least in midwater. Debris density increased after the storm, particularly at the sampling site closest to shore, reflecting inputs from land-based runoff and re-suspension.

Marine Debris Monitoring and Assessment (Lippiatt et al. 2013)

The report describes NOAA Marine Debris Program (MDP) standardized, statistically valid methodologies for conducing rapid assessments of the debris material type and quantity, including surveys conducted at beaches and in water bodies. The Surface Water Methods sections describes rigorous, standardized methodologies for assessing floating plastics, and discusses details related to robust survey designs for coastal and offshore waters. Typical methods to monitor marine debris are listed, including pelagic plankton sampling through oblique plankton towns, Neuston nets, and the Manta trawl, and continuous plankton recorder. The report evaluated the different methodologies and developed guidelines for methods and project design. The report also led to more rigorous testing in coastal waters in a technical study conducted by Versar, Inc in 2012. Benthic (seafloor) marine debris analyses are also described in the document. Generally, for shallower environments, less than 20 meters, dive surveys along line or strip transects are suggested for assessment of seafloor debris. Different benthic trawls are discussed and referenced for deeper environments; however, there this type of trawling definitely has negative impacts to the seafloor environments.

A Comparison of Neustonic Plastic and Zooplankton Abundance in Southern California's Coastal Waters (Moore et al. 2002)

The density of neustonic plastic particles was compared to that of zooplankton in the coastal ocean near Long Beach, California. Two trawl surveys were conducted, during an extended dry period when there was little land-based runoff, the second shortly after a storm when runoff was extensive. On each survey, neuston samples were collected at five sites along a transect parallel to shore using a manta trawl lined with 333 µ mesh. Average plastic density during the study was 8 pieces per cubic meter, though density after the storm was seven times that prior to the storm. The mass of plastics was also higher after the storm, though the storm effect on mass was less than it was for density, reflecting a smaller average size of plastic particles after the storm.

Guidance on Monitoring of Marine Litter in European Eeas (MSFD Technical Subgroup on Marine Litter 2013)

The Marine Directors of the European Union and related entities have developed a common strategy that focuses on the methodology and technical and scientific implications related to the Marine Strategy Framework Directive that requires European Member States to develop strategies that should lead to programs of measures to understand environmental health. The document acts as a guidance document on how to monitor beaches, surface waters, seafloor litter, litter in biota, and micro litter. Visual observations and net tow methodologies for analyzing surface waters for trash are described. It is noted that the methods described can also be applied to riverine litter monitoring, by observation from bridges or similar. For understanding litter on the seafloor, transect analyses completed by divers are discussed. Specifically, for sampling microplatics, a net is recommended that is located outside of the wake zone when deployed by a vessel. The report also recommends lab analyses and separating material by size and type.

Prevalence of Microplastics in Singapore's Coastal Marine Environment (Ng and Obbard 2006)

This study documents the presence and abundance of microplastics (>1.6 µm) in Singapore's coastal environment, including beaches and offshore. Sampling protocols for the collection and analysis of microplastics were developed, and beach sediments and seawater (surface microlayer and subsurface layer) samples were collected from nine different locations around the coastline. Low density microplastics were separated from sediments by flotation and polymer types were identified using Fourier transform infrared (FTIR) spectrometry. Microplastics were detected in four of seven beach environments and the highest quantities were found on two of the more popular beaches. Polyethylene, polypropylene and polystyrene microplastics were also found in the surface microlayer (50–60 µm) and subsurface layer (1 m) of coastal waters. The presence of microplastics in sediments and seawater is likely linked to waste disposal activities from industry and recreational uses.

Marine Litter Monitoring Programmes – A Review of Methods with Special Reference to National Surveys. (Rees and Pond 1995)

Several approaches to monitor marine debris along shorelines (not offshore) are described in the paper, concluding that no standard techniques can be universally employed for monitoring marine debris but the use of volunteers is essential to achieve a large-scale survey.

Marine Debris Survey Manual. NOAA Technical Report NMFS 108. (Ribic et al. 1992)

NOAA Technical Report that describes various techniques to monitor marine debris through visual observations, trawling, and shoreline measurements. This document was updated in 2012 and 2013 with updated information.

Personal Communications with Heather Richard, Romberg Tiburon Center Graduate Student in 2013 and 2014. (Richard 2014)

Heather Richard, a graduate student at the Romberg Tiburon Center, carried out research analyzing floating plastics in San Francisco Bay using a manta trawl, with a 0.333 mm mesh towed at less than 2 knots. Richard also conducted microplastic monitoring off of multiple docks on the San Francisco Bay. The technique used to collect samples off the docks included pumping water from different levels in the water column through a net. Richard is available to participate in the design of our project and may assist with some field work.

Personal Communications with Chelsea Rochman. Postdoctoral Scholar in the Aquatic Health Program in the School of Veterinary Medicine at the University of California, Davis (Rochman 2014)

In fall 2014, Chelsea Rochman will carry out microplastic research in the Sacramento River Delta and Chesapeake Bay. Rochman is currently developing a research plan and plans to collect samples using a continuous pump and/or collection of 4L water samples from various locations in the project area. Rochman will be serving on the Technical Advisory Committee and will assist in project design aspects.

Monitoring the Abundance of Plastic Debris in the Marine Environment (Ryan et al. 2009)

Techniques to measure plastic is the environment are explored, including techniques to measure plastic pollution floating on surface waters, plastic suspended in waters, plastic on the sea floor, and plastic entering the ocean through runoff. The report concludes that large numbers of net-based surveys are essential to adequately characterize the abundance of plastic floating at sea. Visual observation techniques are also explored, which may be an alternative to equipment-based techniques. The report also summarizes the protocols used to assess plastic debris loads in urban runoff, mainly referencing techniques used by the Algalita Marine Research Foundation. Table 2 included in the report states that the manta trawl can be used to sample the surface and mid stream region, hand net to sample surface and edge habitats, weighted net to sample the mid-water region, streambed sampler can sample the bed load, and a scoop device can be used to sample the bottom sediments.

Assessment of Marine Debris on the Belgian Continental Shelf (Van Cauwenberghe et al. 2013)

A comprehensive assessment of marine litter in three environmental compartments of Belgian coastal waters was performed. Abundance, weight and composition of marine debris, including microplastics, were assessed by performing beach, sea surface and seafloor monitoring campaigns during two consecutive years. Beach debris was analyzed at each beach in the project area in a systematic method by selecting 100 meters of beach and classifying and analyzing trash within a designated area. Floating debris was evaluated by surface samples collected with a neuston net with a 2 x 1 meter opening and 1 mm mesh size. The net was towed for 1 km at a speed of 1 to 2 knots. Seafloor debris was collected in accordance to the UNEP guidelines using an otter trawl (with 10 mm mesh) and a beam trawl (with a 10 mm mesh). In the surface and seafloor samples, microplastic dominated by weight, which is different than results from the beach research.

Personal communications with Ian Wren, San Francisco Baykeeper (Wren 2014)

San Francisco Waterkeeper partnered with San Francisco Estuary Institute (SFEI) to carry out microplastic research in San Francisco Bay in 2011. The project included carrying out five manta trawl surveys to analyze the surface waters after a storm event along the East Bay shoreline and San Francisco Embarcadero**.** The samples were sent to the University of Washington Tacoma for analysis to quantify microplastics. The highest concentrations were found along the San Francisco shoreline and concentrations from other sites were consistent with other urban estuaries analyzed by the University of Washington group, including Puget Sound and Chesapeake.

6. Summary of Pertinent Findings

6.1. Street Sweeping

6.1.1. Methodologies

Commonly employed strategies for assessing street sweeping effectiveness include the following:

- **Comparing test and control streets or sweeping routes** (Weston 2010, Herrera 2009, Newman et al. 1996);
- **Comparing paired watersheds or basins** (Selbig and Bannerman 2007, Lippner et al. 2001); and,
- **Comparing single streets, routes, or watersheds before versus after sweeping or enhanced sweeping** (Selbig and Bannerman 2007, Sartor and Boyd 1972, Pitt and Shawley 1981).

Common strategies for measuring trash or dirt collected include:

- **Measuring the amount of trash (or dirt) on the street** (Sartor and Boyd 1972, Sutherland 2011, Herrera 2009, Newman et al. 1996, Pitt and Shawley 1981);
- **Measuring trash in storm drain inlets or outlets** (caught by various full capture devices or litter traps) (Herrera 2009, Walker and Wong 1999, Lippner et al. 2001, Lippner and Moeller 2000, Marais and Armitage 2004a and 2004b); and
- **Measuring the amount of trash (or dirt) in the sweeper truck after sweeping** (Weston 2010, EOA 2007, Herrera 2009).

Some methodologies utilized small, focused samples, while others used broader data such as total weight or volume of dirt in the sweeper at the end of a sweeping route. Another approach applies trash or dirt to the road, and then assesses the various fates of the applied dirt or trash (Breault et al. 2005, Sartor and Boyd 1972, Sutherland 2011). Some studies used models to simulate results of sweeping under varied scenarios based on previously collected data (Riccio and Litke 1986, Sutherland and Jelen 1997). One Seattle study (Herrera 2009) combined multiple assessment methods in order to estimate from a mass balance the quantity of sediment transported through stormwater conveyance systems.

Comparing test and control streets or sweeping routes

Using this method, control streets may be defined as streets receiving no sweeping, or streets receiving routine (un-enhanced) sweeping. The test streets are characterized by either the use of enhanced sweeper equipment or by a more frequent sweeping schedule.

Comparing paired watersheds

A paired watershed or paired basin approach utilizes a test and control watershed or basin. First, sampling results are gathered on streets and in water quality samples during a calibration period, during which no sweeping (or no enhancement) is performed in either watershed or basin. The relationship between the street dirt and water quality is measured, representing the baseline for the study. Sweeping then starts (or is enhanced) in the test watershed or basin. Once sweeping begins (or is enhanced), samples are again collected and changes in either street-dirt and/or water quality resulting from street sweeping could then be quantified by use of statistical tests (Selbig and Bannerman 2007).

Comparing single streets, routes, or watersheds before and after sweeping

In this method, street dirt samples are collected before sweeping occurs (immediately to one or two days prior, depending on the study). After sweeping, the same sample collection method is conducted and the results compared. In a variation on this technique, known quantities of dirt or trash are spread on the road surface and after sweeping any remaining street dirt/trash is measured.

Measuring the amount of trash (or dirt) on the street

Street dirt is commonly measured using a hand-held vacuum (shop-vac) or by manually sweeping and spraying to collect samples. Selbig and Bannerman provide in-depth descriptions of how the shop-vac operated to ensure sampling accuracy and repeatability.

Measuring trash (or pollutants) in storm drain inlets or outlets

This technique is used as a more direct assessment of the influence of street sweeping over the amount of urban trash or pollution entering stormwater conveyance systems. Litter traps, such as the Side Entry Pit Trap (SEPT), are inserted into catch basin inlets (Walker and Wong 1999, Marais and Armitage 2004a, 2004b). Trash collected by these traps is then collected for analysis. Other studies have attached mesh traps to outfalls (Lippner et al. 2001) and evaluated sweeping based on the outfall-trap contents. Some studies have found results from drain inlets/outlets to be quite different from effectiveness as measured by street-dirt sampling methods.

Measuring the amount of trash (or dirt) in the sweeper truck after sweeping

Using this method, street dirt or trash is removed from the sweeping equipment after a pass or route has been completed. Study design may include measurement of total volumes and/or weight or may sample the swept debris for trash contents or constituents of concern.

6.1.2. Effectiveness of Removing Trash

Street sweeping can be an effective trash control measure, removing 90 to 100 percent of trash in streets under ideal conditions (Riccio and Litke 1986, Sartor and Boyd 1974, Sutherland and Jelen 1997, Sutherland 2011). The most pertinent findings regarding the effectiveness of street sweeping at intercepting and removing trash in streets prior to entering MS4s are provided below:

Sweeper Type

- Typically, sweeping efficiency increases with increasing particle size. This is typical for all sweeper types, and is especially important for mechanical sweepers, which are primarily effective at removing larger particles (as opposed to fine sediment) (Sutherland 2011, and Sutherland and Jelen 1997).
- New-technology equipment (regenerative and vacuum sweepers) have been shown to be more effective at removing fine solids and pollutants, but may or may not show an improvement over mechanical sweepers when removing street litter. (Breault et al. 2005, Sutherland 2011, and Sutherland and Jelen 1997, Lippner and Moeller 2000).
- For large (>5mm) material (e.g., trash), no studies to-date have shown that there are significant differences in sweeper efficiency between different types of sweepers.

Frequency

- Generally, as the frequency of street sweeping increases, street dirt and litter removal rates increase. However, diminishing returns may be expected at some point (i.e. at higher frequencies, the marginal increase of sweeping will produce lower gains in efficiency) (Newman et al. 1996). This is likely due to the lower efficiency of sweepers at lower street-dirt and litter loading levels (Pitt 2004a, Pitt and Shawley 1981).
- Sweeping frequency should be greater than rainfall frequency. If sweeping occurs at longer intervals than inter-event dry periods, there is a higher likelihood that pollutants will be flushed into stormwater conveyance systems before being collected by sweepers (Marais and Armitage 2004, Walker and Wong 1999). Once rainfall events are more frequent, the effectiveness of sweeping likely drops below 50 percent (Marais and Armitage 2004).

Operational Practices

- Driver speed and attention matters. Slower speeds remove more street dirt (and litter). Five miles per hour is the recommended speed to optimize sweeper performance and miles swept per day (Sartor et al. 1974, Southerland 2011, Herrera 2009).
- Sweeping close to the curb is important. Street litter accumulation increases as distance from the curb decreases, with 95% of street litter found within 18 inches of the curb (Fleming 1978, as cited by Riccio and Litke 1986).
- The presence of parked cars during sweeping can greatly reduce sweeping effectiveness. The reduction of one parked car on a block can increase the effectiveness by as much as 28 percent (Riccio and Litke 1986).

6.1.3. Data Gaps

- **Few studies focused on trash –** Most studies are focused on sediment and sediment-bound pollutants. These studies often assess the ability of street sweeping programs to reduce fine sediment, while overlooking effects on trash. While trash removal has been a traditional motivation for street sweeping (for aesthetic purposes), studies focused on street sweeping, trash, and stormwater quality are quite rare.
- **Street trash accumulation patterns –** Studies have characterized street dirt and dust loading (Pitt et al. 2004b), but little study has been conducted to determine these patterns for trash accumulation on streets, in curbs, and within storm drain inlets.
- **Street trash washoff patterns –** Even for street dirt and dust, relatively few studies have characterized washoff patterns (Pitt et al. 2004b). Further study is required to determine the ways in which street trash are mobilized by rainfall.
- **Cost-Benefit Information is not adequately addressed –** There is a general lack of cost-benefit analysis found for the major municipal maintenance practices included in this literature review (street sweeping, storm drain inlet cleaning, storm drain line flushing, and street flushing). There is especially little comparison evaluating trash reduction costs from sweeping as compared to other trash control measures.

6.2. Partial Capture Devices

Findings regarding the performance and/or effectiveness of partial-capture trash treatment devices installed within California, the United States and internationally are provided below.

- A pilot study conducted by the Watershed Protection Division of the City of Los Angeles Department of Public Works, Bureau of Sanitation indicated that storm drain inlet openings screen covers prevent approximately 83.2 to 84.6 percent of trash from entering the storm drain inlet over the course of one year (City of Los Angeles 2006b).
- A pilot study of a litter boom conducted by the County of Los Angeles Department of Public Works indicated that litter boom performance is approximately 80 percent. A four-boom containment system tested in Jamaica Bay (Queens, New York) during a two-year pilot study indicated that boom effectiveness was 75 percent. In addition, a Melbourne, Australia study (McKay and Marshall 1993) released tagged litter items upstream of litter booms to determine floating boom performance. The results varied from 12 percent to 50 percent recapture.
- Trash racks at pump stations are very common and are "essential" since they screen out large objects capable of damaging pumps (USDOT 1982).
- Trash racks can remove 80 to 100 percent of large, hard trash and 40 to 100 percent of soft, deformable trash (e.g., plastic bags) (Nielsen and Carleton 1989 in Fletcher et al. 2004).
- Trash rack removal effectiveness of floatables is suggested to be 5 to 14 percent (McKay and Marshall 1993 in Allison et al 1998b).

6.3. On-land Trash Assessments

Findings regarding the implementation of on-land trash assessment methods within California, the United States and internationally are provided below.

- Both qualitative and quantitative assessment protocols have been effectively used by public agencies and non-governmental organizations to assess the level of trash/litter on streets and sidewalks and detect improvements (or the lack there of) over time. The primary advantage of qualitative survey methods is the low cost of implementation, which enables a greater number of sites to be assessed with the same resources. Qualitative methods have been shown to reflect quantitative measurements of litter conditions (GVLS 2007).
- Repeated sampling of the same site could reduce questions regarding temporal variability of sites. Likewise, surveying a greater number of sites within an area can improve accuracy of spatial extrapolation / interpolation. Furthermore, the quality of scorer training and extent of scorer experience will likely affect accuracy and precision of index scores and score subjectivity.
- A potential advantage of a semi-quantitative method is that the subjectivity and uncertainty of scoring when using a qualitative method is reduced by providing a quantitative objective base for judgments made via qualitative (visual) assessments.
- Quantitative methodologies are often detailed, including trash counting, categorizing, as well as collection of many related parameters at the site. Although these methods are relatively rigorous, the time to perform each assessment would be much greater than the time required for visual qualitative methods. However, the results of quantitative studies have illuminated trash generation characteristics that may be useful for developing or improving simple, yet accurate, methods.

6.4. Receiving Water Monitoring

Researchers have successfully performed monitoring for micro and macro-trash in flowing freshwater systems (e.g., creeks, channels and rivers) and marine environments. Findings pertinent to the implementation of receiving water methods via the TCT project are provided below.

- Trash monitoring methods have been established for marine open water and shoreline sampling. Numerous studies have deployed various types of monitoring equipment to evaluate the densities of trash in these environments. Lessons learned on the feasibility and accuracy of different types of equipment and monitoring designs through these studies will assist the TCT project in developing trash monitoring methods specific to flowing (i.e., lotic) water bodies.

- A limited number of studies have attempted to quantify the concentrations and loads of trash (micro or macro) transported by a freshwater flowing receiving water (e.g., channel, creek, river) during base/low or storm flows. Those studies that have attempted to quantify trash transport used a combination of hand nets, manta trawls, and steambed samplers. Additional studies evaluating the accuracy, precision and reproducibility of data collected via these methods is needed.

7. References

7.1. Street Sweeping

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Appendix A

Summary of Reviewed Street Sweeper Characterization and Effectiveness Monitoring Studies

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Appendix A. Summary of Reviewed Street Sweeper Characterization and Effectiveness Monitoring Studies

Study	Measure of Effectiveness	Equipment	Treatment	Results/Effectiveness of Trash Removal
Breault et al. 2005		Mechanical + vacuum		
Alameda (EOA 1999)	Control – Treatment	Broom Sweeper	Increased from monthly to twice monthly	Not effective
Caltrans LMPS (Lippner et al. 2001)	Control – Treatment for dry weight, volume and count	Manual Pickup	Increased from monthly to weekly	2-29% Dry weight 7-32% Volume 19-28% Count
Lippner and Moeller 2000	Whether or not the reduction of trash (by volume, weight and count) was statistically significant at the 95 percent level	Mobile M-8A Broom Sweeper	Increased from monthly to weekly	Not effective
Cape Town (Marais et al. 2004)	Comparing amount of trash in catch basin inserts to amount removed from street sweeping in the Commercial Business District	Sweeper + manual sweeping	Increased from daily to 2-3 times daily	Increase from 83% to 99% of trash removed by street sweeping
Cape Town (Marais and Armitage 2004)	Ratio of number of days between street sweeping to number of days between significant storms		Varying sweeping frequency	Less than 50% when frequency of street sweeping is greater than the number of days between rain events
Floatables Control (Newman et al. 1996)	Item count, Surface Area & Weight Percent Reduction (Baseline –Treatment) /Baseline	Mechanical sweeper + Broom	Manual sweeping in addition to street sweeping	
Parked Cars (Riccio and Litke 1986)	Increase in probability that that street will be made acceptably clean according to a score card system	Modeling based on existing data	Simulated reduction in one car	Up to 28% Most effective for the dirtiest streets
Street Surface Contaminants (Sartor et al. 1974)	Unknown	Unknown	Street Sweeping	95-100%
Review of Street Sweeping Knowledge (Sartor and Gaboury 1984)	End of pipe measurement		Varying sweeping frequency	Greater than 50% when sweeping interval is 0.5 to 1 times the inter-storm period
Madison, Wisconsin USGS (Selbig and Bannerman)	Difference in paired-basin relationship (streets and basins monitored)	Vacuum, regenerative air, and mechanical	Sweeper type and for mechanical brooms	Water contaminants focus

Study	**Measure of Effectiveness**	**Equipment**	**Treatment**	**Results/Effectiveness of Trash Removal**
			frequency	
Seattle (Herrera 2009)	Street dirt yields, reduction in street dirt, and storm drain dirt accumulation	Regenerative air	Varying sweeping frequency	
Palo Alto (Teresi 2008)	Difference in volume removed	Mechanical broom sweepers	Parking restriction on streets when sweeping	Annual increase of 350 yards in a 145-acre area
Real World Sweeper Performance (Sutherland 2008)	Difference between amount removed by sweeper and what was laid down on the street	Crosswind NX regenerative, Whirlwind MV vacuum, and Eagle FW mechanical sweeper	Different sweeper performance for different size ranges	For 2.0-6.37 mm particles: 95.8%Mechanical 99.3% Vacuum 99.4% Regenerative
Street Sweeping Computer Model (Sutherland and Jelen 1997)	Computer model of the amount of sediment removed	Tandem Mobil mechanical and TYMCO vacuum-assisted, Elgin Crosswind regenerative, and Enviro-Whirl vacuum sweeper	Different sweeper performance for different size ranges	Particles greater than 6.37mm: 87% Tandem 92% Regenerative 96% Vacuum
San Diego (Weston 2010)	Street dirt yields (collected material)	Vacuum, regenerative air, and mechanical	Sweeper type and varying frequency	
Melbourne, Australia (Walker and Wong 1999)	Reduction in gross solids loads of stormwater runoff passing through catch basins	Mechanical and regenerative air	Sweeper type and varying frequency	