Sediment Management Practices

Clean Watersheds for a Clean Bay Task 4 Literature Review

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List of Abbreviations and Acronyms

ac	Acre
BASMAA	Bay Area Stormwater Management Agencies Association
BMP	Best Management Practice
ft^3	Cubic feet
m^3	Cubic meter
ft	Feet
hr	Hour
in	Inch
kg	Kilogram
km	Kilometer
L	Liter
MDL	Method detection limit
m	Meter
mg	Milligram
µm	Micrometer (micron)
MRP	Municipal Regional Stormwater NPDES Permit
MS4s	Municipal Separate Storm Sewer Systems
NPDES	National Pollutant Discharge Elimination System
PCBs	Polychlorinated Biphenyls
Lbs	Pounds
Bay Area	San Francisco Bay Area
SFRWQCB	San Francisco Regional Water Quality Control Board
SWRCB	State Water Resources Control Board
TMDL	Total Maximum Daily Load
USEPA	United States Environmental Protection Agency
yr	Year

1. INTRODUCTION

Due to elevated levels of polychlorinated biphenyls (PCBs), mercury and other pollutants of concern in sport fish in San Francisco Bay (Bay), the California Office of Environmental Health Hazard Assessment issued an interim advisory on the consumption of some fish caught from the Bay. The advisory led to the San Francisco Regional Water Quality Control Board (SFRWQB) designating the Bay as an impaired water body on the Clean Water Act Section 303(d) list and the subsequent development of Total Maximum Daily Load (TMDL) water quality restoration programs targeting PCBs and mercury. The general goals of the TMDLs are to identify sources of PCBs and mercury to the Bay and implement actions to control these sources and protect beneficial uses of the Bay. One pathway for conveyance of PCBs and mercury identified in the TMDLs is urban stormwater. Priority actions related to urban runoff are addressed through the Municipal Regional Permit (MRP) for stormwater discharges in the Bay Area issued to 76 municipalities and agencies, collectively known as Permittees. Provisions C.11 and C.12 of the MRP address mercury and PCBs, respectively.

Clean Watersheds for a Clean Bay (CW4CB) is a grant-funded project designed to assist Permittees in implementing priority actions called for in the mercury and PCB TMDLs and corresponding requirements in MRP Provisions C.11 and C.12. The Bay Area Stormwater Management Agencies Association (BASMAA), in collaboration with BASMAA member agencies and participating Bay Area cities, manages the CW4CB project. The CW4CB project includes the following seven major tasks, which are intended to comply with MRP provisions associated with PCBs and mercury (in parentheses):

1. Project management, oversight and reporting;
2. Pilot watershed selection;
3. Property identification and referral (C.11/12.c);
4. Municipal sediment removal and management practices (C.11/12.d);
5. Stormwater treatment retrofits (C.11/12.e);
6. Risk communication (C.11/12.f); and,
7. Outreach and technology transfer.

This literature review is an initial step in implementing Task 4, municipal sediment management. Task 4 is evaluating on a pilot-scale methods to enhance the pollutant load reduction benefits of municipal operation and maintenance activities that remove sediment from streets and storm drain system infrastructure. Older industrial areas in the Bay Area urban landscape with elevated PCBs will be targeted, with mercury and other pollutants being a secondary consideration. The project will work with municipal staff to test enhancing removal of sediments and associated particle-bound pollutants during routine activities such as street sweeping, storm drain inlet cleaning, storm drain system piping maintenance, and pump station maintenance. The evaluation will also include consideration of street and piping flushing (potentially with recycled water) and capture, collection, and/or routing to the sanitary sewer.

1.1. PURPOSE AND SCOPE OF LITERATURE REVIEW

This literature review summarizes past relevant Bay Area studies and peer-reviewed studies carried out in other states or countries on particular municipal sediment management practices. The sediment management topics on which the literature review is based are outlined in MRP Provisions C.11.d and C.12.d and include:

- Street sweeping,
- Stormwater conveyance system cleaning, and
- Street flushing and capture.

The purpose of this review is to present available information from studies that evaluated the effectiveness of the management practices listed above to remove sediment and associated pollutants (especially PCBs and mercury) from streets and other paved surfaces and stormwater conveyance systems before entering receiving waters. Because studies that quantify effectiveness are limited, summaries of relevant studies[1] are presented to provide adequate background in order to identify affordable and practical ways to enhance sediment management practices in high priority areas and to identify management priorities. This literature review also summarizes major findings and makes recommendations to improve our collective understanding of how to improve the effectiveness of sediment management practices to reduce PCB and mercury loadings to the Bay. Finally, a cost-benefit analysis is presented to assist Bay Area municipalities in designing and implementing specific sediment management strategies.

1.2. Use of the Document

This literature review was developed under the oversight of the CW4CB Project Management Team (PMT), which is made up of the BASMAA Executive Director and representatives from several BASMAA agencies (i.e., Bay Area stormwater management programs). The literature review is intended to be used by the PMT and CW4CB's municipal partners to inform the development of the aforementioned municipal sediment management pilot-scale evaluations.

1.3. Document Organization

The literature review is organized in the following sections:

Section 1. Introduction, Purpose and Scope
Section 2. Background and Methods
Section 3. Street Sweeping Studies
Section 4. Stormwater Conveyance System Cleaning Studies
Section 5. Street and Storm Drain Line Flushing Studies
Section 6. Summary of Findings
Section 7. Costs of Sediment Management Practices
Section 8. Cost/Benefit Analysis of the Evaluated Sediment Management Practices
Section 9. Data Gaps
Section 10. Recommendations
Section 11. References

[1] Lists of attributes to select the most relevant studies to summarize were created and described in the methodology section (3.0).

2. BACKGROUND AND METHODS

The San Francisco Estuary Institute (SFEI) recently completed a California Proposition 13-funded project entitled "Regional Stormwater Monitoring and Urban BMP Evaluation" that focused on characterizing PCBs and mercury in urban runoff in the Bay Area and potential control measures for these pollutants (e.g., McKee et al. 2006 and Yee and McKee 2010). The project provides valuable background on PCBs and mercury, including current knowledge of these pollutants, their sources, distribution in the environment and Bay Area, and sediment transport processes. This section describes pertinent general information related to PCBs and mercury and the factors that may affect the effectiveness of sediment management measures to remove or control associated pollutant loads. In addition, because PCBs and mercury tend to be bound to particulates, sediment transport processes are primary pathways through the stormwater conveyance system, and consequently are briefly described below. Note that this literature review does not describe PCB and mercury sources; rather it focuses on potential methods to manage these pollutants in the street and storm drain pathways in order to reduce loads to the Bay. Because this section serves simply as basic background for the literature review, the reader is referred to the studies conducted through the Proposition 13 project (http://www.sfei.org/urbanstormwaterBMPS), and especially McKee et al. (2006), for additional details on PCB and mercury sources, sediment transport, and other related topics.

2.1. General Information Regarding PCBs and Mercury

PCBs are considered a legacy pollutant, meaning that peak production and release to the environment occurred years ago; however, the impact to receiving waters, in particular the Bay Area, continues to be significant because PCBs degrade slowly in the environment. Monsanto, an agricultural chemical company, commercially produced PCBs from 1929 to 1977 under the trade name Aroclor and is considered one of the major producers of this pollutant (McKee et al. 2006). The total U.S. production of PCBs has been estimated to be approximately 640,000 tons (Breivik et al. 2002).

According to Erickson (1992), PCB use can be grouped into three main categories:

1) Controllable closed systems where leakage is avoided by design during the lifespan of the equipment;
2) Uncontrollable closed systems, which are technically closed but where leakage usually occurs (also referred to as nominally closed); and
3) Dissipative (open-ended) uses, which involves non-recoverable PCBs that come in direct contact with the environment (also referred to as open-ended applications).

Keeler et al. (1993) divided the dissipative category into two smaller groups of plasticizers and other uses (e.g., flame retardants, paints, inks, sealants, and carbonless copy paper). It is not known to what extent PCBs use in the Bay Area fell within the three categories described above. Although the production of PCBs was banned in the U.S. in 1979, closed systems such as capacitors and transformers continue to be in use in the U.S.

Mercury is both a legacy pollutant and a contemporary pollutant. Unlike PCBs, which are synthetic, mercury can be extracted in the raw form by mining. Peak production and use of mercury occurred twice in U.S. history. First, it was mined extensively during the Gold Rush in California[2] and a second time after World War II. The use of mercury in batteries and latex paint, two of the largest uses of mercury in the U.S. between 1950 and 1990, was banned in 1991. In addition, the mining of mercury as a primary mineral commodity was prohibited in the U.S. as of 1992 (McKee et al. 2006). However, it is still obtained as a by-product in other mining activities and in natural gas extraction (USGS 2011). Another source of mercury in the U.S. is the chlor-alkali process[3], though McKee et al. (2006) noted that no chlor-alkali plants have been identified in the Bay Area. Current uses of mercury , including dental services, lighting, and switches, medical and other types of instruments, as well as the use and improper disposal of old equipment, still contribute mercury to the environment (McKee at al. 2006).

Sources of PCBs and mercury to Bay Area stormwater conveyance systems include sediment erosion from current and former industrial areas where PCBs and mercury were used. The largest use of PCBs was electrical equipment such as transformers and capacitors. Another source of PCBs is demolition and remodeling of buildings that were built when PCBs were used in building products such as caulk.

For both PCBs and mercury, studies have shown that the highest median concentrations are found in industrial areas. The spatial distribution of PCBs tends to be more “spotty,” and therefore, more variable than mercury. PCB concentrations in bulk sediment and near surface soils range across eight orders of magnitude whereas mercury concentrations range across three orders of magnitude (Yee and McKee 2010). McKee et al. (2006) determined that the significant differences between PCBs and mercury concentrations were likely due to a combination of source characteristics and the dispersion of mercury by means of long-range atmospheric transport. Knowledge of PCB and mercury sources and of the factors that may affect their concentrations is important in estimating potential pollutant loads and the effectiveness of sediment management practices.

The next section on sediment transport briefly summarizes the processes that mobilize sediment-bound pollutants (e.g., PCBs and mercury) from source areas into stormwater conveyance systems.

2.2. SEDIMENT TRANSPORT PROCESSES

Runoff from increased imperviousness and other factors related to urbanization mobilizes particulate material that accumulates on streets and other paved surfaces and in stormwater conveyance systems. Large storms may also erode pervious surfaces and streams, further increasing the sediment supply to inlets and the stormwater conveyance system. In addition to the contribution of PCB and mercury from transported sediment, tires from heavy vehicles that transport materials from industrial areas transfer sediment, sometimes containing PCBs and/or mercury, from private properties to adjacent streets and gutters[4]. Consequently, the stormwater conveyance system can provide a main pathway from urban PCB and mercury source areas to the Bay. Although less polluted sediment contributed from the

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[2] The Guadalupe River watershed in south SF Bay has been shown to have highly elevated mercury concentrations as a result of the upstream New Almaden mercury mine. Once the largest producer of mercury in the U.S., this mine produced an estimated 38,000,000 kg of mercury from the time it was claimed in 1845 until its closure in 1975, yielding a gross revenue in excess of $60,000,000 (SFBRWQCB 2000).

[3] This term refers to two chemicals, chlorine and an alkali (sodium hydroxide or potassium hydroxide), which are simultaneously produced as a result of the electrolysis of saltwater.

[4] The City of Oakland carried out a PCB source identification and abatement study (Kleinfelder 2006) in the Ettie Street Pump Station watershed and found that elevated PCB concentrations in street right-of-ways were related to contaminated sediment that originated from nearby properties.

upstream watersheds may dilute stormwater runoff pollutant concentrations, the impact from elevated PCB and mercury concentrations is still significant (McKee et al. 2006). The evaluation of sediment management practices in this literature review focuses on the potential to reduce or control PCB and mercury loads to Bay.

The mass of a pollutant transported in stormwater in a particular particle size range is a product of the mass of the sediment load and the concentration of the pollutant in that particle size range (McKee et al. 2006). Smaller particles are mobilized more than larger particles at low flows, and therefore constitute the majority of the sediment mass being transported. However, under high flows, larger particles can have a far greater mass of the total sediment load than the smaller particles. Yee and McKee (2010) noted that the high spatial heterogeneity of pollutant concentrations in over 600 sediment samples from the Bay Area reflected the intermittent nature of many pollutant release events (e.g. accidental spills) and sediment transport processes. Consequently, the relative mass, or size, of the particles being transported is an important factor along with the relative concentration of the pollutants within various particle size ranges (McKee et al. 2006).

2.3. PARTICLE SIZE DISTRIBUTIONS

To evaluate the effectiveness of sediment management measures to control PCB and mercury concentrations associated with various particle sizes, it is important to understand the relationship between particle sizes and pollutant concentrations and mass. Generally, high concentrations of particle-bound pollutants (e.g., PCBs and mercury) are assumed to be associated with smaller particles (Xanthopoulos and Hahn 1990) due to a larger surface-to-volume relationship and the efficient adsorption properties of fine particles such as clay minerals (Krumgalz et al. 1992). A settling experiment conducted by Yee and McKee (2010) provides some insight into the relationship of PCBs and mercury to particle size. The study analyzed a limited number of stormwater runoff samples[5] for PCB and mercury concentrations in three separate size fractions:

1) Material that settled out in less than 2 minutes (approximately >75 µm);
2) Material that settled in 2-20 minutes (approximately 75-25 µm); and
3) Material that had not settled within a 20-minute period (approximately <25µm).

For five out of six stormwater samples about 50-70% of the total PCBs settled within 20 minutes (fractions > 25 µm) (Figure 1). Conversely, for all six samples only about 10-30% of the mercury settled out within 20 minutes (Figure 2). Thus mercury was more difficult to settle and therefore associated with finer particles to a greater extent than PCBs.

Analysis of sediments from the Guadalupe River in San Jose, CA, and its tributaries (McKee et al. 2005 and Austin 2006) found a similar relationship between particle size and mercury concentration. Results indicated that greater concentrations of mercury were found on finer size particles; however, there were not enough data to determine a clear relationship between mercury and grain size fractions (McKee et al. 2006).

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[5] Samples were collected during three separate rain events from a storm drain line near the Bay margin in Hayward, CA in February 2007 and Richmond, CA site in January 2008.

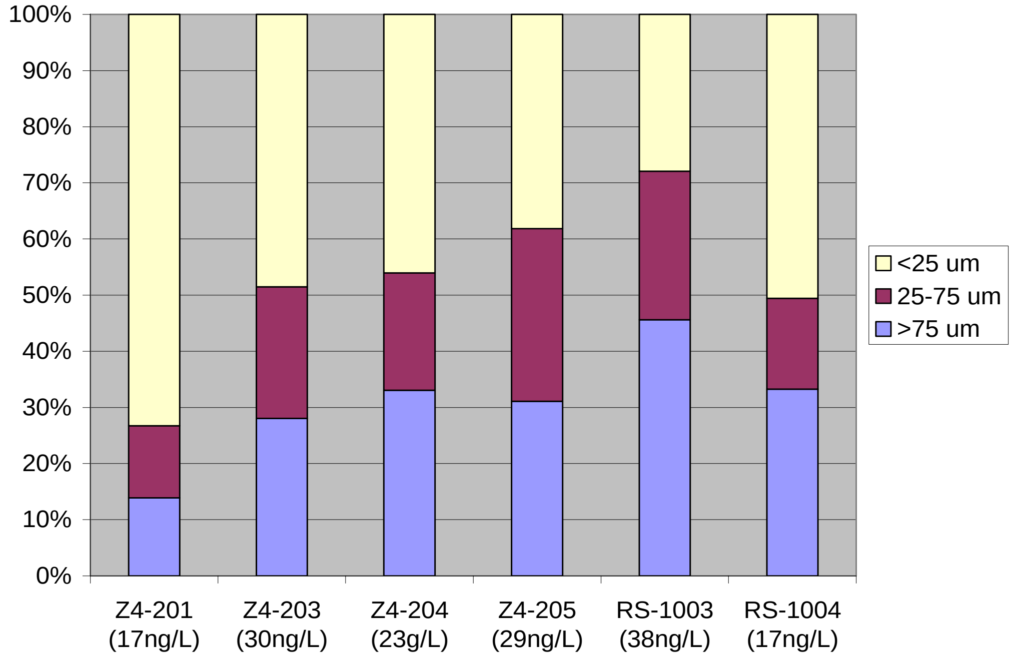

Figure 1. PCBs in settled fractions from stormwater runoff samples at Hayward (Z4) and Richmond (RS) storm drains (as presented in Yee and McKee 2010). Samples (with corresponding PCB concentrations) are shown on the x-axis, with percentages of particle fractions on the y-axis.

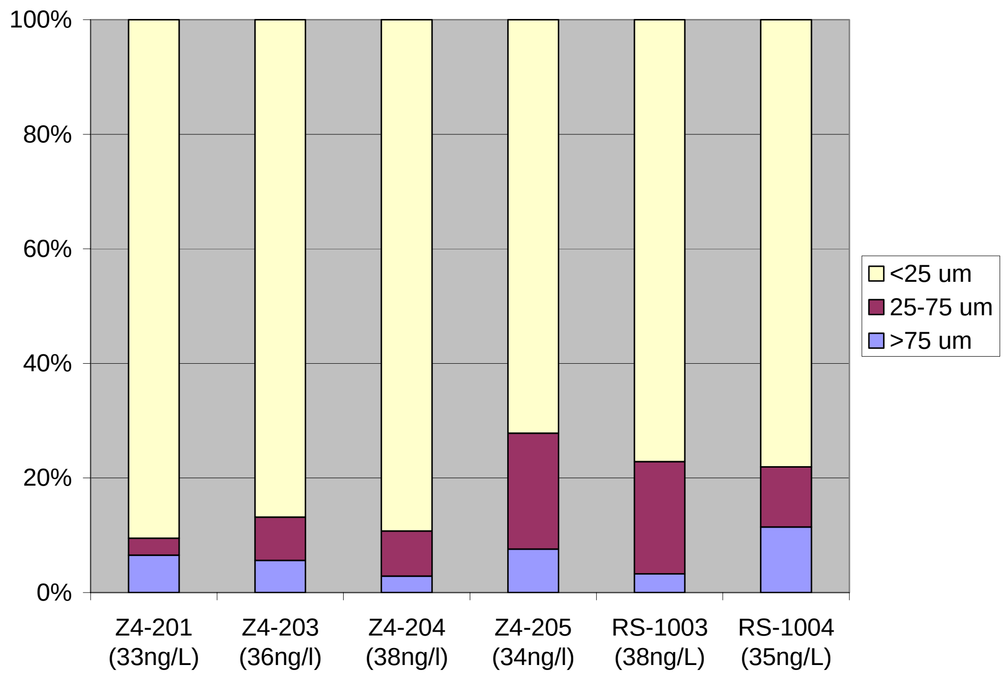

Figure 2. Mercury in settled fractions from stormwater runoff samples at Hayward (Z4) and Richmond (RS) storm drains (as presented in Yee and McKee 2010). Samples (with corresponding mercury concentrations) are shown on the x-axis, with percentages of particle fractions on the y-axis.

2.4. STREET SURFACE SEDIMENT/DIRT

The concentrations of mercury and PCBs on Bay Area sediment/dirt collected from street surfaces have been characterized by a number of studies. McKee et al. (2006) summarize PCB data collected in the Ettie Street catchment in Oakland, California, an area where elevated PCB concentrations have been found in sediments. Concentrations ranged from 0.28-7.35 mg/kg with a mean of 1.1 mg/kg and a coefficient of variation of 1.7, suggesting that variability in these data is relatively high.

EOA (2007b) conducted sampling of sediments in catch basins and gutters for PCB analysis in industrial locations in Richmond, California that have exhibited elevated PCB concentrations. Results from the 18 gutter samples indicated a PCB range of about 0.07-2.80 mg/kg with a mean concentration of 0.86 mg/kg and a coefficient of variation of 0.95. These two data sets are fairly similar in range and average concentration.

Yee and McKee (2010) conducted a more comprehensive sampling program focused primarily in industrial areas in a total of 20 areas distributed around the Bay Area.[6] Phase I conducted from June through September 2007 collected a total of 267 sediment and soil samples, which were collected from street surfaces near the gutter (n=137), inside drop inlets (n=112), near the lip of drop inlets (n=9), and roadside soils (n=5). Phase II was conducted in September 2008 when a total of 94 more locations were sampled, including drop inlets (n=53), sediment around inlet grates (n=31), street surface dirt (n=6), and driveways (n=3). The study characterized 153 data points as street surface sediment and the 90th percentile concentrations were 0.28 mg/kg PCBs and 0.51 mg/kg mercury. The sites that had PCBs concentrations above the 90th percentile were located in Richmond, Oakland, Port of Oakland, San Francisco, South San Francisco, San Carlos, Sunnyvale, and San Jose, all of which are densely populated urban areas with industrial land uses.

These data indicate that there is a large variation in PCB and mercury concentrations within industrial land uses. Yee and McKee (2010) also point out that the mercury and PCB site data do not necessarily correlate, i.e., the PCB hot spots are not necessarily the same as the mercury hot spots though there is some overlap.

2.5. STREET SWEEPER DATA

Table 1 and Table 2 summarize PCB and mercury data, respectively, from samples of sediments collected by street sweepers in Alameda County (Salop 2006) and Contra Costa County (EOA 2007a, EOA 2007b). The tables show the municipalities in which the samples were obtained, the predominant land use associated with the sampling site, the number of samples analyzed and the concentration measured or the range of concentrations[7].

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[6] Areas included Albany, Benicia, Berkeley, Concord, El Cerrito, Emeryville, Hayward, Oakland, Pittsburg, Port of Oakland, Richmond, San Bruno, San Carlos, San Francisco, San Jose, San Leandro, South San Francisco, Sunnyvale, unincorporated Contra Costa County, and Vallejo.

[7] There are a total of 209 individual chlorinated biphenyls, 17 of which were analyzed using Method 8082. Thus, the total concentration equals the sum of the concentrations of the individual congeners. Where the analysis for an individual congener is below the method detection limit (MDL), it is necessary to assume a value. In these studies, the range in PCB concentrations reflects the difference between assuming a non-detect equals zero or a non-detect equals the MDL/2.

As illustrated in Table 1, observed PCB concentrations tend to fall into three tiers: 1) those with relatively higher concentrations (> 0.10 mg/kg), including those sampled from Richmond, Martinez, and Berkeley; 2) relatively moderate concentrations (0.050-0.100 mg/kg) in Walnut Creek, Pinole, Orinda, and Brentwood; 3) and relatively low concentrations (<0.050 mg/kg) in Newark, Pleasanton, Concord, and Livermore. Salop (2006) suggested that the trends in Alameda County could be explained by the age of development, where older cities like Berkeley tended to have higher PCB concentrations. Based on these data, age of development rather than land use is the more important factor affecting PCB concentrations.

Table 2 shows the observed mercury concentrations in street sweeper materials. The locations with higher concentrations (> 0.2 mg/kg) were Berkeley, Richmond, Martinez and Pinole. Locations having concentrations in the moderate range (0.1-0.2 mg/kg) include Orinda, Walnut Creek, and Concord. Locations with the lowest observed concentrations (< 0.1 mg/kg) include Hayward, Newark, Pleasanton, Fairfield-Suisun, and Livermore. In general, cities with elevated concentrations of PCBs also had elevated mercury concentrations, but it was not always the case.

Salop also reported the percent fines (<63µm) of the collected material less than 2mm. The percent fines ranged from 3-18% with the highest PCB and mercury concentrations found in those samples where the percent fines ranged from 11-14%. Salop also recorded the sweeper type, and it is interesting to note that the range of percent fines collected by the regenerative air sweeper (8-18%) was higher that the range collected by the mechanical broom (8-11%) and wet vacuum sweepers (4-7%).

2.6. Comparison of Street Sweeper and Street Surface Data

A comparison was made of PCB concentrations in sweeper and street surface samples from the City of Richmond, where both types of data were collected, albeit at different times. The PCB concentrations in the two samples of street sweeping material from Richmond ranged between about 0.2-0.9 mg/kg, whereas the street surface concentrations based on the 18 gutter samples in Richmond ranged from 0.07-2.8 mg/kg. Thus the street sweeper data, although quite limited in terms of sample size, were less variable than the gutter sample data.

A similar trend appears to be valid for mercury. For example, the range of street dirt data reported by Yee and McKee (2010) was 0.08 to 1.11 mg/kg for Berkeley and the data reported by Salop (2006) for concentrations in sweeper material indicates a range of 0.17 to 0.27 mg/kg. The Salop (2006) dataset was limited to three data points. Concord presents a somewhat different pattern in that the range of sweeper data (0.07-0.18 mg/kg) is generally lower than the range of street surface data (0.17-0.24 mg/kg).

In summary, these street sweeper data, which reflect a composite of sediment collected along a road segment, tend to be less variable than discrete data from samples collected at specific locations along the road segment, and consequently are not as skewed (a few very high concentrations among many lower values) as the street surface data.

Table 1. PCB concentrations (mg/kg)[1] in sweeper samples.

Source	Location	Predominant Land Use					
		Residential		Mixed Commercial/Residential		Industrial	
		#	(mg/kg)	#	(mg/kg)	#	(mg/kg)
Salop 2006	Berkeley	1	0.07	1	0.14	1	0.12
	Hayward	1	0.01	1	0.05	1	0.03
	Newark	1	0.02	1	ND	1	0.003
	Pleasanton	1	0.01	1	0.01		
	Livermore	1	0.01	1	ND		
EOA 2007b	Brentwood	1	0.001-.02[3]	1	0.05-0.08[3]		
	Concord	1	0.01-0.03[3]	1	0.04-0.06[3]	1	0.01-0.02[3]
	Martinez	1	0.10-0.11[3]	1	0.15-0.18[3]	1	0.10-0.12[3]
	Orinda	1	0.02-0.05[3]	1	0.05-0.07[3]		
	Pinole	1	0.07-0.09[3]	1	0.02-0.04[3]		
	Richmond			1	0.22-0.22[3]	1	0.37-0.40[3]
	Richmond			1	0.90-0.93[3]		
	Walnut Cr.	1	0.02-0.06[3]	1	0.05-0.07[3]		

1. Dry weight
2. PCB concentrations equals sum of individual congeners. Lower end of range assumes ND=0; upper end assumes ND=MDL/2.

Table 2. Mercury concentrations (mg/kg)[1] in sweeper samples.

Source	Location	Land Use					
		Residential		Mixed Commercial/Residential		Industrial	
		#	(mg/kg)	#	(mg/kg)	#	(mg/kg)
Salop 2006	Berkeley	1	0.22	1	0.17	1	0.27
	Hayward	1	0.05	1	0.12	1	0.08
	Newark	1	0.05	1	0.04	1	0.04
	Pleasanton	1	0.07	1	0.05		
	Livermore	1	0.03	1	0.03		
EOA 2007b	Brentwood	1	0.05	1	0.08		
	Concord	1	0.07	1	0.09	1	0.19
	Martinez	1	0.14	1	0.34	1	0.17
	Orinda	1	0.05	1	0.15		
	Pinole	1	0.29	1	0.25		
	Richmond			2	0.20-0.39	1	0.41
	Walnut Cr.	1	0.12	1	0.13		

1. Dry weight

2.7.

LITERATURE REVIEW METHODOLOGY

The methodology used for the literature review was to focus on two types of studies: 1) representative studies that were conducted in the Bay Area or other semi-arid areas and 2) studies (preferably peer-reviewed) conducted outside of the Bay Area that may be applicable to the Bay Area. The street sweeping studies tended to fall into three categories:

1. Monitoring studies of street sweeper effectiveness and characterization of pollutants on roadways;
2. Modeling tests to predict potential street sweeping effectiveness under a range of conditions; and
3. Review articles that tended to integrate the literature and discuss the current understanding of street sweeping practices.

Bay Area studies were identified by obtaining referrals from PMT members and reviewing the SFEI Proposition 13 study products and referred studies, including referring to the bibliographies of these studies for additional information. In addition, some leading academic researchers[8] in the field were contacted to request references to the most useful studies and information that they could share based on their specific experiences in sediment management. All studies that were exclusively conducted in the Bay Area or were broader studies that included one or more sites in the Bay Area were included in the review.

To find studies outside of the Bay Area, a search was conducted for peer-reviewed publications using journal article databases and indexes, including Environmental Sciences and Pollution Management, Web of Science, Compendex and CE Database. In addition, the Google search engine was used to search for both peer-reviewed and non-peer reviewed publications and white papers. Several key word strings were used for all database, index and online searches and are listed below.

- Catch basin/storm drain inlet/ gully pot[9] cleaning with or without the term effectiveness
- Catch basin/storm drain inlet/gully pot maintenance with or without the term effectiveness
- Street cleaning/sweeping with or without the term effectiveness
- Street flushing/washing with or without the term effectiveness
- Sediment management/municipal sediment management with or without the term effectiveness
- Combination of PCBs and the following terms: abatement, street cleaning, storm drains, catch basins/inlets/gully pots, sediment management, industrial land use, and effectiveness
- Combination of mercury and the following terms: abatement, street cleaning, storm drains, catch basins/inlets/gully pots, sediment management, industrial land use, and effectiveness
- Fine sediment or total suspended solids and street cleaning/sweeping/washing and inlet/catch basin/gully pot cleaning with or without the term effectiveness

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[8] Robert Pitt, University of Alabama; Roger Bannerman, Wisconsin Department of Environmental Resources; Mike Stenstrom, University of California-Los Angeles; and Mike Barrett, University of Texas-Austin.

[9] The term gully pot is used in Europe, Australia and New Zealand to refer to a stormwater inlet or catch basin.

- Particle size distribution and the following terms: street sweeping/washing/cleaning, inlet/catch basin/gully pot cleaning and sediment management with or without the term effectiveness

- Sediment management in industrial areas with or without the term effectiveness

Furthermore, bibliographies from relevant studies and literature reviews on urban wet-weather flow from the Water Environment Research Federation journal were reviewed for additional references.

The International BMP Database (http://www.bmpdatabase.org/), which stores detailed information about structural and non-structural BMP projects, was also searched for relevant studies.

A large number of studies conducted outside the Bay Area were identified and prioritized based on the following desirable attributes:

- Representative of Bay Area or semi-arid climate
- Peer-reviewed literature
- Relatively recent publications (generally since 2000)
- Study conducted in industrial area or hot spot area
- Addressed representative land use type (industrial or mixed industrial)
- More emphasis on monitoring rather than modeling
- Addressed particle size distributions
- Addressed effectiveness
- Addressed costs

For street sweeping, the following attributes were also considered:

- Addressed a variety of sweeper types including advanced street sweepers
- Robust study design in terms of adequate controls, sampling, etc.
- Addressed runoff water quality

Additional attributes for stormwater conveyance system cleaning and street flushing and capture were:

- Addressed sediment (rather than stormwater) monitoring[10]
- Measured sediment quality

Studies that were not considered for this literature review included the following:

- Tests conducted in a laboratory under strictly controlled conditions
- Modeling studies
- Tests conducted on freeways
- Studies evaluating the combined effectiveness of stormwater conveyance system cleaning and a structural BMP
- Tests conducted under ideal conditions (e.g., inside buildings on smooth surfaces)
- Model projections of street sweeper performance
- Tests conducted on freeways
- Tests conducted on specific facilities (e.g., ports)
- Test results reported in vendor associated publications.

[10] Although stormwater runoff quality was considered important, it was considered more relevant to summarize studies with sediment quantity and quality data as CW4CB monitoring will focus on sediment loadings.

Tables 3 and 4 list the studies on street sweeping, stormwater conveyance system and street flushing that were conducted outside of the Bay Area and focused on during this literature review and identifies the corresponding attributes among those listed above. Appendices A - C summarize the studies that are summarized in Sections 3-5.

Table 3. Studies conducted outside of the Bay Area regarding street sweeping.

Reference	Applicable to Semi-Arid Climate	Peer-Reviewed[11]	Addresses Variety of Sweeper Types	Statistical Study Design and Analysis	Street Loading Reduction Monitoring	Runoff Water Quality Monitoring	Costs	Comments
Pitt 1985		X	X	X	X	X	X	Sweeper effectiveness study conducted in Bellevue, Washington which has different climate regime than Bay Area. Focus was on effectiveness of sweeper types on street load reduction and water quality.
Blosser 2000			X				X	Sweeper evaluation analysis authored by public works employee with City of Olympia, Washington. Major focus on costs and practical implementation issues associated with different sweeper types.
Pitt et al. 2004a			X		X	X		Review article with focus on buildup-washoff and effects of street sweeping on dust and dirt loadings, and ability of sweepers to remove fine particulates.
Pitt et al. 2004b		X	X		X			Review article with focus on buildup-washoff of street dust and dirt and effects of street sweeping on street dust and dirt load, and implications for modeling.
Breault et al. 2005		X	X	X	X	X	X	USGS street sweeper effectiveness study conducted in New Bedford, Massachusetts. Focus on effectiveness of sweepers to remove dust and dirt from roadways.
Shilling 2005			X				X	Review article. Literature review conducted for Ramsey-Washington Metro Watershed District, North St. Paul, Minnesota.
Selbig & Bannerman 2007		X	X	X	X	X		USGS street sweeper effectiveness study conducted in Madison, Wisconsin. Comprehensive multi-year study design with paired catchments and controls.

[11] Assumed to be either peer reviewed journal article, federally sponsored document (e.g., USEPA, USGS), or report peer reviewed by independent panel of experts.

Reference	Applicable to Semi-Arid Climate	Peer-Reviewed[11]	Addresses Variety of Sweeper Types	Statistical Study Design and Analysis	Street Loading Reduction Monitoring	Runoff Water Quality Monitoring	Costs	Comments
Rochfort et al. 2007			X	X	X	X	X	Street sweeper effectiveness study conducted in Burlington, Ontario. Multi-year study design that included washoff studies.
Law et al. 2008		X	X	X	X	X	X	Street sweeper effectiveness study conducted in Baltimore, Maryland by Center for Watershed Protection. Includes review of literature and effectiveness estimates by sweeper type and frequency.
Herrera 2009		X	X	X	X		X	Street sweeper effectiveness study in Seattle, Washington. Included evaluating effects of sweeping on need to and frequency of catch basin cleaning.
Weston 2010	X	X	X	X	X	X		Street sweeper effectiveness study in San Diego, CA. Evaluating effects of advanced sweepers.

Table 4. Studies conducted outside of the Bay Area regarding stormwater conveyance cleaning and street flushing.

Reference	Rep. of Semi-Arid Climate	Peer-Reviewed[12]	Sediment Monitoring (Quantity and/or Quality)	Particle Size Distributions	Pollutant Load Reductions[13]	Effective-ness	Costs	Comments
Amato et al. 2010		X	X	X	X	X		Review of available scientific and municipal studies and expert consultations to summarize past research on the effects of street cleaning and washing in the abatement of PM[14] emissions.
Gromaire et al. 2000		X			X	X		Evaluation of municipal street washing procedures on three different streets in a central Paris district with a combined sewer system. The pollutant load associated with street washing was compared to both the surface runoff load and the catchment's dry weather pollutant load. The maximum street surface pollutant load was compared to the load removed using regular street washing procedures.
Grottker 1990		X			X	X		Grottker studied approximately 200 gully pots in different catchments located in Germany and analyzed their capacity to remove pollutants, subsequently using the results to build a simulation model.
Herrera 2009			X	X		X	X	Conducted in Seattle, WA, the 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 street and catch basin cleaning might affect that balance.

[12] Assumed to be either peer reviewed journal article, federally sponsored document (e.g., USEPA, USGS), or report peer reviewed by independent panel of experts.

[13] Studies that evaluated pollutant load reductions due to change in application of sediment management practice.

[14] Atmospheric particulate matter (PM) is a complex mixture of components arising from a number of emission sources (anthropogenic and natural) and atmospheric processes (secondary PM). Two common categorizations of PM are PM_{10} (particles with mean aerodynamic diameter <10 µm) and $PM_{2.5}$ (particles with mean aerodynamic diameter <2.5 µm), which is considered the fine fraction (Amato 2010).

Reference	Rep. of Semi-Arid Climate	Peer-Reviewed[15]	Sediment Monitoring (Quantity and/or Quality)	Particle Size Distributions	Pollutant Load Reductions[16]	Effective-ness	Costs	Comments
Jartun et al. 2008		X		X				Jartun et al. evaluated sediment in 68 stormwater traps around a harbor area in the urban city Bergen, Norway to identify sources of pollutants and their pathways via the stormwater conveyance system to the surrounding water body.
Law et al. 2008			X	X	X			Law et. al. (2008) conducted an effectiveness study in Baltimore, Maryland that addressed pollutant removal rates for street sweeping and storm drain cleanout programs in the Chesapeake Bay Basin.
Pitt and Field 2004		X	X		X	X		Pitt and Field (2004) reviewed and summarize past studies of catch basin inlet devices, including two extensive EPA-funded case studies conducted in Bellevue, WA and Stafford Township, NJ.

[15] Assumed to be either peer reviewed journal article, federally sponsored document (e.g., USEPA, USGS), or report peer reviewed by independent panel of experts.
[16] Studies that evaluated pollutant load reductions due to change in application of sediment management practice.

2.8. TERMINOLOGY

There is no generally accepted terminology to describe how well a stormwater pollutant control measure works, thus the terminology used in the literature varies widely. Various terms used in the literature include performance, efficiency and effectiveness. This literature review primarily uses the term effectiveness to describe the overall reduction in mass of sediment or mass of PCBs or mercury due to a sediment management measure. The term cost-benefit (rather than cost-effectiveness) is also used as a measure of the cost of collecting a given mass of sediment or mass of pollutant. The one use of the term efficiency is in the context of street sweeping, where it is common practice to use the term "pickup efficiency" as the percent reduction in street sediments achieved by a sweeper.

The units for expressing effectiveness can be as an absolute reduction in mass or as a percent of the mass available. Absolute reduction has the advantage of being more directly comparable to TMDL load reduction targets.

3. STREET SWEEPING

Some of the original research conducted in the early 1980s including the Nationwide Urban Runoff Program (USEPA 1983) indicated that street sweeping was not an effective measure for water quality treatment, but these studies were for the most part conducted using mechanical broom sweepers. In the last decade or so, there has been technological changes in street sweepers including the introduction of advanced street sweeping equipment that include regenerative air sweepers and vacuum assisted sweepers.

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.

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

Much of the focus of these technologies has the goal of removing finer particulates which can contain a disproportionate amount of those pollutants that tend to associate with particulates, including for example, metals and certain pesticides. For this reason, the literature review methodology focused on the more recent publications, while still examining all the work conducted in the Bay Area irrespective of when it was conducted.

The focus of the review was on street sweeper effectiveness, and it is useful to explain the definitions of effectiveness and efficiency that are used particularly in this review. In this report, two measures of effectiveness are used: (1) reduction of dust/dirt load (lbs/curb mile or kg/km), and (2) runoff water quality improvement or reduction in pollutant loads in runoff.

Dust and dirt load refers to the mass of material exclusive of trash and vegetative debris per curb length (e.g., lbs/curb mile).The reduction in dust/dirt load can be reported in two ways. The first way is the reduction measured by comparing the load of dust/dirt on the roadway prior to the passage of the sweeper to that following the passage of the sweeper. This is sometime referred to as pick-up efficiency. The second way is the cumulative reduction in the dust and dirt load that takes into account the frequency of sweeping, and is estimated by comparing a swept test road segment with an unswept control road segment. The control could be a separate segment monitored at the same time as the test segment (this has the advantage that the control and test segments experience the same rainfall patterns) or could be the same segment with monitoring conducted during a period of non-sweeping.

Although many sources addressed the effectiveness of street sweeping to reduce dust and dirt loads, the reduction of the loads of finer particles is very critical for at least two reasons. One, a number of studies have shown that certain pollutants (e.g., mercury) have higher concentrations in the finer fraction, so where there is a substantial amount of finer material in the dust and dirt loading, removal of the finer fraction can increase water quality benefits for these types of pollutants. Secondly, research conducted on washoff indicates that the finer fractions are the most likely to be mobilized during typically sized storms (Pitt et al. 2004a). Consequently, where provided, effectiveness estimates are also summarized for effectiveness to remove the finer fractions of dust/dirt.

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 less studies of sweeper performance include runoff measurements, this was one of criteria used in selecting literature sources to review.

In much of the literature effectiveness measurements are expressed as a % reduction, and are therefore used herein. But the reader should be aware that the use of % reduction can be misleading because of a bias towards higher % reduction on dirtier roads, independent of the type of sweeper. For this reason, overall street surface load reduction effectiveness is also presented in the form of lbs/curb mile or kg/km removed.

Lastly, please note that the terminology used for the amount of material on a road surface is referred to with different terminology in various sources. Many of the original references use the term "dust and dirt load", and should not be confused with the pollutant load associated with a runoff event. A recent publication by Selbig and Bannerman (2007) use the term "street dirt yield." Dust and dirt also can be defined differently depending on the source, but herein it refers to material that generally passes through a 2000 µm (2 mm) sieve.

Appendix A includes key attributes and findings of each summarized study for the reader to easily compare and contrast findings[17].

3.1. Bay Area Studies

Studies summarized below are organized chronologically, from oldest to most recent, to represent the development of work in street sweeping throughout the Bay Area.

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, but accounted for about 73 percent of the pesticides, and about 51% of the metals. Data on nutrients and PCBs did not show this propensity to attach to finer particles.

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.

[17] Note that only main points of the summaries are included in the table, and it is recommended to read the entire summaries for complete information.

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).

PCBs were also measured on street surfaces in San Jose[18], and data indicated that the PCB loading in lbs/curb mile for PCBs in the test samples was about 1.2E-3 lbs/curb mile.

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.

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

Pitt (1979) conducted a study of the effectiveness of street sweeping at 5 locations at 3 sites (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 generally conducted daily or weekly and was sustained for about 4 to 6 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/curb mile. However for site classified as poor asphalt, the removals was 40%, not much different from the other sites, however the load reduction was 540 lbs/curb mile. The reason for this large difference is that the loading on the poor condition asphalt was 1400 lbs/curb mile, compared to 200-400 lbs/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). He also determined that, 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

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[18] This study measured PCBs by analyzing individual Aroclors which was a trade name used by Monsanto Company and represent a mixture of of individual PCB congeners. Method detection limits tend to be higher when analyzing Aroclors than when analyzing individual PCB congeners.

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.

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. 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. After about two or three passes a week, there is little improvement in street surface loadings. Sweeping could not reduce the surface loadings to below 200 lbs/curb mile irrespective of sweeping frequency. Sweeping intensely prior to winter storms was recommended.

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.

A test was conducted using mechanical and regenerative air sweepers working either side of a road segment and alternating sides to ensure comparable initial (pre sweeping) loadings. 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. The regenerative air sweeper was found to be slightly more effective than the broom sweepers but the effect was dependent on the initial loadings. For fairly clean streets where the initial loadings was about 400 lbs/curb mile, the effectiveness of RA sweeper was about 61% compared to broom sweeper effectiveness of 53%. If initial loading was 850 lbs/curb mile, the RA sweeper effectiveness was estimated at 69% compared to 64% for the mechanical broom.

By comparing the watershed loads during runoff events with the initial surface road 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.

San Jose Street Sweeping Equipment Evaluation Report (WCC 1994)

Woodward Clyde Consultants tested 5 sweepers on 20 test routes in San Jose, California. The sweepers included a new and old Mobil broom, Elgin broom, Tymco regenerative air, and Elgin regenerative air. The goal of the study was to evaluate the relative effectiveness of the sweepers to remove copper, lead, and zinc on roadways. The sampling included hand vacuuming the test routes prior to sweeping so that the effectiveness analysis could take into account the difference in surface loading (lbs/curb mile) amongst the test routes. Dust and dirt collected in the hoppers of the sweepers were screened using a 1 cm square mesh and separated into five size fractions between 75 and 1000 µm and analyzed to estimate the mass of copper, lead and zinc collected per curb mile swept, and the effectiveness of each sweeper in removing smaller particles.

A frequency analysis of baseline copper concentrations showed elevated concentrations of copper (> 200 mg/kg) on routes that had average daily traffic (ADT) values that were as high as 32,000 to 52,000 vehicles/day compared to a an average for all routes of about 21,000/day.

A statistical analysis of sweeper performance indicated that the new Mobil broom and regenerative air sweepers removed significantly more dust and dirt from the roads than the Elgin broom and old Mobil broom. The regenerative air sweepers removed the highest amount of copper per mile or about 0.017 to 0.026 lbs/curb mile. The new Mobil broom sweeper collected a modest of copper in the range of 0.01 to 0.016 lbs/ curb mile. The Elgin broom and older Mobil broom sweepers picked up the least amount of copper in the range of 0.005 to 0.01 lbs/curb mile.

An analysis of copper concentrations and mass indicated that copper concentrations increased as particle size decreased such that the concentration of copper was as high as 0.15 mg/kg in the particle size range <75 µm compared to about 0.05 mg/kg for particles > 700 µm. However, the largest percentage of copper by mass was in the 170-425 µm size fraction. The Elgin regenerative air was the best sweeper at picking up particles in this size range and almost 60% of the copper collected by the Elgin sweeper was in this size range. The Elgin broom was the least capable of picking up the smaller particles and most of the copper collected by the Elgin broom sweeper was in the > 700 µm size range.

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

EOA evaluated trends in the annual volume of sweeper materials collected by various agencies in Alameda County from 1991 through 1997, with special emphasis on data from FY 92/93, 93/94, 94/95, and 96/97. 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 mile swept in the county. The analysis also distinguished the dry and wet season volume collected.

For the agencies other than Oakland, the 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.

A Review of Source Control Options for Selected Particulate-Associated TMDL Pollutants (Salop 2004)

Salop (2004) conducted a desktop analysis based on existing information to estimate the range of removals of PCBs and mercury achieved by Alameda County MS4s as part of their sediment management programs, which included street sweeping, storm drain facilities cleaning and channel de-silting. For each effectiveness evaluation summarized below, the estimates presented are provided a range and a 'best' estimate of the mass of PCBs and mercury removed, where the best estimate corresponded to the median and the range corresponded to the 25th to 75th percentile estimate.

Salop identified four factors that could affect efficiency: type of sweeper, operation and maintenance practices, commitment of local agencies to adapt street sweeper programs to address water quality concerns, and physical geography. Efficiency factors were based on sweeper types and assigned 50% for high-efficiency sweepers (dry vacuum sweepers), 30% for medium efficiency sweepers (wet vacuum and regenerative air), and 10% for low efficiency sweepers (mechanical broom). These efficiencies were based on street sweeper modeling study projections. Efficiency factors were then assigned to each MS4 in Alameda County based on the mix of sweeper types contained in their sweeper fleets. The mix for a number of agencies included regenerative air sweepers and one agency (ACPWA) reported using a wet vacuum sweeper. Efficiency factors ranged from 10-30% depending on the MS4.

Salop then estimated the amount of PCBs and mercury removed from street sweeper programs based on PCBs and mercury data collected in storm drain inlets, catch basins, and pump stations as there were no data on PCB and mercury concentrations in street dust and dirt. For Alameda County as a whole, the best estimate for PCBs was 0.6 kg, with a range of 0.3-2.0 kg. The best estimate for mercury was 1.2 kg with a range of 0.6-1.9 kg.

Salop estimated benefits associated with conversion of sweeper types to more efficient sweepers and benefits associated with increasing sweeper frequency from monthly to weekly. Conversion to high-efficiency sweepers was estimated to increase the mass of PCBs removed from 0.6 kg to 1.7 kg (best estimate) and mass of mercury from 1.2 kg to 3.4 kg (again best estimate). Benefits for increased frequency of sweeping using current mix of sweepers indicated an increase in PCBs of 0.2 kg (best estimate) and in mercury of 0.3 kg.

Municipal Maintenance and Sediment Management: Evaluation of Source Control Options for TMDL Implementation (Salop 2006)

Salop conducted targeted studies to confirm previous estimates of pollutants removed by street sweeping, inlet cleaning and pump stations. Salop collected and analyzed thirteen samples taken from the hoppers of various types of street sweepers in 5 municipalities in the County of Alameda. The study design called for sampling in two municipalities located in either the northern, southern or eastern portions of the county. In Berkeley three samples were collected with regenerative air sweepers operating in industrial, residential and mixed (commercial residential) areas. In Hayward three samples were collected with mechanical broom sweepers in the three types of land uses. In Newark, three samples were obtained with wet vacuum sweepers in residential and mixed use areas, and mechanical broom in industrial areas. In Pleasanton, two samples were obtained with regenerative air sweepers operating in residential and mixed land use areas. In Livermore, two samples were taken with wet vacuum sweepers in mixed and residential areas. Samples taken in Piedmont consisted primarily of vegetative matter and were not analyzed.

Samples were also analyzed for particle sizes in three fractions: <63 µm, 63-2000 µm, and >2000 µm. The percent by mass of fines in the first two fractions varied from 3-18%. The five samples collected with regenerative air sweepers contained the highest percentage of fines ranging from 8-18% with a mean of 11%. By contrast the percent of fines collected in the hoppers of the four mechanical broom sweepers ranged from 3 -11% with a mean of about 6.5%. The three wet vacuum samples ranged between 4-7% with a mean of 5 %. Although obviously a small sample taken from diverse locations, the data does suggest that the regenerative air sweepers are more efficient in picking up smaller particles than the other two types of sweepers.

PCB concentrations ranged from non-detect (2 samples) to 0.136 mg/kg (dry). The samples obtained in Berkeley were the highest measured corresponding to 0.107 mg/kg for the industrial site, 0.136 mg/kg for the mixed use site, and 0.067 mg/kg for the residential site. The percent fines collected in the mixed use site was 11% and in the industrial site 14%. (Percent fines for the residential site not reported because of lack of sufficient sample). PCB concentrations in samples from other municipalities ranged from 0.012-0.047 mg/kg (Hayward), ND-0.018 mg/kg (Newark), 0.008-0.018 mg/kg (Pleasanton), and 0.004-0.006 mg/kg (Livermore). Salop concluded from these data that the higher concentrations in Berkeley could be attributed to the older age of development in this municipality, and that industrial land uses did not necessarily result in the highest concentrations of PCBs.

Mercury concentrations ranged from 0.03 mg/kg (dry) generally in the municipalities in the eastern portion of the county, to 0.27 mg/kg at the Berkeley industrial site. The range of mercury concentrations in the various municipalities was: 0.17-0.22 mg/kg (Berkeley), 0.05-0.12 mg/kg (Hayward), 0.04-0.05 mg/kg (Newark), 0.05-0.07 (Pleasanton), and 0.03 (Livermore).

Salop then obtained estimates of the volume material collected by the sweeper programs in the municipalities as contained in Annual Reports ending in FY 2002/2003 and estimated the reduction in loads of mercury and PCBs by converting these estimates to mass and applying the measured concentration data by region. The estimates indicated that 2-8 kg of PCBs were removed annually during the period analyzed with 90% of the removal associated with those municipalities located in the northern portion of the county (which includes Oakland which is responsible for about 50% of the material collected). The estimated range of mercury was 5-8 kg/year, and again 90% of the reduction was estimated to occur in the northern portion of the county.

Fairfield-Suisun Urban Runoff Management Program (EOA 2006)

EOA conducted a study in the cities of Fairfield and Suisun City to characterize street sweeping constituents and effectiveness of street sweeping as water quality measure. Materials collected by sweepers at one commercial site and one residential site in each city were sampled and analyzed for selected metals, petroleum products, chlorinated and organophosphate pesticides, and PCBs. Chromium, copper, lead, nickel and zinc were detected in all samples with concentration ranges as follows: copper (18-26 mg/kg), lead (5-45 mg/kg), nickel (9-22 mg/kg), and zinc (62-91 mg/kg). Mercury was detected in 3 of the 4 samples with concentrations ranging from 0.03 to 1.2 mg/kg. PCBs were all below the detection limit of 0.2 mg/kg[19].

EOA estimated the annual mass of constituents removed from street sweeping based on these data and information on the total volume and mass of material collected and reported by the two cities. The estimates were made using statistical representations for selected inputs in a Monte-Carlo framework. The distribution of annual load reductions from sweeping was then provided including the mean, median, and 10^{th} and 90^{th} %ile values. For both cities, the projected load reduction for mercury in both cities was 2.2 lbs (mean) with a 10^{th} %ile load reduction of 0.016 lbs and a 90^{th} %ile load reduction of 3.3 lbs.

Development of Typical Concentration Values for Pollutants of Concern in Contra Costa County, CA (EOA 2007a)

EOA collected and analyzed street sweeping materials from 17 routes in seven cities in Contra Costa County consisting of Brentwood, Concord, Martinez, Orinda, Pinole, Richmond, and Walnut Creek. The routes were located in residential, mixed and industrial areas. The routes were swept with different types of sweepers including regenerative air (12 routes) and mechanical broom (5 routes).

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[19] These samples were analyzed as Aroclors, which are a mixture of individual PCBs, and results in higher detection limits than the analysis for individual congeners.

Street sweepers samples were analyzed for metals, hydrocarbons, pesticides and PCBs. Results indicated that PCBs, total mercury, copper, nickel, and PBDEs were consistently detected in street sweeping material. The PCB concentrations ranged from 0.015-0.932 mg/kg (assuming non-detects equal to half the method detection limit). The highest concentrations were found in the mixed and industrial land use routes in Richmond where the range of PCBs was 0.244-0.932 mg/kg. The second highest set of samples was in Martinez where the PCB concentration ranged from 0.114-0.174 mg/kg with the highest concentration at the mixed land use. Mercury concentrations ranged between 0.05-0.41 mg/kg with highest concentrations found in Richmond (0.20-0.41 mg/kg), Pinole (0.22-0.29 mg/kg), and Martinez (0.08-0.34 mg/kg).

The study also analyzed some samples for concentrations in the bulk sediment (<2000 µm) and in the fine sediments (<63µm). The analysis was conducted for samples collected in Brentwood, Richmond and Martinez. The PCB concentrations for the Richmond site were 0.369 mg/kg in the bulk sediment, and 0.530 mg/kg in the fine fraction. In the Martinez sample, the bulk concentration was measured at 0.151 mg/kg, compared to 0.071 mg/kg in the fine fraction. The mercury concentration in the Richmond sample was 0.40 mg/kg in the bulk sediment compared to 0.90 in the fine fraction. The mercury concentration in the Martinez sample was 0.34 mg/kg in the bulk sediment compared to 0.60 mg/kg in the fine fraction. So, except for the PCB concentrations in Martinez, the remaining three samples indicate enrichment in the finer fraction.

A statistical analysis indicated that industrial mercury concentrations were significantly higher than residential data, and that mercury and PCB data were significantly elevated in older developments (early 1900s) compared to data from more recently developed areas. This latter finding was incorporated into an analysis of loads from the various municipalities in Contra Costa County. The estimated load reduction in the County credited to street sweeping was 1 0.kg of PCBs and 1.85 kg of mercury.

Summary of Polychlorinated Biphenyls (PCBs) Data in Sediment Collected from Richmond, California Streets and Storm Drains (EOA 2007b)

EOA collected and analyzed 47 sediment and water samples from streets, storm drains, and private properties in primarily southwestern portion of the City of Richmond, and analyzed the samples for PCBs. Nineteen of the samples were obtained from material collected by street sweepers in 2006 and 2007. The mean of the 13 samples above detection was 0.262 mg/kg. The highest concentrations sampled were from industrial areas with a maximum concentration of about 2.8 mg/kg. In general street sweeping material contained lower concentrations of PCBs than sediment collected from street gutters or storm drains.

3.2. Studies Conducted Beyond the Bay Area

Studies summarized below are organized alphabetically by author.

City of Olympia Public Works Department Issue Report (Blosser 2000)

Blosser prepared a short report discussing whether the City of Olympia, Washington should utilize an advanced street cleaner in lieu of requiring on-site stormwater treatment for the proposed Capital Mall expansion. This source provides a discussion of the practical considerations that public agencies must deal with in evaluating alternative control strategies that include street cleaning. The street sweeper that was selected for evaluation was the Schwarze EV-1 high efficiency vacuum sweeper, whose capital costs ($290,000) and annual O&M costs ($50,000) would be borne by the applicant.

City staff raised a number of issues regarding the EV-1 including maneuverability, difficult to maintain due to hydrostatic drive, inability to work during wet weather, slow speed (4 mi/hr), new and unproven technology, and sweepings would be dirtier and more difficult to dispose. Discussions with other agencies that had purchased the EV-1 indicated that those municipalities that had avoided problems were those that conducted extensive training and had access to technical support. Also having access to a local dealer who could provide training and technical support was key. It was also noted that the EV-1 drives differently than other sweepers, and has a wide-swinging rear end that can be troublesome if the driver is not used to it. The author concludes that the risk of failure for this approach would not be greater than the risk with a structural treatment measure, where it is more difficult to judge adequate performance.

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. Trace metal and PAH concentrations were generally greatest on fine grained particles (<63 µm), although copper concentration was highest in the gravel fraction (>2mm).

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 vacuum sweeper. The vacuum sweeper efficiency was higher for all particle size classes from gravel to silt/clay.

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 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 is not effective. For higher loading, the removal performance could be in range of 25-50%.

New technology sweepers such as regenerative air sweepers showed improved performance for removing finer particles, especially in areas with intermediate street loadings. (The hypothesis 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 upswept 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.

The effects of sweeping on outfall quality will be limited given that roads are only one of several sources of pollutants in urban areas. Analysis of data collected in Bellevue, Washington indicated that streets contribute less than 10% of the total solids, but much larger amounts of metals and organics in the form of chemical oxygen demand (COD). Moreover, rainfall tends to remove the smaller particles, whereas conventional street sweeping is effective in removing the large particles.

Nonetheless, 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.

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).

Characterizing and Controlling Urban Runoff through Street and Sewerage Cleaning (Pitt 1985)

The author reports on a comprehensive study of street sweeper effectiveness conducted at two 100 acre residential sites in Bellevue, Washington from 1980-1983. The study involved an extensive runoff water quality monitoring program involving over 400 storm events. The Bellevue area has a distinctive rainfall pattern typically involving many small rainfall events that generate relatively low runoff (25-35% of rainfall). A source area evaluation indicated that streets were the major source of lead (60%) and zinc (44%) and COD (45%), but only accounted for about 9% of the solids load.

About 600 samples of street dirt accumulations were collected from the two test areas during the 2-year project. Most of the particles in the street dirt samples were in the 125 µm to 1000 µm range. An analysis of the particle distribution in the runoff showed that smaller particles are mobilized more easily than larger particles. For example, approximately 50% of the particles less than 63 µm in size are mobilized by rainfall events, compared to about 10% in the 500-1000 µm range.

Street dirt loadings were reduced to about 50-100 grams/curb meter (approximately 200-400 lbs/curb mile) following rain events of 6mm (2.5 inches) or greater. Approximately 8.5 to 19 g/curb-meter (34-76 lbs/curb mile) were removed during a typical rain event. Of this, approximately 4-6 g/curb meter (16-36 lbs/curb mile) were particles less than 125 µm, accounting for 33-50% of the solids in the runoff.

Street cleaning tests using mechanical sweepers were conducted using an intensive 3 day per week frequency and no sweeping (control) with the sweeping/no sweeping alternated between the two sites. During the street sweeping tests, street loadings ranged from about 40-300 g/curb-meter (160-1200 lbs/curb mile) with an average of about 115 g/curb meter (460 lbs/curb mile). The loadings were reduced to about 20-200 g/curb meter (80-800 lbs/curb mile) with an average of about 60 g/curb meter (240 lbs/curb mile) after cleaning. Particle size smaller than about 350 µm were not substantially affected by street cleaning, however very substantial removals were observed in the large particles.

A series of special tests were conducted in September and October of 1982 to compare the effectiveness of a standard and modified regenerative air sweepers with the mechanical sweepers. Both the modified and standard regenerative air sweepers showed substantially better performance than the regular mechanical sweeper, especially for the finer particle sizes.

Bellevue street cleaning O&M costs were about \$13/curb kilometer (\$21/curb mile).

A Summary of the 2004, 2005 & 2006 Field Seasons (Rochert et al. 2007)

Rochert et al. conducted fifteen sweeping effectiveness tests over a three period (2004 -2006) on a road segment in Markham Road, Toronto, Canada. The tests were conducted in June through November of each year. Each test included collection and analysis of dry material removed by hand sweeping a 4 m wide by 20 m long stretch of curb lane, and collection and analysis of wet sample obtained by washing with tap water a similar length of lane. Sediment was divided into three fractions (<64 µm, 64-2000 µm, and >2000 µm) for analysis for total metals, nutrients, PAHs, and TOC. The wet samples were analyzed for similar constituents including dissolved metals, total suspended solids (TSS), and volatile suspended solids (VSS).

Two types of sweepers were tested: a conventional mechanical sweeper, an old regenerative air sweeper, and a new regenerative air sweeper. The new technology regenerative air sweeper was the only sweeper effective in removing a statistically significant mass of solids from the road surface, but only from the southbound lanes where the unswept dust and dirt loading was about 150 kg/curb km (605 lbs/curb mile) in 2005 and 225 kg/curb km (907 lbs/curb mile) in 2006. The corresponding removal effectiveness was about 70%. In the northbound lanes, there was no significant change in surface loadings with the newer regenerative air sweeper because the unswept dust and dirt loading were quite low ranging from about 25-50 kg/curb km (100 – 200 lbs/curb mile). These loadings are considered a residual level, beyond which further removal was unlikely, independent of the sweeper type.

The newer regenerative air sweeper significantly removed the silt and clay fraction (< 63 um) in the southbound lane. The pre swept mass of silt of clay was about 10 kg/curb km (40 lbs/curb mile) and post swept silt and clay loading was about 2.5 kg/curb km (10 lbs/curb mile) resulting in an effectiveness of 75%.

Simulated runoff was generated by spraying potable water on the swept and unswept road segments and collecting and analyzing samples in the runoff for various constituents, including solids (TSS), selected metals, and selected hydrocarbons. The dissolved copper data did not show any significant changes due to street sweeping. Dissolved zinc was reduced in one case only, with the new regenerative air sweeper in the dirtier northbound lane. There were no significant changes in the concentrations of selected PAHs including Pyrene, Phenanthrene, and Fluoranthrene.

Runoff toxicity testing was also conducted using microtox and 96 hour rainbow trout LC50 test. The rainbow trout toxicity tests indicated that the toxicity of the runoff both before and after sweeping was minimal (the lowest % survival was approximately 70%) and there was no difference in toxicity in the runoff from the swept and unswept road segments.

Street Sweeping – Report No. 1 State of the Practice (Shilling 2005)

Shilling prepared a series of reports as part of a Street Sweeping Project for the Ramsey Washington-Metro Watershed District, Minnesota. Report 1 addressed the existing state of practice. The report also included information on street sweeper costs. The report cites several sources that indicated that the initial capital cost of sweeper could range from $100,000 for a mechanical broom sweeper that had a life of 5 years, to $200,000+ for a vacuum assisted sweeper that had a life of 8 years. Operation and Maintenance (O&M) costs for the mechanical sweeper were given as $40 per curb mile (for one pass of sweeper) versus $20 per curb mile for the vacuum sweeper (costs are in 2005 dollars).

Shilling also did an analysis of annual O&M cost for different sweeper types and frequency of sweeping. The annual O&M cost for mechanical sweeping varied from $2,235 per curb mile for weekly sweeping to $520 per curb mile for monthly sweeping. The comparable annual O&M cost for vacuum sweeping was given as $1,260 for weekly sweeping and $290 for monthly sweeping. Shilling did not indicate why the O&M costs were higher for mechanical sweepers, but mechanical sweepers have more moving parts subject to wear.

Shilling cites the Chesapeake Bay 2000 Agreement that concludes “regardless of absolute cost-effectiveness, street sweeping is one of the few easily implemented practices for use in highly developed urban areas that will clearly reduce sediment, and any associated pollutants, and provide for improved water quality to often severely degrades streams.”

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 which involved a multi-year (2001-2006) multi-catchment monitoring that evaluated the effectiveness of weekly sweeping with mechanical, vacuum assisted, and regenerative air sweepers. The catchments, all residential varying from 50-90 acres in area, included a control catchment (no sweeping) and two test catchments where sweeping was alternated in subsequent years. Data were collected on street dirt yield (lbs/curb mile) using vacuum sweepers, and runoff quantity and quality monitoring using flow based automatic samplers. Measurements of street dirt yield before and after sweeping were used to estimate pickup efficiency expressed as a % of the yield prior to sweeping. Water quality parameters included particulate and 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.

City of San Diego Street Sweeping Pilot Study (Weston 2010)

The City of San Diego is conducting pilot tests to evaluate the effects of sweeping frequency on reducing pollution, specifically debris and trace metals associated with fine sediment, and if newly acquired vacuum-assisted sweepers are more efficient or cost effective than conventional sweepers. The sweepers selected for the study were the Schwartz A7000 regenerative air sweeper and an Elgin Whirlwind vacuum sweeper along with the City's currently owned Johnson 4000 mechanical sweeper. Three pilot areas are being tested in Mid-City, Clairmont, and La Jolla Shores and include residential and commercial land uses.

The two-year study began in April 2007 and is near completion. Testing has been conducted under two wet seasons and two dry seasons. The first phase focused on street sweeper effectiveness and frequency, and the second phase addressed monitoring runoff to evaluate benefits to water quality.

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. Thus 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 only about 50 lbs/curb mile and this reduced to about 30 lbs/curb mile if twice-weekly sweeping was conducted. However, there were no discernable differences in the effectiveness (grams of metal removed per curb mile) based on sweeping frequency.

Preliminary results indicate that street sweeping has a positive impact on water quality. Comparisons indicate that the vacuum sweeper is more effective in reducing pollution than the mechanical sweeper on flat, even street surfaces, while the mechanical sweeper works equally well on uneven, hilly streets.

Based on these findings, the City plans to utilize the vacuum sweepers on the flat routes with good road surface conditions and well-defined curb and gutter. This sweeping modification will allow the City to benefit from improved water quality without affecting existing budgets and resources.

Potential long-term modifications to the City's street sweeping program include the following:

- Transition the City's fleet of sweepers to more equitable mix of vacuum and mechanical sweepers (50% vacuum, 50% mechanical);
- Identify residential areas interested or requesting enhanced (e.g., once per week) sweeping;
- Identifying commercial and industrial routes for aggressive (e.g., twice per week) sweeping; and
- Sweeping center medians along high traffic roadways.

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. It is one of the few studies reviewed that attempts to evaluate a relationship of street sweeping with catch basin cleaning. 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. At each site, a portion of site was unswept to provide a control, and a portion of swept. 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 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 prior to sweeping.

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. Sweeping also reduced the mass of pollutants on the swept segments compared to the unswept controls by as much as 78 percent (PAHs), various phthalates (29-65%), and zinc (18%). 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 that 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.

The particle size distribution of the street dirt and catch basin samples was fairly similar between the swept and unswept test sites. While there were some differences for specific sites, there was no consistent pattern observed across all sites. The industrial area generally exhibited somewhat higher percentages of fine-grained particles (fine sand plus silt/clay) for catch basin sediment (24 to 51 percent) than in the two residential basins (10 to 51 percent in catch basin sediment). Truck traffic in the industrial area may have contributed to the larger amount of fine-grained material present on the streets.

Concentrations of pollutants (i.e., metals and PCBs) were higher in the samples collected from the industrial site compared to the two residential sites. Cadmium, lead, and zinc concentrations were generally higher in the industrial catch basins compared to the two residential study areas. Furthermore, in most cases, concentrations of cadmium, copper, lead, and zinc were higher in the catch basin samples than street dirt and street sweeping material. This was likely due to the greater proportion of fine-grained material found in the catch basin sediment since finer material. Overall, PCB concentrations collected from the industrial study area (34 to 910 µg/kg dry weight) were typically higher than the concentrations measured in the two residential study areas (<19 to 73 µg/kg dry weight). The variability in PAH concentrations observed at each test site made it difficult to distinguish trends between the different media or study areas.

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 pounds (15,400 kg) of dry sediment, while annual cleaning of catch basins in the area is estimated to have removed about 6,200 pounds (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.

Baltimore Street Sweeping Study (Law et al. 2008)

Law et al. (2008) conducted an effectiveness study in Baltimore, Maryland that addressed pollutant removal rates for street sweeping and storm drain cleanout programs in the Chesapeake Bay Basin. Two sampling sites, Catchment F (Lanvale Street) and Catchment O (Baltimore Street), were monitored for water quality runoff. Both catchments were approximately 30 ac in size and were about 70% impervious. Land use was primarily high density residential in the form of row houses. The study included water quality monitoring during a 15-month baseline period (Sept. 2004-Dec. 2005) during which existing street sweeping frequency (1 or 2 times per week) was followed. During the treatment period (Jan. 2006 – July 2007), sweeping was increased to twice a week on all streets in Catchment O and reduced to once per week on all streets in Catchment F. This change in frequency corresponded to an increase in curb miles swept per week of about 150% in Catchment O and a decrease in curb miles swept of about 45% in Catchment F. Sweeping was conducted using an Elgin Whirlwind© MV 4 Wheel Vacuum Air Sweeper.

Flow composite samples were obtained from 17 events during the baseline period and 11 events during the test period at Catchment O and 15 events during baseline and 7 events during test period at Catchment F. In addition to water quality samples, 41 first flush grab samples were obtained at Catchment O. Bedload samples were also obtained: 8 samples at Catchment O and 2 samples at Catchment F. Streets were also hand swept in Catchment O yielding a total of 10 samples of street particulate matter (SPaM) before sweeping and 10 samples following sweeping.

The water quality data did not show any statistically significant differences in runoff concentrations between the baseline and test periods. Factors cited for this finding include the relatively small number of samples, the difficulty of isolating street runoff from other sources, and the concern that automatic water samplers may not obtain representative samples especially with respect to the larger and denser particles.

Average SPaM loadings was about 645 lbs/curb mile prior to sweeping, and 553 lbs/curb mile following sweeping, corresponding to an approximately 14% reduction in loading. Forty percent of the mass of the SPaM was in the 250-1000 um size range, compared to only about 4% for the SpaM less than 63 um. A similar distribution was found for metals and nutrients with the exception of copper where approximately 18% of the copper was found the fraction less than 63 um.

A conceptual model was developed by the authors that took into account various factors that affect sweeping performance and inlet sediment retention. Based on the conceptual model and best professional judgment regarding the effects of these factors, the authors recommended that sweeper pickup efficiency for weekly sweeping would vary from about 25% for mechanical broom to 60% for regenerative air or vacuum assisted sweepers. For monthly sweeping, the estimated efficiencies decreased to 18% for mechanical broom and 42% for regenerative air/vacuum assisted sweepers.

The monitoring study characterized the material removed from storm drain inlets[20] in both residential and commercial/industrial land uses in two different physiographic regions. Four inlets in each of the four groups[21] were sampled to determine the rate of accumulation of material in the time period

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[20] The storm drain inlets were designed without a sump and are considered a flow-through or 'self-cleaning' component of the stormwater conveyance system.

[21] Sixteen storm drain inlets were grouped into four categories that represented the various combinations of land use types and physiographic regions in the study.

between a spring and fall (2006) cleanout. Inlet samples were analyzed for particle size distribution, total solids, nutrients and metals. Although samples were analyzed for metals, it was noted that an insufficient number of samples were collected to sufficiently characterize the patterns in water quality pre- and post-treatment.

Different land uses resulted in significantly different monthly accumulation rates, with inlets in commercial/industrial land uses having higher accumulation rates of material. Daily accumulation rates were found to be statistically significant for both land use types, with residential land use ranging from 0.001 to 0.005 ft^3/day and commercial/industrial land use from 0.011 to 0.013 ft^3/day. Material removed from the inlets consisted of, on average, 52% leaves and other organic matter, 39% sediment and 9% trash.

The particle size distribution for the inlet material, especially the coarser fractions, was found to be similar to the distribution for the SPaM, which was likely due to the 'self-cleaning' inlets. For all inlets, an average of 86% of total sediment was between 0.25 mm and 4.0 mm. About 60% of commercial/industrial inlet samples were found to be between the 0.25-2.0 mm fractions.

A total of eight bedload samples were collected. The average mass of bedload collected was 225g (standard deviation of 114g) per sample, which typically represented material accumulated over a 1-2 week period. The monitoring set-up did not function as expected, and consequently, the amount of bedload material collected was considered an underestimation.

Information generated from the project's literature review, municipal practices survey, and monitoring data, though limited, was used to estimate pollutant removal efficiencies for inlet cleaning using the conceptual model created for this study. The estimated range in pollutant removal efficiencies for total solids was 18% and 35% for annually and semi-annually, respectively.

4. STORMWATER CONVEYANCE SYSTEM CLEANING

For the purposes of this literature review, the term "stormwater conveyance system" refers to the constructed conveyance system designed to transport water to receiving waters during runoff events. The conveyance system includes storm drain inlets, underground pipes, and pump stations. Different terms have been used in literature in reference to storm drain inlets, which serve as the entry point to the underground storm drain pipe system and are generally designed to reduce flood risks and convey flow to the underground pipe system. Types of storm drain inlets include:

- Drop Inlet - inlet structure where the outlet pipe is at approximately the same height as the structure's base. [22] Drop inlets are also referred to as simple inlets in the United States (U.S.). Drop inlets are intended to be "self cleaning" and effectively pass water and sediment directly into the outlet pipe. Drop inlets are not designed to provide substantial storage capacity for sediment or other material.

- Catch Basin - inlet structure built with the outlet pipe at some height above the base of the structure in order to provide a sump for storage of sediment and other materials. The base of the sump is typically 0.5 to 1.0m below the bottom of the outlet (Pitt and Field 2004) and collects particulates and non-floatable litter that have passed through the inlet grate and settled out during smaller storms. The sump is meant to provide a layer of water over the accumulated material to minimize resuspension of the solids via scouring by the inflow. Catch basins work most effectively when the accumulated material is removed before the storage capacity is lost. Terms used for catch basins in other countries include gully pot (e.g., United Kingdom and Germany), catchpit (e.g. New Zealand), and stormwater trap (e.g., Australia and Norway).

Because a stormwater conveyance system includes various components (e.g., inlets, drain lines and pump stations) that accumulate sediment at different points in time and based on various factors, available studies evaluating these individual components were collected and are summarized below.

Appendix B includes key attributes and findings of each summarized study to facilitate comparing and contrasting findings.

4.1. BAY AREA STUDIES

Studies summarized below are organized chronologically, from oldest to most recent, to represent the development of work in stormwater conveyance system cleaning throughout the Bay Area.

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

In addition to the street sweeper tests described above, Sartor and Boyd conducted a limited study involving two controlled tests to determine the effectiveness of catch basins to retain sediment in a residential area of San Francisco. The catch basins were standard, made of concrete with curb inlets and cast iron gratings. The first test evaluated the effectiveness of an empty catch basin to remove solids from injected fire hydrant water mixed with previously collected street sediment. Results indicated that, for a simulated heavy rainfall intensity (1/2 in/hr), the catch basin was reasonably effective in removing coarse solids, i.e., solids with a diameter larger than 246 µm, but ineffective at removing fine solids. The retention time was less than a minute for low flows, which is consistent with the catch basin being effective in removing only coarse material. The study found that removal efficiencies also

[22] Most storm drain inlets in the Bay Area are believed to be drop inlets (Sommers 2011, personal communication).

decreased with respect to time. The authors speculated that this was due to unstable conditions of hydraulic turbulence and resuspension, but noted that this conclusion was based on limited data.

The second test investigated the hydraulic flushing effect of inlet water on preexisting catch basin contents. 'Clean' water was added at several predetermined flow rates to three catch basins that had not been cleaned for several months. The catch basins were described as containing several thousand pounds of solids, with a layer of water and floating debris up to the outlet level. The initial discharged water was supernatant water, with some floating debris and particulate matter suspended by the turbulent flow. After one hour, approximately one percent of the initial solids in the catch basin were removed. The results indicated that most of the material originally contained in the catch basin appeared to remain, regardless of the runoff volume.

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

As part of this study, Pitt (1979) constructed a catch basin (with a sump), according to recommendations by Lager and Smith (1976), and partially filled it with sediment and fluorescent particle tracer material to monitor the routing of particulates in a stormwater drainage system. The catch basin was installed in a street corner of the study area, with eight manholes between its installation and an outfall on Coyote Creek. Five-hundred lbs of sediment material, made up of a similar particle distribution as the street surface dirt measured in the study area, was added to the constructed catch basin. Furthermore, 2.5 lbs of yellow fluorescent particles were mixed with the bottom half of the sediment material in the catch basin, and 2.5 lbs of green fluorescent particles were mixed with the top half.

Samples were collected five times from the catch basin, the eight downstream manhole locations, and the creek outfall between September 1977 and January 1978. During that time, there were more than 10 days of rain, including four significant storms. Storm drain inspections were also routinely conducted during this time period to document the depth of sediment in the main storm drain and in the adjacent laterals, which were all flushed out at the beginning of the study.

Results indicated that some of the sediment and tracer material was removed from the catch basin during dry weather flows. A general decrease in relative concentrations between the catch basin and outlet was noted; however, there were large variations in the data results. The concentrations of fluorescent particles in the catch basin did not significantly change with time. Yellow particles were not found at most of the manhole sampling locations during some of the sampling periods. This was expected because the yellow material located at the bottom of the catch basin would only be discharged into the stormwater conveyance system during larger storms. The authors found that the overall depth of material in the catch basin decreased approximately 20%.

A Demonstration of Non-Point Source Pollution Management on Castro Valley Creek (Pitt and Shawley 1981)

In addition to conducting a two-year study of the effectiveness of street sweeping at sites located within the Castro Valley Creek watershed, Pitt and Shawley (1981) presented data from an Oakland study conducted in September 1979 (Shawley 1980) to make observations about inlet particulates in the Castro Valley area. For the Oakland study, the Alameda County Flood Control District examined 20 residential storm drain inlets that were cleaned every year or every two years and measured an average of 60 lbs. of dry particulates in each inlet. Based on these results, the authors estimated that about 12,000 pounds (2% of the total annual runoff yield) of dry particulates were present in a total of approximately 200 inlets in the Castro Valley area. The sediment accumulation or washout rates were unknown.

Results from analysis of the sediment in the 20 inlets indicated that the median total solids particle size was approximately 2,300 µm, which was substantially greater than that of the street dirt measured in the authors' study (500 µm). However, results from a one-time cleanout were compared to a two-year street sweeping study, which explain the large difference in particle sizes.

Storm Inlet Pilot Study (Mineart and Singh 1994)

Mineart and Singh (1995) carried out an extensive study in Alameda County to determine the optimal frequency of storm inlet cleaning that achieved the maximum pollutant removal. Sixty storm drain inlets[23] were selected for the 11-month study (December 1992 to October 1993) in residential, commercial and industrial land use areas. Within each of the three land uses, 20 inlets were studied, of which five were cleaned monthly, five semi-annually, five quarterly, and five annually.[24] Qualitative observations showed that trash and leaves were the most common materials found in inlets in the three land uses. Other material found in all three land uses included soil and decomposing organic material. Sediment volume and mass were recorded for each inlet cleaning, and materials from a subset of the inlets were analyzed for pollutants. A grain size analysis indicated that over 80% of all inlet sediments were sand (within the range of 62-2,000 µm). The inlet sediments contained a variety of pollutants typically found in urban stormwater runoff, including metals (lead, zinc and copper), petroleum hydrocarbons, and polynuclear aromatic hydrocarbons (PAHs).

The greatest average removed mass per cleanout was achieved through semi-annual cleanouts. In general, total annual sediment volumes removed increased with increased cleaning frequency in all land uses. However, in terms of total sediment mass removed, that trend was most evident in industrial land use. The study showed that for all land uses monthly inlet cleaning removed the most sediment on an annual basis (3-5 cubic feet), and therefore the greatest mass of pollutant. Quarterly, semi-annual and annual cleanings removed 1.5 to 2.5 cubic feet annually, except for industrial inlets, where debris accumulation was not observed when cleaned annually.

For residential land use, monthly cleaning removed approximately 70% more mass than that removed by quarterly or semi-annual cleanings. However, annual cleaning removed approximately 50% more than quarterly and semi-annual cleaning. Annual cleaning also removed more sediment volume than quarterly and semi-annual cleaning in residential land use. The authors did not give a reason for these unexpected results. For commercial land use, monthly cleaning removed approximately 70% more mass than that removed by quarterly cleaning, approximately 30% more than semi-annual cleaning, and 40% more than annual cleaning. For industrial land use, there was a clear decrease in sediment volume and mass removed with decreased frequency. Monthly cleanings removed about 30% more mass than quarterly cleanings, 50% more mass than semi-annual cleanings, and 80% more than annual cleaning.

The study also evaluated seasonal differences in sediment volumes and mass removed for the four cleaning frequencies. Differences in sediment removed were evaluated for the wet season (October to April) and dry season (May to September). Monthly cleaning was carried out during both the wet and dry seasons, quarterly cleaning twice during each season, semi-annual cleaning once during the wet season and once near the end of the dry season, and annual cleaning near the end of the dry season. Data from the four cleaning frequencies were combined together for each land use. Median values showed that slightly more volume accumulated during dry weather in residential land use, but slightly

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[23] All inlets selected for the study were drop inlets, as opposed to catch basins (with sumps), and were 41 in long by 25 in wide, with depths ranging from 16 to 54 in.

[24] Results were extrapolated to calculate annual values, since data were collected for 11 months.

more accumulated in commercial and industrial land use during the wet season. However, because of the large variability in data, especially in the commercial and industrial land uses, the authors noted that this difference was not significant.

Samples from inlets cleaned semi-annually had the lowest metal (lead, zinc and copper) concentrations, though the reason for this was not clear. Concentrations of lead and zinc appeared to increase over time. Overall, sediment samples collected from inlets cleaned annually had higher average metal concentrations than sediments from inlets cleaned monthly. Seasonal differences did not affect metal concentrations.

Increasing the cleaning frequency to monthly appeared to significantly increase the removal of copper. However, this was based on sediment samples from inlets in two illegal dumping areas, where concentrations of 1,140 mg/kg (commercial) and 1,500 mg/kg (industrial) were detected. Assuming similar 'hot spot' areas were found during regular monthly cleanings, the copper load would be reduced by 11-12 %. If these two high concentration areas were not included in the estimate, there would only be a one percent decrease in the annual copper load to the Bay.

Because cost-benefit was not evaluated, the authors recommended that annual cleaning be continued until more information about staffing and resource needs associated with increased frequency was obtained. The authors also recommended that municipalities consider other alternatives to increased inlet cleaning, such as improving inlet design, using more effective equipment to clean inlets, eliminating pollutants at the source (e.g., illicit discharge control programs and public education), and placing more emphasis on other maintenance activities (e.g., street sweeping). In addition, the authors recommended monthly inlet inspections during the wet season in potential illegal dumping areas. The study results suggested increasing cleaning frequency in identified hot spots or inlets that consistently accumulate sediment should be effective, especially if data are collected when inlets are cleaned to target and optimize the cleaning program.

A Review of Source Control Options for Selected Particulate-Associated TMDL Pollutants (Salop 2004)

Salop (2004) conducted a desktop analysis based on existing information to estimate the range of removals of PCBs and mercury achieved by Alameda County MS4s as part of their sediment management programs, which included street sweeping, storm drain facilities cleaning and channel de-silting. For each effectiveness evaluation summarized below, the estimates presented are provided a range and a 'best' estimate of the mass of PCBs and mercury removed, where the best estimate corresponded to the median and the range corresponded to the 25^{th} to 75^{th} percentile estimate.

Data submitted by the MS4s to various Alameda County Annual Reports (FY 1997-98 through FY 2000-01) was used to calculate a total annual average volume of waste material collected from stormwater conveyance system[25]. Based on communications with ACCPW staff, it was estimated that approximately 25% of the volume of the total collected material from the storm drain facilities was

[25] Data is submitted by each municipality as a total value for volume of material collected from a stormwater conveyance system, which includes inlets, catch basins, culverts, V-ditches, pump stations, open channels and watercourses. Consequently, volume calculations for each facility type cannot be estimated. Additional limitations include 1) differences in types and volumes of material removed from different facility types; 2) varying proportion of facility types among agencies and unincorporated areas; and 3) lack of known method to convert volumes of material collected for disposal into an associated sediment volume or mass (Salop et al. 2004).

sediment. In addition, the study used data from past local studies[26] to develop estimates of mass of PCBs and mercury (and their concentrations) removed in collected material, which Salop noted added additional uncertainties to the data results.

Pollutant concentrations and Alameda County municipalities were grouped into urban (pre-1950s development), mixed urban and recent urban land use categories. Salop et al. (2004) roughly estimated the percentage of volume removed from each land use type as 30% from pre-1950s urban, 20% from mixed urban and 50% from the recent urban. Based on samples collected in inlets, catch basins and pump stations and the study's 'best' estimates, the pre-1950s urban land use type had both the highest total PCB and mercury sediment concentrations of 0.138 mg/kg and 0.3 mg/kg, respectively. The mixed and recent urban land use types had the same estimated total sediment concentrations for PCBs and mercury of 0.113 mg/kg and 0.3 mg/kg, respectively.

The estimated concentrations calculated from past studies were used to estimate the PCB and mercury mass removed from storm drain inlets, catch basins, and pump stations in the study year (2004). The study estimated that ACCWP municipalities and unincorporated areas removed a total PCB mass of 2.6 kg and 1.0 kg of total mercury mass.

Based on Mineart and Singh (1994) study, Salop et al. (2004) projected a 30% increase of additional collected material if cleanout frequency was increased from annual to semi-annual[27]. It was estimated that the additional mass of pollutants removed from semi-annual cleanouts would result in an additional decrease of 0.0007 mg/Kg of total PCBs, or a 0.2% decrease from the annual total PCB concentration. In addition, the additional removed mercury mass would results in an additional decreased of 0.3 mg/kg of total mercury, or a 43% decrease from the annual total mercury concentration. It would roughly cost Alameda County MS4s an additional $300,000 due to increased disposal costs.

Using past data from Alameda County and BASMAA Joint Stormwater Programs' 2000-2001 investigations, Salop et al. (2004) also estimated PCB and mercury concentrations in sediment removed by channel de-silting carried out by the Alameda County Flood Control and Water Conservation District (District). District data on volumes of dredged material from 1990-2002 was used to calculate an average annual sediment amount. Total PCB and mercury concentrations for dredged sediment were estimated for each of the land use types described earlier. The pre-1950s urban land use type had the highest estimated total PCB concentration of 0.049 mg/kg, while the mixed urban and recent urban land use types had estimated total PCB concentrations of 0.032 mg/kg and 0.0023 mg/kg, respectively. The highest estimated total mercury concentration was 0.3 mg/kg for the mixed urban land use type. The other two estimated total mercury concentrations were 0.2 mg/kg and 0.1 mg/kg for the pre-1950s urban and recent urban land use types, respectively. It was estimated that the District removed 2.3 kg of total PCB mass and 20.5 kg of total mercury mass.

In order to estimate the additional pollutant mass that could be removed with increased channel de-silting, Salop et al. (2004) compared de-silting practices between the periods 1990-2004 and 1979-89. Based on higher de-silting rates in the earlier time period, it was estimated that a range of 1.5-13.8 kg additional total PCBs would be removed, with a best estimate of 5.1 kg of total PCBs, and a range of

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[26] Data sources included the Program (Salop et al. 2002a, Salop et al. 2002b, and BASMAA[26] Joint Agencies (KLI and EOA 2002), and a mercury sampling investigation conducted by Contra Costa County in 2000 (Contra Costa County Public Works Department, unpublished data).

[27] Mineart and Singh (1994) found that semi-annual cleanouts increased the volume of removed material, especially in industrial areas.

18.4-77.5 kg of total mercury removed, with a best estimate of 38.8 kg of total mercury, or 48% more than that later time period, would be removed. Based on median costs from channel-desilting projects carried out between 1998 and 2002, increasing de-silting rates was estimated to cost between $1 and $9 million annually.

Municipal Maintenance and Sediment Management: Evaluation of Source Control Options for TMDL Implementation (Salop, 2006)

In 2005 Salop conducted targeted studies to confirm previous estimates of pollutants removed by street sweeping, inlet cleaning and pump stations. For the inlet cleaning study, fourteen samples were collected from the same targeted regions and land uses that were described in the street sweeping study. Out of the 14 samples, six were taken from residential land use, five from mixed (commercial and light industry) land use, and three from industrial land use.

Samples were also analyzed for particle sizes in three fractions: <63 µm, 63-2000 µm, and >2000 µm. The average particle size distribution showed that 5% of the total dry mass was in the <63 µm particle size fraction, 63% in the 63-2000 µm fraction and 32% in the >2000µm. Several samples from individual land uses were not analyzed. Overall, the mixed land use category had the highest percentage of fines in the first two fractions, ranging from 5-33% with a mean of 17%. The next highest was in residential, ranging from 3-19% with a mean of 12%. The industrial land use areas had the lowest percentage of fines with a range of 3-20% and a mean of 9%.

As with the street sweeping waste, PCB concentrations were significantly higher in Berkeley, regardless of land use. The highest (0.590 mg/kg) was found in the mixed land use, with 0.182 mg/kg found in the industrial land use, and 0.166 mg/kg in the residential. The percent fines in each of these samples were, respectively, 22%, 20% and 19%. However, the highest percentage of fines in the first two fractions (33%) was in a mixed land use area in Livermore, where a much lower PCB concentration was observed (0.064 mg/kg). The following ranges of PCB concentrations were found in the remaining municipalities: 0.009-0.066 mg/kg in Hayward, 0.013-0.095 mg/kg in Newark, 0.003-0.014 mg/kg in Pleasanton, and 0.007-0.064 mg/kg in Livermore. A single sample in Piedmont resulted in a PCB concentration of 0.065 mg/kg.

Mercury concentrations ranged from 0.04 mg/kg to 0.38 mg/kg. Again, the highest concentrations were in the City of Berkeley, with 0.38 mg/kg in the industrial area, 0.27 mg/kg in the mixed area, and 0.24 in the residential area. One other high concentration value of 0.24 mg/kg was found in a Piedmont sample. The remaining concentrations were as follows: 0.04-0.18 mg/kg in Hayward, 0.05-0.08 mg/kg in Newark, 0.05-0.06 mg/kg in Pleasanton, and .06-.11 mg/kg in Livermore.

To estimate the volume of material collected from storm drain inlets, Salop used data for the years 2000-01 and 2004-05 reported by all municipalities of the material collected from storm drain facilities[28] on a monthly basis. Salop assumed that 75% of the average collected from these years would account for the 'best[29]' estimate of material collected from storm drain inlets and that the wasted collected from the urbanized land uses (residential, mixed and industrial) was proportional to the areas covered by

[28] When reporting amounts of waste collected on a monthly basis, municipalities did not distinguish what type of storm drain facility was cleaned or from what type of land use. Therefore, it was necessary to estimate the amount collected from an individual facility.

[29] Salop et al. (2006) developed 'low', 'best' and 'high' estimates, which corresponded with 25th, 50th and 75th percentile calculations. For the purpose of this summary, the 'best' estimates will be reported.

each. He then calculated the mass of PCBs and mercury contained within the material collected using the average concentrations measured for each land use type and region[30]. Results indicated that inlet cleaning removed between 0.5 and 1.6 kg of mass of PCBs, with a best estimate of 1.1 kg, and a range of 0.8 and 2.3 kg of mercury mass, with a best estimate of 1.5 kg.

Salop carried out a study to determine if increasing the inlet cleaning frequency would increase the amount of material collected, and thus, the mass of PCBs and mercury. In industrial areas of the three study regions, a total of 11 test sites were cleaned and sampled during a dry period midway during the rainy season, while fourteen control sites were only visually inspected. Test and control sites were again inspected the following year before the beginning of the rainy season. Sediment volumes did not change in the control sites over the time period. Salop concluded that either no additional material entered the inlets or the inlets had reached a steady state where inputs to the inlet were equal to the outputs. The test sites accumulated 30-40% of the volume that was removed at the beginning of the study period.

Results from this study and earlier estimations (described above) were used to estimate the increased amount of PCBs and mercury mass that would be collected with one additional wet season inlet cleanout. For both PCBs and mercury, less than 0.1 kg mass of each would be collected, a slight gain from one yearly cleanout. Salop did note that the amount that accumulated in each inlet appeared to be related to its type of construction. The older type of inlet, found in the Berkeley industrial area, was built as a catch basin with a sump and had greater storage capacity as compared to newer inlets designed to flush out during storms.

Salop also analyzed material collected from two pump stations, one associated with a railroad overpass in Pleasanton and the other from the Ettie Street pump station in Oakland[31]. PCB concentrations were highest at the Ettie Site (0.028 mg/kg), with 0.005 mg/kg measured at the Pleasanton pump station. Mercury concentrations were 0.32 mg/kg at the Pleasanton station, while a 0.27 mg/kg concentration was measured at Ettie. Percent fines in the first two fractions were relatively the same at both pump stations, with 2% at Ettie and 5% at Pleasanton. An estimated solids volume of 2.4 cy was removed from the Pleasanton station, though the volume of suspended material contained in the liquid fraction that drained during the dewatering process was not included. The estimated amount of solids accumulated in four sumps within the Ettie station was 33 cy. Salop estimated that <0.01 kg of both PCBs and mercury was collected in the Pleasanton pump station. The Ettie station material had <0.01 kg of PCBs and <0.03 kg of mercury. Using the highest PCB concentration measured during the period 2000-2006 (3,263 µm), Salop estimated that the 33 cy of volume of material collected from the Ettie Street pump station could have as much as 0.3 kg of PCB mass.

Desktop Evaluation of Controls for Polychlorinated Biphenyls and Mercury Load Reduction (Mangarella et al. 2010)

Mangarella et al. (2010) carried out a desktop evaluation to to assess the efficacy of source and treatment controls to prevent or remove PCBs and mercury from entering the stormwater conveyance system. Information from McKee et al. (2006) was used to characterize sources by land use, which were then used to calculate estimates of the annual loads of mercury and PCBs to the Bay from various land

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[30] Municipalities were grouped into regions as follows: the Northern region included the cities of Berkeley and Piedmont, the Southern region included the Cities of Newark and Hayward, and the Eastern region included Livermore and Pleasanton.
[31] This effort was coordinated through a Proposition 13-funded project conducted by the City of Oakland.

use categories. The 'unit loading[32]' for both mercury and PCBs were found to be highest for industrial and commerical areas. Using the results from the source and land use characterization analysis, the report evaluated various Better Management Practice (BMP) scenarios and evaluated their effectiveness in terms of reducing loads to the Bay. Scenario results showed that the most effective BMPs were those that addressed source control, rather than treatment, such as drop inlet cleaning and street sweeping. Application of these two source controls in elevated industrial areas were thought to result in relatively higher PCB load reductions. Street washing was found to result in low load reductions. The report recommends that future local studies take into account land use type and condition, which are considered important in characterizing loads and prioritizing controls, and that local agencies consider updating the workbooks as part of the planned studies.

To assess the effectiveness of each BMP, existing data were used to estimate baseline load reductions and reductions associated with BMP implementation. Regional projections were then estimated based on area, land use or population. Much variability in the local and regional data existed, because most of the data was obtained from municipal agencies as part of their annual stormwater permit reporting requirement in a particular county. Agencies reported the volume of material collected from the maintenance of their entire storm drain facilities. Specifics, such as distinguishing between components of a stormwater conveyance system (e.g., inlet versus storm drain pipe) and characterizing volumes of material removed by types of land use or neighborhoods, were not reported. Thus, for each BMP scenario, the authors identified various assumptions and reasons for uncertainties in the results.

The major sources of uncertainty comprised of: 1) load reductions projected over 20 years were based only on current data; 2) data from local studies was used in combination with regional study results to project Bay area-wide load reductions; 3) information was inadequate to take into account land use in every scenario, a factor shown to greatly influence pollutant loads; 4) most data did not address PCBs and mercury specifically, so the effectiveness results were presented as general estimates based on the authors' understading of existing literature; and 5) load reductions were calculated for individual scenarios, and benefits from the application of a combination of BMPs was not taken into account. The authors presented this report as a 'work in progress' and designed the workbooks to be manipulated and refined by the user once more data was available from subsequent studies implemented in the Bay Area.

PCB Source and Abatement Study (Dunlavey 2011, Personal Communication)

In 2000, the Bay Area Stormwater Management Agencies Association (BASMAA) member agencies collaborated to measure concentrations of PCBs, mercury and other POCs in embedded sediments within stormwater conveyance systems. The primary goal of the Joint Stormwater Agency Project (JSAP) was to characterize the distribution of pollutants among land uses in watersheds draining to the San Francisco Bay (Bay). The JSAP report (KLI and EOA 2002) documented 83 sites in the Bay area with PCB contamination, two of which were located in the City of San Jose (San Jose). The two sediment samples had PCB concentrations of 26.75 mg/kg and .65 mg/kg.

Sediment samples from four locations[33] in San Jose were composited into the two JSAP samples. As a result, it was not possible to determine the source of the elevated PCB concentrations, so three of the

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[32] Unit loading was calculated by dividing the annual loads from each land use by the area of that land use.
[33] Four sediment samples were combined into two composite samples that were then analyzed for PCBs: the Leo Ave. and Burke Street samples were combined into the first sample, and the West Home St. and Auzerais/Sunol samples were combined into the other.

four sites were resampled in 2001. The follow-up testing confirmed the Leo Avenue area as having elevated concentrations of PCBs, while no PCBs were detected at the other locations. The sampling and analysis of PCBs congener distribution pointed to either properties adjacent to Leo Avenue or the vicinity of the Southern Pacific railroad tracks at the end of Leo Avenue as the source of PCB contamination.

The follow-up Leo Avenue sample resulted in a much lower concentration of 1.18 mg/kg, as compared to the initial high PCB concentration of 26.75 mg/kg. The reason for the large discrepancy between samples that were taken four months apart was not clear. However, one factor that was considered was a storm drain cleanout event carried out on behalf of Premier Recycling that had occurred one month before the initial sampling that detected the highly elevated PCB concentrations. The cleanout occurred as a result of a San Jose issued Notice of Violation and subsequent Administrative Citation due to Premier's workers washing dirt from the property's paved areas directly into the storm drain. The Violation and Citation were unrelated to PCBs at Leo Ave since it had not yet been identified as an area with elevated PCBs concentrations. In response to the Citation, Premier Recycling had a contract service perform a flushing of the storm drain laterals on their property and a portion of the main line stormwater conveyance system under Leo Avenue from just upstream of where their lateral connects and downstream to the main line on S. 7th Street. Shortly after Premier Recycling had performed its line flushing, the San Jose Department of Transportation (DOT) flushed the main storm sewer line on Leo Ave. It was not known to what extent the line flushing may have removed sediments that had been trapped for a long period of time.

In 2004, San Jose staff once again sampled various inlets and manholes in the vicinity of Leo Avenue. This sampling effort showed significantly lower PCB levels (1-5 mg/kg) than had been found in the prior years. In the following year (2005), San Jose hired Clean Harbors, an environmental services company, to clean out the Leo Avenue storm drain inlets, publicly owned laterals, and the Leo Ave main line from the western cul-de-sac to S. 7th Street. Prior to the line cleaning by Clean Harbors, San Jose Department of Transportation (DOT) took video of the Leo Ave main line and discovered that a section of the western end of the line was substantially blocked with accumulated sediment. During their line cleaning, Clean Harbors removed a large amount of gravel and silt from the blocked section of the main line. Clean Harbors suspected that there may be a break in the Leo Ave main storm sewer line because of the high gravel content and larger grain size characteristics of the sediment. Subsequent to the line cleaning, DOT performed follow-up video of the Leo Ave main storm sewer line and did not find a break in the line but did find a dip in the storm drain line where much sediment had accumulated. With the exception of accumulated sediment remaining in the line at the low point (dip in the line), the follow-up video of the line taken by DOT showed that it was clean. The water and sediment that was removed from the line was collected into a single 5000 gallon tanker and disposed of at a hazardous waste facility. The collected material was estimated to be made up of 20% solids and 80% water (a relatively high percentage of solids according to Clean Harbors). The 2005 storm drain line cleanout removed 3,500 kg of solids and approximately 0.004 - 0.07 kg of PCBs based on the range of PCB concentrations previously measured in Leo Ave storm drain line sediments.

The cost for Clean Harbors to perform the one-day cleanout and dispose of the collected material at the hazardous waste facility was approximately $25,000. Although this amount includes Clean Harbors' field crew and transport and disposal of the material, it does not include San Jose staff time, analytical testing costs, and cost to video the storm drain line before and after the line cleaning. San Jose estimated that the amount could increase to $50,000 if these latter costs are considered. As of March 2011, the sediment in the stormwater conveyance system had not been reanalyzed to determine the effectiveness of the storm drain cleanout.

4.2. STUDIES CONDUCTED OUTSIDE THE BAY AREA

Stormwater conveyance system pollutant removal studies from outside the Bay Area are summarized below and organized alphabetically by author.

Pollutant Removal by Gully Pots in Different Catchment Areas (Grottker 1990)

Grottker (1900) studied approximately 200 gully pots in different catchments in Hannover, West Germany and analyzed their capacity to remove pollutants, subsequently using the results to build a simulation model[34]. The author examined two basic types of gully pots – dry and wet. The dry type had a slotted bucket and drained after each storm; however, its contents remained wet for a time, because the ventilation and temperature within the pot were low. The wet type was similar to what is also known as a catch basin, with a small settling pit where sediments could accumulate.

The following characteristics of each catchment draining to each gully pot were examined in the study: percent imperviousness, road surface type, gutter size, and the slope of the road surface. In addition, sediment dry weight, particle size distribution, organic matter content and ion exchange capacity were analyzed at the time the annual pollutant removal of each gully pot was determined. Correlation analysis found that there was not a significant relationship between any of the parameters analyzed and catchment characteristics. Furthermore, there were no significant correlations found between the parameters, with the exception of small particle sizes and the ion exchange capacity. The author noted that the correlation analysis results confirmed that the pollutant removal effectiveness of a gully pot was mainly dependent on the flow rate. In addition, the author found that the average annual dry weight of the collected material was about the same as that of a pollutant load of a single storm. Thus, the sediment removal effectiveness of the gully pots appeared to be minimal.

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. It is one of the few studies reviewed that attempts to evaluate a relationship of street sweeping with catch basin cleaning.

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 that 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

[34] This portion of the study is not considered relevant to this literature review and is therefore not presented in this summary.

well as monitoring by measuring down to the surface of the sediment was subject to some uncertainty.

The particle size distribution of the street dirt and catch basin samples was fairly similar between the swept and unswept test sites. While there were some differences for specific sites, there was no consistent pattern observed across all sites. The industrial area generally exhibited somewhat higher percentages of fine-grained particles (fine sand plus silt/clay) for catch basin sediment (24 to 51 percent) than in the two residential basins (10 to 51 percent in catch basin sediment). Truck traffic in the industrial area may have contributed to the larger amount of fine-grained material present on the streets.

Concentrations of pollutants (i.e., metals and PCBs) were higher in the samples collected from the industrial site compared to the two residential sites. Cadmium, lead, and zinc concentrations were generally higher in the industrial catch basins compared to the two residential study areas. Furthermore, in most cases, concentrations of cadmium, copper, lead, and zinc were higher in the catch basin samples than street dirt and street sweeping material. This was likely due to the greater proportion of fine-grained material found in the catch basin sediment since finer material. Overall, PCB concentrations collected from the industrial study area (0.034 to 0.91 mg/kg dry weight) were typically higher than the concentrations measured in the two residential study areas (<0.02 to 0.07 mg/kg dry weight). The variability in PAH concentrations observed at each test site made it difficult to distinguish trends between the different media or study areas.

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 pounds (15,400 kg) of dry sediment, while annual cleaning of catch basins in the area is estimated to have removed about 6,200 pounds (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.

Runoff of particle bound pollutants from urban impervious surfaces studied by analysis of sediments from stormwater traps (Jartun et al. 2008)

Thirty-one harbors and fjords in Norway have high concentrations of polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs) and heavy metals, leading to dietary consumption advisories of certain fish and crustaceans. Jartun et al. evaluated sediment in 68 stormwater traps[35] around a harbor area in the urban city Bergen, Norway to identify sources of pollutants and their pathways via the stormwater conveyance system to the surrounding water body. The study was carried out in October

[35] Structure is similar to a gully pot or catch basin with a sump. Each stormwater trap had a diameter of 1 m and a depth of about 3 m with an effective sediment trap of >60 cm located at the bottom of each stormwater sediment trap, giving each unit a capacity to capture 450–500 L of sediment.

and November 2004, two of the rainiest months of the year. Sediment samples were analyzed for PCBs, PAHs, total organic carbon (TOC), heavy metals, and grain size.

The study detected PCBs in 63 out of 68 samples with a detection limit of 0.0004 mg/kg (based on seven congeners). The median PCBs concentration was 0.080 mg/kg, with a range of <0.0004 - 0.704 mg/kg. Concentrations of PAHs had a median of 3.4 mg/kg, with a range of <0.2 - 80 mg/kg. The detection limit was 0.2 mg/kg. Concentrations of mercury were relatively low, with a median of 0.06 mg/kg and a range of <0.01 - 2.81 mg/kg (detection limit 0.01 mg/kg). The authors explained that the maximum mercury concentration was due to an excavation site located close to the stormwater trap where the sample was collected.

The sediments collected from the stormwater traps were mostly inorganic, with a median TOC content of 4.3%, ranging from 0.4–39%. Authors found that the high content of 39% TOC was due to runoff from a waste pile at a renovated building. A Principal Component Analysis of the investigated components indicated a correlation between TOC, PCBs, PAHs and mercury. The authors explained the correlation by a strong sorption between PCBs and PAHs to soil organic matter (Krauss et al. 2000) and the relationship between organic matter and mercury as described by Sanei and Goodarzi (2006).

The grain size distributions of 21 sediment samples ranged from mostly clay and silt to mostly coarse sand. The median grain size ranged from 23–646 µm, with diameters 250–300 µm being the most frequent. However, several samples had very fine-grained particles even up to the 90 percentile of the samples, making them available for stormwater dispersion in suspended form.

Baltimore Street Sweeping Study (Law et al. 2008)

Law et. al. (2008) conducted an effectiveness study in Baltimore, Maryland that addressed pollutant removal rates for street sweeping and storm drain cleanout programs in the Chesapeake Bay Basin. Two sampling sites, Catchment F (Lanvale Street) and Catchment O (Baltimore Street), were monitored for water quality runoff. Both catchments were approximately 30 ac in size and were about 70% impervious. Land use was primarily high density residential in the form of row houses. During the treatment period (Jan. 2006 – July 2007), sweeping was increased to twice a week on all streets in Catchment O and reduced to once per week on all streets in Catchment F.

The monitoring study characterized the material removed from storm drain inlets[36] in both residential and commercial/industrial land uses in two different physiographic regions. Four inlets in each of the four groups[37] were sampled to determine the rate of accumulation of material in the time period between a spring and fall (2006) cleanout. Inlet samples were analyzed for particle size distribution, total solids, nutrients and metals. Although samples were analyzed for metals, it was noted that an insufficient number of samples were collected to sufficiently characterize the patterns in water quality pre- and post-treatment.

Different land uses resulted in significantly different monthly accumulation rates, with inlets in commercial/industrial land uses having higher accumulation rates of material. Daily accumulation rates were found to be statistically significant for both land use types, with residential land use ranging from

[36] The storm drain inlets were designed without a sump and are considered a flow-through or 'self-cleaning' component of the stormwater conveyance system.
[37] Sixteen storm drain inlets were grouped into four categories that represented the various combinations of land use types and physiographic regions in the study.

0.001 to 0.005 ft^3/day and commercial/industrial land use from 0.011 to 0.013 ft^3/day. Material removed from the inlets consisted of, on average, 52% leaves and other organic matter, 39% sediment and 9% trash.

The particle size distribution for the inlet material, especially the coarser fractions, was found to be similar to the distribution for the street particulate matter (SPaM), which was likely due to the 'self-cleaning' inlets. For all inlets, an average of 86% of total sediment was between 0.25 mm and 4.0 mm. About 60% of commercial/industrial inlet samples were found to be between the 0.25-2.0 mm fractions.

A total of eight bedload samples were collected. The average mass of bedload collected was 225g (standard deviation of 114g) per sample, which typically represented material accumulated over a 1-2 week period. The monitoring set-up did not function as expected, and consequently, the amount of bedload material collected was considered an underestimation.

Information generated from the project's literature review, municipal practices survey, and monitoring data, though limited, was used to estimate pollutant removal efficiencies for inlet cleaning using the conceptual model created for this study. The estimated range in pollutant removal efficiencies for total solids was 18% and 35% for annually and semi-annually, respectively.

Catch basins and Inserts for the Control of Gross Solids and Conventional Stormwater Pollutants (Pitt and Field 2004)

Pitt and Field (2004) review and summarize past studies of catch basin inlet devices, including two specific EPA-funded case studies. Although three types of stormwater conveyance system inlet structures are described, the authors focus on a type of inlet structure with a sump that typically extends 0.5 to 1.0m below the bottom of the outlet. The authors conclude that catch basins (with sumps) remove up to 30% of the suspended solids load that enters the structure. However, much of this material is relatively coarse (larger particle sizes) and therefore may lack mobility and have relatively low pollutant concentrations. The authors also recommend features to optimize catch basin performance and identify an ideal catch basin design, with a large enough sump to trap a significant amount of material and a hooded outlet to withstand higher flows with little scouring.

The first EPA-funded case study was conducted in Bellevue, WA as part of the Nationwide Urban Runoff Program (Pitt 1985). The purpose of this study was to characterize Pacific Northwest stormwater quality and to evaluate the effectiveness of street and catch basin cleaning. The Bellevue area has a distinctive rainfall pattern typically involving many small rainfall events that generate relatively low runoff (25-35% of rainfall). For a period of three years (1980-1983), the study monitored sediment accumulations at more than 200 locations in the stormwater conveyance system including catch basins, simple inlets[38] and manholes in two mixed, medium density residential and commercial areas in Bellevue. Four separate types of conditions were examined in each of the two study areas: no controls, street cleaning alone, catch basin cleaning alone, and both street and catch basin cleaning together. The runoff stormwater quality of both areas was measured, and comparisons were made between the two areas while evaluating the effectiveness of the sediment management practices. Catch basin and other storm

[38] Pitt and Field (2004) describe a simple inlet as having a grating at the curb and a box, with the discharge outlet located at the bottom of the box, which connects directly to the main stormwater conveyance system or combined sewer system.

drain sediments had a much smaller median particle size than street sediments, suggesting that storm drain sediments potentially have higher pollutant concentrations than sediments captured by street sweepers.

When comparing the two areas under the four types of "treatment" conditions, Pitt expected to find the same results (i.e., reduction of outfall total solids concentrations) between the two areas. While most comparisons were consistent with that assumption, such as when comparing the effects of both street and catch basin cleaning in both areas, Pitt found some comparisons yielded different results than expected. For example, in one study area, when effects of both street and catch basin cleaning were compared to a control site, the outfall total solids concentrations were significantly higher than when no cleaning was conducted. Several explanations have been proposed since the study was conducted. One potential explanation given is that older street equipment was not as efficient as newer equipment in removing the particles that are washed off and potentially remove the larger particles that armour the finer particles, potentially increasing the solids discharges.

Sediment accumulation in the inlet structures was measured during this study using two approaches. For one approach, the structures were cleaned in the beginning of the project and subsequently surveyed nine times over two years (1979-1981) to determine the depth of accumulating material. Sediment loading was found to be constant over the first two years. During the second year the stormwater conveyance system contained about twice as much contaminated sediment at any one time as there was on the street. The stormwater system did not appear to flush out a large amount of sediment during the two years, likely due to the mild rainfall. The study found that, in inlet structures, depth below the outlet appeared to be the most significant factor affecting the maximum sump volume available. Catch basins accumulated sediments until reaching approximately 60% of the total sump capacity, when the sediment reached equilibrium (i.e., scour balancing new deposition). In one study area, nine of the most sediment-filled catch basins were located near streets that did not have curbs and had extensive nearby sediment sources (hillsides).

Storm drain pipes were also studied for sediment accumulation. It was assumed that the critical slope for sediment accumulation was less than one percent. A one-time survey found that pipes that had significant amounts of sediment were either sloped less than 1.5% or located close to a source of sediment. In one study area, most of the sediment found was in pipes that were located in an area that was not swept and was close to major sediment sources. Sediment from inlet structures and street dirt were tested and found to have similar pollutant concentrations.

The second EPA-funded case study (Pitt et al. 1994 and 1999) was more recent and carried out in a residential area of Stafford Township, NJ to evaluate the stormwater pollutant removal effectiveness of a catch basin (with a sump) and two proprietary filtering devices that were retrofitted into storm drain inlets. Paired samples that represented composite inflow and outflow stormwater were collected at each of the three devices and chemically analyzed. The catch basin was the only device that showed statistically significant reductions of several important pollutants including total solids (median removal rate of about 20%) and suspended solids (median removal rate of about 30%). The study also found that the filter devices increased suspended and volatile solids, likely due to the washing through of decomposing organic material trapped by the filter screens.

5. STREET AND STORM DRAIN LINE FLUSHING

The following section summarizes studies that addressed the effectiveness of street flushing or street washing to remove sediment and other solids from street surfaces and prevent them from entering the stormwater conveyance system. Street flushing is also used in some cities, such as Paris (Gromaire et al. 2000) to keep sidewalks and streets clean in densely populated areas and improve air quality by reducing the amount of particulates resuspended into the air from street surfaces (Amato et al. 2010).

The summaries below illustrate what is currently known about the effectiveness of this sediment management practice. Results are summarized in the following text and grouped into Bay Area studies or studies conducted outside of the Bay Area. Appendix C includes key attributes and findings of each summarized study for the reader to easily compare and contrast findings[39].

5.1. Bay Area Studies

Ettie Street Pump Station Watershed Studies (Kleinfelder 2006, Kleinfelder 2007, and Salop 2007)

Kleinfelder (2006) summarized a project carried out between June 2004 and June 2006 in the Ettie Street Pump Station watershed in Oakland, California to further investigate, identify, and abate sources of PCB-containing sediment in the watershed. The identification of PCB sources included the following steps:

1. Reviewing environmental records and inspection of suspect properties that were potential PCB sources;
2. Collection and analysis of sediment samples from the public right-of-way (ROW) locations in front of or nearby suspect properties; and,
3. Collection and analysis of sediment samples from private properties identified as potential sources of PCBs during the public ROW sampling.

Several data sources, including online databases and city files, were used to identify businesses and properties that were potentially contributing PCB-containing sediment to the stormwater conveyance system. Based on these results, the City of Oakland inspected 121 sites and facilities and subsequently prioritized them according to their potential to contribute PCB-containing sediments to the watershed.

Based on the results of this process, 37 high priority sites and 16 medium/low priority sites were chosen for sampling in public ROWs in front or nearby the selected sites. PCB concentrations in the 37 high priority sites ranged from 0.023 to 31 mg/kg. Twenty-two of the 37 sites had PCB concentrations exceeding a residential soil environmental screening level (ESL) for PCBs of 0.22 mg/kg. PCB concentrations at the 16 lower priority sites ranged from 0.0093 to 0.99 mg/kg. Nine samples exceeded the ESL.

To further identify the potential PCB sources, 23 locations at 19 private properties were chosen for composite sediment sampling based on the public ROW analysis and site visits. PCB concentrations from private property samples ranged from 0.04 to 93 mg/kg. Private properties with PCB concentrations exceeding 1 mg/kg were reported to the California Department of Toxic Substances Control for potential abatement actions. The SFRWQCB and other local agencies took responsibility for

[39] Note that only main points of the summaries are included in the table, and it is recommended to read entire summaries for complete information.

providing oversight to properties with PCB concentrations less than 1 mg/kg but above the residential soil ESL of 0.22 mg/kg.

Results from analysis of the ROW areas were used to identify 11 high priority areas for potential abatement. These areas were prioritized based on PCB concentration, feasibility of the selected abatement methodologies, proximity to the Ettie Street Pump Station and distance to residences. The two highest priority areas (Area 1 and 2), both identified as illegal dumping sites, were chosen for abatement. Before abatement began, City of Oakland staff removed all dumped debris from both locations.

During the abatement (May 15 - 24, 2006) excess dry sediment was removed from both locations using either a Bobcat excavator or a brush and shovel. Paved surfaces at both sites considered to be in good condition were then cleaned with a high-pressure washer. Sediment and wash water were collected and vacuumed into a self-contained vacuum truck. Sediment and wash water were analyzed for disposal purposes. Lead concentrations were considered hazardous according to CA regulations, and the sediment was disposed of at a hazardous waste landfill.

The abatement removed approximately 1.1 cubic yards (cy) of material, including 0.6 cy of dry sediment and 0.5 cy of wet sediment from Area 1. For Area 2, about 16.6 cy was removed, consisting of 16 cy of dry sediment and 0.6 cy of wet sediment. This equated to approximately 1.2 tons[40] of sediment removed from Area 1 and 18.7 tons of sediment removed from Area 2.

The total PCB concentrations in the dry sediment collected from Areas 1 and 2 were 2.7 mg/Kg and 0.3 mg/Kg, respectively. The total mass of PCBs removed from both areas was estimated at 0.0085 kg, with 0.0028 kg removed from Area 1 and 0.0057 kg removed from Area 2.

The cost of abating and disposing of approximately 20 tons of sediment containing about 0.0085 kg of PCBs from 921 linear feet of street (Areas 1 and 2) was approximately $100,000, or 0.9 grams per $10,000. This amount included disposal of the sediment at a Class I Hazardous Waste landfill as a result of elevated concentrations of lead. Based on this figure, the cost estimated to abate the remaining nine identified ROW areas, an additional 7,990 linear feet, with an estimated amount of 0.047 kg of PCBs was $839,000.

Kleinfelder (2006) also reported on the amount of sediment removed by the Alameda County Public Works Agency at the pump station between 2001 and 2006, during which a total of 104 cy was collected. The agency estimated a cost of $27,500 to remove 61 cy (or 70 tons) of sediment. However, this cost only included labor, as the County disposed of the sediment at its own facility. Sampling of the pump station sediment in 2006 showed a PCB concentration of 0.32 mg/kg. The estimated mass of PCBs removed in 2006 was 0.019 kg.

Based on the study results and a qualitative effectiveness analysis, Kleinfelder recommended the following management measures in order of importance: 1) source control, 2) ROW cleaning and sediment management, and 3) storm drain cleanout. Also, the study recommended follow-up sampling of sediments in the abated ROW areas.

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[40] The amount in tons was calculated using a value of 2250 lbs/cy for density of dry sediment based on the CA Integrated Waste Management Board value for dry density.

Kleinfelder (2007) collected five composite samples from the ROWs of Areas 1 and 2 to evaluate abatement effectiveness a year later (May 22-23, 2007). In both areas, samples were collected at the same locations where samples had been collected pre-abatement. In Area 1, PCBs concentrations dropped 42% in front of a private facility (AMG) from a pre-abatement concentration of 7.3 to 4.3 mg/kg and 75% at a storm drain located on a street corner from a pre-abatement concentration of 31 to 7.7 mg/kg. In Area 2, PCB concentrations decreased from pre- to post-abatement levels at the three sample locations by the following percentages: 1) 94% at a vacant lot, from 11 to 0.65 mg/kg; 2) 83% at a private facility (Giampolini), from 2.4 to 0.39 mg/kg; and 3) 27% at another private facility (Precision Casting), from 0.45 to 0.33 mg/kg. The results suggested that PCBs were abated more effectively in areas where PCBs concentrations were initially higher. In one case abatement of PCBs at an adjacent private property (Giampolini) may have contributed to the reduction in levels of PCBs found post-abatement.

Salop (2007) carried out follow-up sampling of non-abated areas in the watershed on May 24, 2007 to supplement Kleinfelder's abatement area sampling. Sampling sites were generally chosen from the list of 11 high priority sites identified in the Ettie Street project by Kleinfelder (2006). Sampling and analytical methods followed those used in the first phase of the project (Kleinfelder 2006). In contrast to the lowered PCB concentrations found in the abated areas, the concentrations in samples collected from the non-abated areas were generally similar to previous results at each sampling site, though Salop noted some uncertainty due to the heterogeneous sample material and inherent laboratory variability observed in prior investigations.

5.2. STUDIES CONDUCTED OUTSIDE THE BAY AREA

A Review on the Effectiveness of Street Sweeping, Washing and Dust Suppressants as Urban PM Control Methods (Amato et al. 2010)

Amato et al. (2010) reviewed available scientific and municipal studies and consulted experts to summarize past research on the effects of street cleaning and washing in the abatement of PM[41] emissions. Mineral dust (atmospheric aerosols originated from the suspension of minerals constituting the soil) has been shown to be a main component of PM_{10} and $PM_{2.5}$ and has shown a clear origin from road dust resuspension, especially in highly urban areas (Keuken et al. 2010 and Putaud et al. 2004). Lenschow et al. (2001) estimated that up to a 15% reduction in road dust emissions from paved roads could be achieved with effective control measures such as street sweeping and washing at urban background[42] locations and at the street level.

The sediment removal efficiency of water flushing using high-pressure jet equipment (without sweeping) was highly variable (20-65%), and the authors found limited benefit from street cleaning when measuring street cleaning waters (Bris et al., 1999; Gromaire et al., 2000). Small (6%) to no reductions in PM_{10} levels have been found with water flushing, with or without street sweeping (Düring et al., 2005/2007, John et al. 2006 and Norman and Johansson 2006). However, PM_{10} reductions in

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[41] Atmospheric particulate matter (PM) is a complex mixture of components arising from a number of emission sources (anthropogenic and natural) and atmospheric processes (secondary PM). Two common categorizations of PM are PM_{10} (particles with mean aerodynamic diameter <10 µm) and $PM_{2.5}$ (particles with mean aerodynamic diameter <2.5 µm), which is considered the fine fraction (Amato 2010).

[42] Urban locations distanced from sources and broadly representative of city-wide background concentrations, e.g., elevated locations, parks and urban residential areas (UK Department for Environment, Food and Rural Affairs website 2011).

morning hours suggested that they could have been due to the wetting of the road surface just hours before, which reduced dust re-suspension, rather than actually removing PM_{10} particles.

In a few studies, the combined use of street sweepers and washing reduced road dust and ambient PM emissions (Chang et al., 2005; Chou et al., 2007). Street sweepers, followed by washing with a pressurized jet, decreased the PM daily mean concentrations by 7-10% (Amato 2009) and total suspended particles[43] concentrations up to 30% (Chang 2005). Reductions in PM_{10} concentrations have been significant in the immediate vicinity of a road (Dobroff 1999) though not in wide areas (ARPA 2003). Keuken et al. (2010) confirmed that local rainfall patterns affect the re-suspension of street dust rather than runoff removing the particles from the street surface. PMx levels decreased with rainfall intensities larger than 2mm/h, which may have resulted in longer periods of a wet road surface.

The results of the summarized studies indicate that, in general, a combination of street sweeping and subsequent washing is a reliable control measure to mitigate PM emission from road dust re-suspension. Langston et al. (2008) showed that short-term effects confound the ability to generalize on emissions reductions over urban areas where the number of streets treated may be low. Amato et al. (2010) noted the need to carry out street cleaning investigations in wider areas (order of magnitude in km^2) in order to increase the absolute emission benefit.

The Quality of Street Cleaning Waters: Comparison with Dry and Wet Weather Flows in a Parisian Combined Sewer System (Gromaire et al. 2000)

Gromaire et al. (2000) evaluated two municipal street washing procedures on three different streets in the Le Marais catchment area of central Paris, which is an old, densely-populated residential and commercial district served by a combined sewer system. The pollutant load to the combined system from street washing procedures was compared to both the surface runoff load and the catchment's dry weather pollutant load. Streets were also washed under a controlled setting to determine the maximum street surface pollutant load, and the results were compared to the load removed using regular street washing procedures.

At the time of the study, municipal street washing procedures were being carried out daily, either manually or using high-pressure water jet equipment. During the early morning hours, valves were opened along the street in order to wash the gutter, while workers manually swept litter into the sewers. Sidewalks and gutters were also washed two to five times a week with pressurized water jet equipment. In addition, for most streets, the gutter and a 1 m-wide strip of pavement next to the gutter were vacuumed five days a week using a small sidewalk sweeper. The vacuuming procedure was not evaluated in this study.

The study sampled street washing water on six different days during dry weather periods. Dry weather flows were monitored at the outlet of the catchment area for two sampling periods of 5 to 7 days each. For wet weather runoff, about 20 rainfall events were studied at each sampling site. Samples were analyzed for suspended solids, organic matter and metals.

To assess the maximum street surface pollutant load that could be made available to runoff, samples were taken from three streets that were cleaned using both a brush and pressurized water jet equipment after a 4 to 5 day dry weather period. The equipment used for this test was the same

[43] Particles ranging in size from 0.1 µm to about 30 µm in diameter (U.S. Environmental Protection Agency website 2011).

(including the same jet pressure and flow rate) used by the municipality in its typical maintenance practices. However, the streets were cleaned for an average of four minutes for one meter of street whereas regular municipal cleaning took approximately two seconds for the same length of street. Even using this prolonged street washing procedure, the authors found that a small percentage of pollutants still remained.

Gromaire et al. compared the estimated pollutant load from regular street washing of the entire catchment to the total dry weather pollutant load measured at the catchment outlet. Street washing water represented less than 15% of the total dry weather load, although it appeared to be a major source of lead. When comparing dry weather flows at the outlet in a period with street washing to one with no street washing, the study found an estimated decrease of 15% in suspended solids, organic matter and copper when street washing was not conducted. The results were attributed to the street surface loads and potential erosion within the sewer system.

In addition, the daily pollutant load removed from street surfaces by regular street washing was compared to the pollutant load removed during a rainfall event and to the maximum load that can be removed from the street surface by a very intensive cleaning with the pressurized water jet equipment. The amount of suspended solids (g/m^2 of street surface) removed daily by street washing was in the same range as the amount of suspended load eroded during a rainfall event. The comparison with the total load that can be removed by intensive washing with a pressurized jet indicated that regular street washing only removed a very small part of the existing street pollutant load.

Finally, the characteristics of particles found in street cleaning waters were compared to the characteristics of particles in runoff. Street washing appeared to remove large biodegradable solids that were not easily removed by rainfall events. In general, heavy metal concentrations in runoff were similar to that of overall available street deposits, but were significantly higher than that of particles removed by street washing. These results indicated that regular street washing procedures did not remove as much of the fine particles associated with heavy metals as that removed by rainfall events.

6. SUMMARY OF FINDINGS

6.1. STREET SWEEPER EFFECTIVENESS

The effectiveness of street sweepers can be measured in a number of ways including: 1) the extent to which street cleaning removes solids and associated pollutants on the roadway, and 2) the extent to which runoff quality is improved. The following sections summarize the findings of the literature review with regard to the effectiveness of street sweeping. The sections are organized by effectiveness assessment method.

Street surface sediment[44] removal was defined herein as the reduction in the amount of sediment on a street removed by a street sweeper. In some literature this was evaluated based on each pass of the sweeper (i.e., street sediment prior to and following passage of the sweeper) and in some sources it was evaluated on a cumulative basis by comparing the dust and dirt on a test road segment versus a controlled (unswept) segment. The latter method has the advantage of incorporating the frequency of sweeping. The key findings are provided below in bulleted format with the supporting documentation following the finding.

- **Street Sweeper Effectiveness Depends on Street Surface Sediment Loading** - Figure 3 compares pre- and post-sweeping solids data (in the form of lbs of solids per curb mile) from the various literature sources reviewed. The data are organized by sweeper type and literature source. The solid line is the no removal line and points below the line indicate removal equal to the difference between the no removal line and the data point. The following findings are illustrated in Figure 3. All sweeper types are effective in removing street sediments, and the effectiveness tends to increase with loading. Moreover, even under the best of circumstances a residual loading of about 100-200 lbs/curb mile remains on the street, so no sweeper can remove all the sediments from a street.

  For relatively clean streets (e.g., <200 lbs/curb mile), all sweeper types are relatively ineffective. For intermediate (most common) street loadings (approximately 200-1000 lbs/curb mile), the most effective sweepers can reduce the loadings to between 100-200 lbs/curb mile. For very dirty streets (that are often dirty because of poor condition), the removals are highest but the residuals are also the highest.

  The scatter in the data shown in Figure 3 reflects the influence of a variety of factors that can affect street sweeper performance in any given test. Such factors include climate, road condition, sweeper frequency, sweeper condition and operation. Poor road conditions have been shown by some sources to be dirtier and more difficult to clean because of texture, cracks and non-smooth conditions. In the City of San Diego (Weston 2010), it was determined that vacuum sweepers should be preferentially deployed where roads were in a good condition to take full advantage of the vacuum sweeper performance (Weston 2010). In the hillier areas, the city determined that mechanical broom sweepers were adequate. Also, some references indicated that mechanical broom sweepers were better able to

[44] There are various terms used in the literature for the material on streets that passes through a standard mesh commonly 2mm in size. Terms such as dust and dirt, street sediment, and street loading are some examples of the terms used to characterize the solid particles on street surfaces. In this report these various terms are used interchangeably.

remove large, heavier objects (e.g., cans) whereas the vacuum sweeper and regenerative air sweepers were not as effective in removing such materials (Blosser 2000).

- **Sweeping Effectiveness Can Increase with Frequency, But There is Point of Diminishing Returns** - The frequency of sweeping is discussed extensively in the literature, although there does not appear to be agreement on the issue. Most sources conducted sweeping tests with a bi-weekly or a weekly schedule, although one study examined a frequency of three times per week (Pitt 1985) and for another, a frequency of five times per week (Pitt and Shawley 1981). The ideal goal is to sweep prior to a forecasted storm as closely as possible, but this is difficult given logistical and resource constraints. Some references suggest that the frequency be set so as to conduct, on average, one or two sweepings between storms. In semi-arid climates such as the Bay Area, some references recommended more intensive sweeping prior to the onset of the wet season.

- **Sweeper Type Comparisons are Best Conducted within a Given Test Where the Researchers Ensured that Conditions for Each Sweeper Were Similar** - Given the variability in the data, it is difficult to see a clear trend showing the relative performance of sweeper types. The best comparisons are those sources where multiple types of sweepers were tested under reasonably identical conditions. For example, the testing conducted by a number of researchers did indicate improved performance with the vacuum assisted and regenerative air sweepers compared to mechanical sweepers (Selbig and Bannerman 2007; Rochert et al. 2007).

- **Advanced Street Sweepers Can Be More Effectiveness in Removing Fine Particulates** - Many of the literature sources examined the effectiveness of street sweeping in removing the finer fraction of solids consisting of silts and clay and finer organic debris (typically less than 63 um). The reasons for this are twofold. One, studies of particles washed off of street during typical storm events (e.g., 0.5-1.0 inches) indicates that most particles are in the finer fraction (Pitt et al. 2004b). Secondly, some constituents such as trace metals tend to be higher in concentration in the finer particles, so the mass of such constituents may be disproportionately higher in the finer fraction.[45] The regenerative air and vacuum sweepers were designed specifically to better address the fine fraction of dust and dirt, and a number of the literature sources supported this finding (Selbig and Bannerman 2007; Rochert et al. 2007). In a local study conducted at various sites in Alameda County (Salop 2006, 2007), data also indicated that regenerative air sweepers tended to collect about 11% of the fines compared to about 6.5% for mechanical sweepers, however these data are from different locations. In order to accomplish this higher efficiency, one source indicated that the speed of the sweeper had to be maintained at about 4 miles per hour (Blosser 2000). Table 5 summarizes information on particle size effectiveness for the three major categories of sweepers. Because of the effects of confounding factors that can affect each study differently and also differences in study design and testing, the effectiveness estimates vary from source to source. With respect to the overall effectiveness of collecting sediment, the table indicates a general trend for somewhat improved effectiveness with the more advanced sweeper types, and within any given study, effectiveness is consistently higher with the more advanced equipment. A number of sources indicated however, that overall

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[45] The mass of the fraction of solids <63 µm generally makes up less than 20% of the mass of solids <2mm, so the mass of constituent associated with the finer fraction is often less than 50% of the total. Thus, although the concentration of certain constituents may increase in the fine fraction, the mass of the constituent is associated with both the fine and coarse fraction.

effectiveness is strongly influenced by how dirty the street is, and this factor may be more important than sweeper type for very dirty streets. Similarly effectiveness as a percent is limited when sweeping cleaner streets, independent of sweeper type. There is much less effectiveness information specific to fine particles in the literature, but in general there is some indication that mechanical brooms are less effective than the more advanced sweepers. An interesting case that illustrates the difficulty of reaching broad consensus is the study of Selbig and Bannerman (2007) that indicated an actual increase in fine particles for mechanical broom and regenerative air sweepers, and the authors thought that perhaps the gutter brooms in these sweepers could actually be grinding up larger particles into smaller ones. This study was conducted in Wisconsin and the effects of winter application of abrasives may also have played a part in this finding.

Figure 3. Comparison of pre- and post-sweeping solids data (in the form of lbs of solids per curb mile) from the various street sweeping studies reviewed.

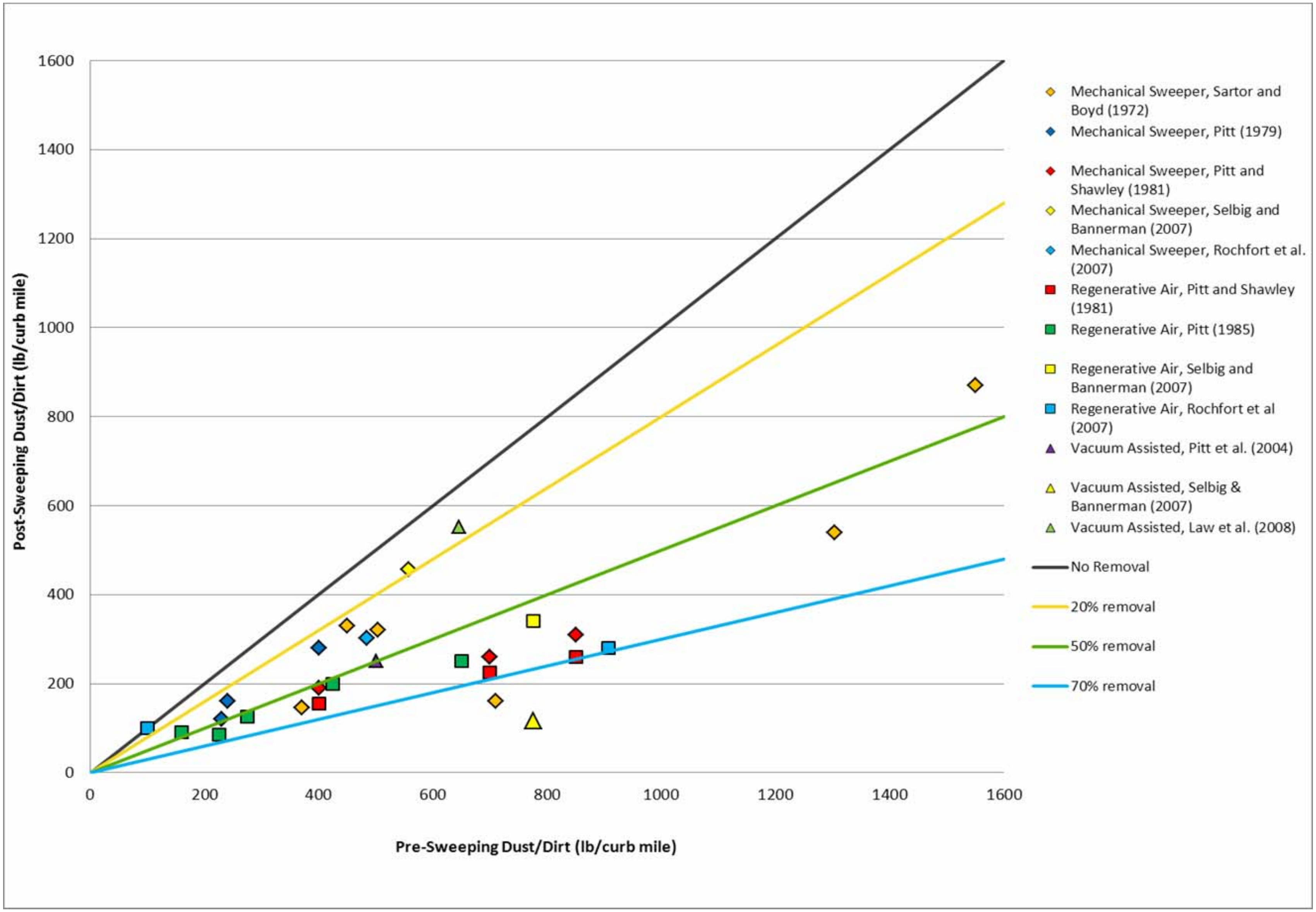

Table 5. Effectiveness of different types of street sweeping equipment to collect coarse and fine particles.

Literature Source	Effectiveness In Removing Fine And Coarse Particles (<2000 µm)			Effectiveness In Removing Fine Particulates (<63 µm)			Comments
	Mechanical Broom	**Regenerative Air**	**Vacuum Assisted**	**Mechanical**	**Regenerative Air**	**Vacuum Assisted**	
Sartor and Boyd 1972	36-78%						
Pitt 1979	34-43%			15-30%			Broom sweepers are only about 20% effective at removing smaller particles (<45 um).
Pitt and Shawley 1981	53-64%	61-69%		36-61%	55-74%		Regenerative air slightly (5-10%) more efficient than broom sweeping especially if streets are initially cleaner.
Pitt 1985		53-62%					Regenerative air sweepers were more effective at removing fine particulates than mechanical sweepers
Pitt 2004a			50%				Vacuum assisted sweeper effective in removing fine particles when streets are dirty (~500lbs/curb mile) but not when streets are clean (~100 lbs/curb mile)
Breault et al. 2005	20-31%		60-92%	13%		39-81%	Controlled sweeper effectiveness tests, which included seeding streets with prescribed amount of graded dirt, indicated vacuum sweeper efficiencies consistently greater (by 1.6 -10 times) than mechanical sweeper for all particle size ranges.
Bannerman 2007		76%	63%	-30%	-50%	10%	Street sweepers significantly reduced the dust and dirt loading on streets, with larger reductions achieved with vacuum assisted or regenerative air sweepers. Mechanical broom sweepers more effective when street dirt yield approaches 1000 lbs/curb mile.

Literature Source	Effectiveness In Removing Fine And Coarse Particles (<2000µm)			Effectiveness In Removing Fine Particulates (<63 µm)			Comments
	Mechanical Broom	**Regenerative Air**	**Vacuum Assisted**	**Mechanical**	**Regenerative Air**	**Vacuum Assisted**	
Rochfort et al. 2007	37%		70%		75%		New regenerative air sweeper tested on both north and southbound lanes was effective in reducing dust and dirt loading only in southbound lane because of higher surface loading. Regenerative air sweeper also able to reduce loadings of fines from 40 lbs/curb mile to 10 lbs/curb mile or 75%.
Law et al. 2008			14%				Vacuum sweeper tested on 2 sites in Baltimore, Maryland.
Herrera 2009		48-90%					Study investigated effectiveness of street sweeping in Seattle, WA.

6.2. EFFECTIVENESS OF STREET SWEEPING IN IMPROVING RUNOFF WATER QUALITY

A number of sources attempted to measure the effectiveness of street sweeping in terms of improving the quality in the runoff water. Most of these efforts were unable to measure a statistically reliable improvement. One study that indicated a statistically valid improvement in water quality was conducted in Milwaukee using a Schwarze Industries Enviro Whirl I (Pitt et al. 2004a). The study documented a 40% reduction (at 80% confidence) in TSS concentrations measured at an outfall that drained the test catchment.

Kang et al. (2009) recently published a paper examining why most studies could not document an effect of street sweeping on water quality and concluded that most monitoring studies do not have sufficient statistical power to distinguish the effect of sweeping given the variability in runoff water quality. Conducting a statistical analysis of 15 data sets they found that only four of the studies had sufficient statistical power to determine an effect, and of the four, only a study conducted in Austin, Texas was able to show a statistically reliable difference (at the 95% confidence level) between the solids in runoff from a swept and unswept catchment. The study (Irish et al. 1998) found a reduction in runoff TSS loading based on 402 grab samples collected from 23 natural storm events and 35 rainfall simulation events conducted on a freeway segment in Austin, Texas.

6.3. EFFECTIVENESS OF STORMWATER CONVEYANCE SYSTEM CLEANING

This section identifies major findings based on the studies summarized in Section 4 - Stormwater Conveyance System Cleaning. Nearly all studies reviewed are focused on the removal of sediment and associated pollutants via inlet or catch basin cleaning. The majority of those focus on the effectiveness of catch basins (with sumps) versus drop inlets (without sumps). Although limited, major findings of studies about storm drain line and pump station cleaning are also presented.

6.3.1. Inlet/Catch Basin Cleaning

Most of the studies reviewed address inlet and catch basin cleanouts, sediment characterization, and/or monitoring of sediment accumulation. Of those, most do not define effectiveness or carry out comprehensive effectiveness evaluations. Furthermore, most studies measure inlet sediment and analyze the removed sediment for various pollutants, with a few also measuring particle sizes.

Several factors affect the pollutant removal effectiveness of an inlet or catch basin, including configuration/design, particle size distribution, maintenance and cleanout frequency, rainfall patterns, and inflow velocity. The following sections describe information identified through the literature review regarding these factors.

Configuration

Different configurations and designs of inlet structures affect the amount of material retained within the structure during runoff events. Factors that increase the volume of a catch basin's sump (e.g., greater distance from the outlet pipe to the base of the sump and greater area of the base of the sump) increase solids retention (Memon and Butler 2000). Salop (2006) noted that the amount of materials that accumulated in an inlet appeared to be related to its type of construction, and an older type of inlet found in a Bay Area industrial area in Berkeley with a sump had greater storage capacity than newer inlets designed to flush out during storms.

Particle Size

Coarse material tends to settle more rapidly relative to finer particulates (< 63 µm), while finer material tends to settle in lower velocities due to the longer settling time (Yee and McKee 2010). Thus, coarse material is more likely to be found in inlets during cleanouts, especially in areas with less intensive storms. Studies have confirmed this particle size behavior. Butler et al. (2003) conducted laboratory studies using an experimental catch basin and found that 80-90% of sediment accumulation in the catch basin consisted of particles with sizes ranging from 300-600 µm. Neely et al. (2008) found that sediment samples from inlets had between 22 and 41% materials within the 250-2,000 µm range. The coarser particles may be due to the 'flow-through' design of the inlets evaluated in this study that provide only a short settling time for particles as compared to the experimental catch basin with a sump that Butler et al. (2003) constructed. Although the particle size distribution found in accumulated sediment varies partly due to the type of sediment supply in a watershed and geographic region, rainfall patterns and street dust particle distributions, limited data show that in general, coarse particles tend to dominate the particle size distributions of sediments that accumulate in storm drain inlets, especially in regions such as the Bay Area, where few catch basins with sumps are currently believed to exist.

Maintenance and Cleanout Frequency

The amount of sediment in a catch basin's sump limits the amount of sediment retained during subsequent storms. A catch basin that is not adequately maintained will not function properly and may increase the sediment load to a stormwater conveyance system and consequently to receiving waters. Catch basins have been shown to retain sediment until 60% of the total sump capacity is reached, at which point Pitt and Field (2004) determined that the sediment within the sump had reached equilibrium (i.e., scour balancing new deposition). Pitt (1985) tested inlet capacities by adding sediment to inlets thought to be at equilibrium, and, as expected, the added sediment was not retained but instead washed out by storm flows. Furthermore, in the Castro Valley in the Bay Area, Pitt and Shawley (1981) determined that large storms that occur approximately once a year completely scour out the inlets and stormwater conveyance system. Thus, cleanout frequency is a key factor in sediment retention and the effectiveness of inlets to reduce pollutant loads.

As the frequency of inlet and catch basin cleanouts increases, the cumulative volume and mass of sediment removed also increases. Mineart and Singh (1994) found that, for industrial land use in particular, there was a clear decrease in the annual sediment volume and pollutant mass removed (i.e., total per year) from inlets with decreased cleanout frequency. Semi-annual cleanouts removed the greatest average mass per cleanout, suggesting that this frequency may be relatively cost-beneficial. For residential, commercial and industrial land uses, monthly inlet frequency removed the most sediment volume (3-5 ft^3), when totaled over a period of a year as compared to annual, semi-annual and quarterly cleanout frequencies. A higher frequency of clean out apparently removed accumulated sediment and other materials that otherwise would have been scoured out by stormwater runoff. In general, Mineart and Singh (1994) appeared to be the best source of data found regarding the effectiveness of different cleanout frequencies in the Bay Area. This study evaluated inlets (as opposed to catch basins) and serves as a good starting point in beginning to assess the general effectiveness of inlet cleaning to reduce pollutant loads.

Rainfall Patterns and Inflow Velocity

Generally, stormwater conveyance systems tend to accumulate more sediment in regions with little rain or during periods of low-intensity storms. At lower flow velocities, materials conveyed into an inlet structure by stormwater runoff are more likely to settle out. Sartor and Boyd (1972) found that the retention time in a constructed catch basin was less than a minute during low flows, indicating that the catch basin was effective in removing only coarse material. Turbulence caused by higher flow velocities can cause materials (both coarse and fine) to migrate out of the inlet into the storm drain pipes. Thus, rainfall patterns affect the amount, as well as the particle size distribution, of accumulated sediment in an inlet.

Significant storms tend to be a major factor in sediment retention and the transport effectiveness of a stormwater conveyance system. Pitt and Shawley (1981) found that a Castro Valley, CA rain storm of about 1.5 in total was capable of transporting much of the material through the stormwater conveyance system. Furthermore, Sartor and Boyd (1972) found that for a simulated heavy rainfall intensity (1/2 in/hr), a constructed catch basin was reasonably effective in removing coarse solids, i.e., solids with a diameter larger than 246 µm, and ineffective at removing fine solids. Herrera (2009) noted that, on average, catch basins only accumulated sediment at 10% of their capacity at the end of the study period, due likely to a relative lack of mobilization of sediments by the mild rainfall of the Puget Sound Region (Seattle, WA). In general, understanding the local rainfall regime is helpful in selecting cleanout frequencies and understanding the expected particle size distribution of accumulated sediment.

Relationship of Inlet Cleaning to Street Sweeping

Inlet cleanout removal rates are not independent of street sweeping removal rates. Many of the factors of the Law et al. (2008) conceptual model affecting street sweeping effectiveness also impacted inlet cleanout effectiveness. For example, the total street dirt load and the amount of dirt removed by street sweeping both influence the quantity and particle sizes of sediment that can be trapped within storm drains, inlets or catch basins.

Herrera (2009) found that the amount of sediment removed from street sweeping was higher by as much as a factor of five than the amount of sediment accumulated in catch basins at test sites. Thus street sweeping carried out on a bi-weekly schedule at the test sites was much more effective in terms of sediment removed than annual catch basin cleaning. However, this result was likely climate-specific in that the light intensity rainfall in the region (Seattle, WA) has relatively limited ability to convey street dirt/dust loads to the catch basins.

Pitt and Field (2004) found that sediments collected from inlets and other storm drain sediments (catch basins and manholes) had a smaller median particle size than street sediments. Herrera (2009) measured higher concentrations of cadmium, copper, lead, and zinc in catch basin samples than in street dirt and street sweeping material and noted that this was likely due to the greater proportion of fine-grained material found in the catch basin sediment.

6.3.2. Storm Drain Line Cleaning/Flushing

Only limited information was found on storm drain line cleaning and flushing during this literature review. Storm drain cleanout effectiveness is impacted by the frequency of and method of cleanout (CWP 2006) and the design of the stormwater conveyance system. A one-time survey of sediment accumulation in a stormwater conveyance system found that storm drain pipes with significant amounts of sediment accumulation were either sloped less than 1.5% or located close to a source of sediment (Pitt and Field 2004). An effort by the City of San Jose, CA removed sediments in an industrial area with elevated PCB concentrations. The City hired a private contractor to clean out drain inlets, publicly owned laterals, and the main storm drain line below a short cul de sac street in San Jose (Leo Avenue). The contractor removed a significant amount of sediment (3,500 kg of solids) and approximately 0.004-0.07 kg of PCBs based on the approximate range of PCB concentrations previously measured in the street's storm drain line sediments (1 - 20 mg/kg). Most of the accumulated sediment was found in a 'dip' of the storm drain line (Dunlavey 2011, personal communication).

6.3.3. Pump Station Cleaning

As with storm drain line cleaning/flushing, only limited information was found on pump station cleaning during this literature review. Salop (2006) analyzed PCB and mercury concentrations in material collected from two pump stations, one associated with a railroad overpass in a suburban city (Pleasanton, CA) and the other from an industrial area (Ettie Street pump station in Oakland, CA). The estimated solids removed during a cleanout of the Pleasanton pump station sump was 2.4 cy (2,455 kg). The Ettie Street pump station was not cleaned out during the study but the estimated amount of solids accumulated in its four sumps was 33 cy (33,740 kg). Based on these amounts of solids and the corresponding pollutant concentrations measured, the study estimated that a relatively small mass of PCB and mercury are removed during cleanouts of the pump station sumps - less than 0.01 kg of PCBs and less than 0.03 kg of mercury from each facility. The study also estimated the PCB mass that would be removed during a single cleanout of the Ettie St. pump station based on the highest PCB concentration measured in the sumps since 2000 to be 0.3 kg.

6.4. Effectiveness of Street Flushing

Two areas in the Ettie Street pump station watershed were abated via dry sediment removal and power washing of streets. PCB concentrations measured in sediments collected from these sites were 27 to 94% lower post-abatement compared to pre-abatement (Kleinfelder 2007). The results suggested that PCBs were abated more effectively in areas with higher PCBs concentrations. In one case abatement of PCBs at an adjacent private property may have contributed to the reduction in levels of PCBs.

In addition, Gromaire et al. (2000) found that daily street flushing in a densely populated residential/commercial area of Paris contributed an estimated 15% in loads of suspended solids, organic matter and copper to the outlet flow of a catchment that discharges to a combined sewer system. This demonstrates the ability of street flushing to mobilize additional pollutant loads.

A few studies have evaluated the combined use of street sweeping and street washing/flushing to reduce ambient particulate matter (PM) emissions. In general, based on the monitoring of airborne particulates, a combination of street sweeping and subsequent washing is a reliable control measure to mitigate PM emission from road dust re-suspension. Chang (2005) found that street sweepers, followed by washing with a pressurized jet, decreased airborne total suspended particle[46] concentrations up to 30%.

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[46] Particles ranging in size from 0.1 µm to about 30 µm in diameter (U.S. Environmental Protection Agency website 2011).

7. COSTS OF SEDIMENT MANAGEMENT PRACTICES

Information obtained in the literature review regarding costs of sediment management practices was limited, especially regarding stormwater conveyance system cleaning and street flushing. Based on available information, the following costs are adjusted to 2011 dollars using an online inflation calculator accessed at http://www.usinflationcalculator.com.

7.1. STREET SWEEPING COSTS

Literature sources that addressed costs often addressed life cycle costs on a dollar per curb mile swept basis. Shilling (2005) indicated that life cycle costs for mechanical sweepers was approximately $40 (2005 dollars) per curb mile swept and about $20 for a vacuum sweeper (Shilling 1950). Although this author did not address the reason for the difference, another report indicated that vacuum sweepers have many less wearing parts than mechanical broom sweepers. Shilling quoted a capital cost of approximately $100,000 for a mechanical sweeper compared to a vacuum sweeper of over $200,000. The life of the mechanical sweeper was given as 5 years compared to 8 years for the vacuum sweeper.

In an evaluation of street sweepers, Blosser (2000) for the City of Olympia Washington estimated the cost of a Schwarze EV-1 vacuum sweeper at $300,000, annual operation and maintenance costs at $50,000, and annual capital replacement costs at $30,000 (although he stated that latter figure was conservative). If we assume the equipment is operated 40 hours/week at 4 mph, the total distance travelled per year would be about 8300 miles. Assuming 80% of those miles are associated with cleaning would yield about 6500 curb miles swept per year. If as indicated by Blosser, the O&M costs are about $80,000 per year, the O&M costs on a per curb mile swept would be about $12.

Phone calls were made to three major sweeper manufacturers requesting current cost information for their products. One manufacturer responded that the purchase price for regenerative air sweepers currently range from $170,000-$200,000 depending on options. Dustless regenerative air sweepers that comply with stringent air quality requirements promulgated by the South Coast Air Quality Management District range in price from $250,000 to $280,000.

Discussions with local agencies (City of San Jose and City of Oakland) also provided some insight into two Bay Area street sweeping programs. The City of Oakland relies primarily on mechanical broom sweepers whereas the City of San Jose is moving more towards regenerative air sweepers. According to the contact at the City of San Jose a typical sweeper might sweep about 28 curb miles per day, 5 days a week, and 50 weeks a year for a total of approximately 7000 curb mile swept per year. Using an estimated life cycle cost of $40/curb mile based on several references results in a life cycle cost of about $280,000 per year. Sweeper life depends on numerous factors but a rough rule might be about 10 years during which time a sweeper would have swept about 70,000 curb miles. If the capital cost of a sweeper is $300,000 the capital cost per curb mile is about $4, or about 10% of the overall life cycle cost of operating a sweeper.

7.2. STORMWATER CONVEYANCE SYSTEM CLEANING COSTS

Herrera (2009) conducted a comprehensive street cleaning and inlet cleanout study that determined approximate life cycle costs for the Seattle Public Utilities city-wide catch basin cleaning program at $0.44 per wet kg and $0.78 per dry kg of sediment removed. Inspection, cleaning, material handling, and disposal costs were included in the estimate. In a desktop evaluation, Salop et al. (2004) projected that it would roughly cost Alameda County (Bay Area) MS4s an additional $300,000 to perform semi-annual cleanouts of inlets (as opposed to annual) due to increased disposal costs. In addition, Kleinfelder (2006) reported that the Alameda County Public Works Agency estimated a cost of $30,480 to remove 61 cy (or 70 tons) of sediment from the Ettie Street pump station. However, this cost did not include disposal, as the County disposed of the sediment at its own facility.

7.3. Street and Storm Drain Line Flushing Costs

The only study found that included costs for street flushing was the Ettie Street Pump Station project conducted in the Bay Area. Kleinfelder (2006) calculated that the cost of abating and disposing of approximately 20 tons of sediment containing about 9 g of PCBs from 921 linear feet of street (high priority Areas 1 and 2) was approximately $100,000. This amount included disposal of the sediment at a Class I Hazardous Waste landfill due to elevated concentrations of lead. Based on this figure, the cost estimated to abate the remaining nine high priority areas, an additional 7,990 linear feet of street with an estimated additional 47 g of PCBs, was $839,000.

The only information found on costs for storm drain line flushing was provided by the City of San Jose (Dunlavey 2011, personal communication). The cost for the city to contract with a private company to perform the one-day cleanout and dispose of the collected material at a hazardous waste facility[47] was approximately $25,000. Although this amount includes the company's field crew and transport and disposal of the material, it does not include San Jose staff time, analytical testing costs, and cost to video the storm drain line before and after the line cleaning. San Jose estimated that the amount could increase to $50,000 if these latter costs were considered.

Table 6 summarizes limited information found during the literature review on unit costs for municipal operation and maintenance practices.

Table 6. Unit costs of municipal operation and maintenance practices.

Practice	Approximate Unit Cost	Reference
Street sweeping	$20 - $40 per curb mile.	Pitt 1979, Pitt 1985, Shilling 2005, and Herrera 2009
Storm drain inlet cleaning	$0.44 per kilogram wet sediment removed.	Herrera 2009
Street flushing	$100 per linear foot of street.[1,2]	Kleinfelder 2006
Storm drain line cleanout	$40 to $80 per linear foot of pipe.[1]	Dunlavey 2011, personal communication

[1]Based on very limited data (one site).
[2]Cost includes disposal of sediment as hazardous waste due to elevated lead concentrations.

[47] The City of San Jose tested the collected material for lead, and because of elevated concentrations, chose to dispose of the material at a hazardous waste facility.

8. COST/BENEFIT ANALYSIS OF THE EVALUATED SEDIMENT MANAGEMENT PRACTICES

8.1. BENEFITS

8.1.1. Street Sweeping

The implication for street sweeping for the control of mercury and PCBs discharges to the San Francisco Bay can be addressed through a cost-benefit analysis. Benefits can be assumed to equal the mass of PCBs and mercury collected by street sweeping and can be estimated by combining the information from the literature review on street sweeper effectiveness with concentrations of PCBs and mercury measured on street surfaces in the Bay Area assembled contained in a regional database (SFEI 2010).

The analysis focused on 153 samples taken from street and parking lot surfaces in industrial areas throughout the Bay Area. The SFEI analysis of the PCB data indicated that approximately 100 samples were below the detection limit (0.073 mg/kg). Analysis of the data also showed that most of the mass of PCBs that could potentially be collected by street sweeping would be collected at those sites where concentrations were in the upper 10th percentile (90th percentile and above). Based on this analysis, it was decided that the cost benefit analysis should focus on those approximately 15 sites where samples were in the 90th percentile (0.27 mg/kg PCBs or 0.47 mg/kg mercury) and above.

The cost benefit analysis was conducted where the benefit was assumed to be the mass of PCBs and mercury collected by street sweeping. Estimates of mass collected are given Table 7 for PCBs and mercury where the mass collected is for the areas where sample concentrations were in the upper 10th percentile of the street surface data contained in the SFEI database. Two rows of estimates are provided for each constituent: the upper row corresponds to assumptions chosen to provide a “lower bound” on the mass collected, and the lower row corresponds to assumptions chosen to provide an “upper bound” on the mass collected. For each scenario, the mass collected is estimated for three concentrations: the low concentration (corresponding to the 90th percentile concentration), the best estimate (corresponding to the median) and the highest (corresponding to the mean). Specific assumptions for the columns in Table 6 are provided in the footnotes below the table.

The table indicates that the range of mass of PCBs collected would be 0.04-1.31 kg, with a best estimate in the range of 0.06-0.75 kg. The corresponding mass for mercury would be 0.03-1.45 kg, and the range for the best estimate would be 0.05-0.54 kg. This would indicate that the relative benefits of sweeping would be comparable for mercury and PCBs, although the absolute mass collected, even under the upper bound scenario is low relative to the TMDL targets.

Table 7. Estimated annual mass (kg) and annual cost of collecting PCBs and mercury by sweeping areas in the upper 10th percentile of street surface data contained in the SFEI Proposition 13 project database (SFEI 2010).

		Constituent Concentration (mg/kg)							Mass Collected (kg)		
Constituent	Scenario (Bound)	Low[1]	Best[2]	High[3]	Dust/Dirt Collected[4] (kg/km)	Road Length Swept[5] (km)	Number of Sweepings per Year[6]	Number of Areas Swept[7]	Low[8]	Best[8]	High[8]
PCBs	Lower	0.66	1.09	1.9	28	10	12	17	0.04	0.06	0.11
	Upper	0.66	1.09	1.9	85	20	24	17	0.46	0.75	1.31
Mercury	Lower	0.48	0.78	2.1	28	10	12	17	0.03	0.05	0.12
	Upper	0.48	0.78	2.1	85	20	24	17	0.33	0.54	1.45

1. 90th percentile concentration of data taken on street surfaces (SFEI 2010).
2. Median concentration of data taken on street surfaces (SFEI 2010).
3. Mean concentration of data taken on street surfaces (SFEI 2010).
4. Assumed range in amount of dust and dirt collected by sweepers per km (equivalent to range of 100-300 lbs/curb mile from literature review).
5. Assumed range in length of roads in each hot spot area, intended to bracket road length that could be swept and which would have corresponding elevated concentrations. Range is designed to bracket expected value that is based on 3 km "halo" (Yee and McKee 2010) or area of 7.1 km^2 around each elevated sample and road density of 2.5 km/km^2 (based on arterial road density of 4 miles/square mile for San Francisco: http://www.newgeography.com/content/001316-road-network-density-major-metropolitan-areas).
6. Assumed range in sweeping frequency is monthly to twice per month; therefore, 12 versus 24 sweepings.
7. Number of sites in upper 10th percentile is 17.
8. Mass collected estimated by multiplying concentration times dust and dirt collected, road length swept, frequency, and # of sites.

8.2. INLET CLEANING

As with street sweeping, implications for the control of PCBs and mercury by inlet cleaning are presented as both benefits and costs. The benefit, or effectiveness, of inlet cleaning is presented as the PCB or mercury mass removed per cleanout of an inlet located in an area with elevated pollutant concentrations. This pollutant mass was calculated by multiplying the estimated amount of sediment removed per inlet cleanout by an estimated pollutant concentration in the sediment (Table 8). Data on average sediment removed per inlet cleanout in industrial areas, which are assumed to have relatively high concentrations of PCBs and mercury, were obtained from Mineart and Singh (1994). This study was conducted somewhat recently (in last 16 years) and locally (Alameda County in the Bay Area), addressed industrial land use (among others), had a relatively large sample size (60 total inlets, including 20 inlets in industrial land use), and evaluated several cleaning frequencies. Concentrations of PCBs and mercury in sediment were estimated using the chemistry data from the 236 Bay Area storm drain inlet sediment samples compiled by the Proposition 13 study (SFEI 2010). Assuming cleanout of inlets in areas with elevated pollutant concentrations, the median of the upper 10^{th} percentile was used as a 'best' estimate, the 'low' estimate was based on 90^{th} percentile concentration, and the 'high' estimate was based on the mean of the upper 10^{th} percentile (Table 8). The calculated removed mass was subsequently used to estimate a cost/benefit ratio for inlet cleanouts (Section 8.3). Table 8 shows that the mass of PCBs and mercury collected per cleanout decreases as concentrations decrease. Thus, the most PCB and mercury mass would be removed in areas with elevated concentrations, as expected.

Table 8. Estimated annual mass (kg) and annual cost of collecting PCBs and mercury by inlet cleaning in the upper 10th percentile of inlet/catch basin data contained in the SFEI Proposition 13 project database (SFEI 2010).

	Constituent Concentration (mg/kg)			Sediment	Constituent Mass Collected per Cleanout[5] (mg)					Unit Cost for Removal of Constituent[8] ($/mg)		
	High[1]	Best[2]	Low[3]	Average Mass Collected per Cleanout[4] (kg)	High	Best	Low	Unit Cost/ Wet kg. Sed.[6] ($/kg)	Cost for Removal of Avg. Sed. Mass[7] ($)	High	Best	Low
PCBs	1.5	1.3	0.71	14	20	18	9.8	$0.44	$6.1	$0.30	$0.33	$0.62
Mercury	1.2	1.0	0.65	14	17	14	9.0	$0.44	$6.1	$0.35	$0.43	$0.68

1. Based on mean concentration of the top 10th percentile of the inlet/catch basin data of the Proposition 13 study database (SFEI 2010).
2. Based on the median of the top 10th percentile of the inlet/catch basin data of the Proposition 13 study database (SFEI 2010).
3. Based on the 90th percentile of the inlet/catch basin data of the Proposition 13 study database (SFEI 2010).
4. Average sediment mass removed per cleanout based on an annual cleaning frequency (Mineart and Singh 1994).
5. Constituent mass = sediment mass collected per cleanout multiplied by corresponding concentration.
6. Unit cost for one kilogram of wet sediment collected from an inlet based on estimates from City of Seattle study (Herrerra 2009) and estimated in 2011 dollars. Inspection, cleaning, material handling, and disposal costs were included in the estimate. Costs refer to disposal of material at a local disposal facility without being dewatered.
7. Cost = unit cost multiplied by average mass per cleanout.
8. Unit cost = cost for removal of average sediment mass divided by constituent concentration. Low cost estimate based on high concentration, moderate estimate based on moderate concentration, and high estimate based on low concentration.

8.3. COSTS

8.3.1. Street Sweeping

The second part of the cost benefit analysis is to estimate the annual cost to sweep an area that represents a "hot spot" defined here as having a sample in the upper 10th percentile. The estimated cost to collect PCBs and mercury are provided in Table 9 where the cost of sweeping is estimated at $24 per curb kilometer ($40 per curb mile) swept based on information gathered in the literature review (Pitt 1979, Pitt 1985, Shilling 2005, and Herrera 2009). Assumptions were then needed to estimate the number of curb kilometers contained in an area and the number of times per year the roads would be swept. For the "low bound scenario" it is assumed that the area would have arterial streets ranging from 10-20 km in length and that these streets would be swept either monthly or twice per month. The total annual cost is then the product of the cost/km times the km swept times the frequency times the number of sites (17). This total cost is then divided by the estimated mass of material collected to get a cost benefit expressed as dollars per mg of constituent.

The results of the cost calculations indicate that there is an inverse relationship between the cost to remove the constituent and its concentration. In other words, (based on a constant removed sediment mass), the higher the PCB or mercury concentration, the less expensive it is to remove it. Thus, the 'dirtier,' or more polluted the sediment removed is, the more cost-efficient it would be for a municipality or responsible agency.

8.3.2. Inlet Cleaning, Street Flushing and Storm Drain Line Flushing

To determine the cost corresponding to the benefits of inlet cleaning described above, the unit cost to remove one kilogram of wet sediment[48] ($0.44/kg) via inlet cleaning estimated by a recent study conducted in Seattle, WA (Herrera 2009) was used. This was the only information related to the cost of inlet cleaning found during the literature review; a unit cost per inlet cleanout was not found. Thus, the cost benefit calculations in Table 8 represent a rough estimate for the Bay Area using very limited information. The unit cost ($0.44/kg) was multiplied by the mean sediment removed per cleanout to give a rough estimate of cost per inlet cleanout. This cost was divided by the previously calculated estimated pollutant mass removed per cleanout, to give rough cost-benefit figures in terms of $/mg pollutant removed (Table 8).

Similar to street sweeping, the results of the cost calculations indicate that there is an inverse relationship between the cost to remove the constituent and its concentration. Thus, the more polluted the sediment removed from an inlet is, the more cost-efficient the cleanout is in terms of pollutant removal.

In addition, the Ettie Street study results (Kleinfelder 2006) were used to calculate a rough estimate of $/mg PCBs removed for street flushing and capture and information provided by the City of San Jose (Dunlavey 2011, personal communication) was used similarly for storm drain flushing. Mercury concentrations were not measured during the Ettie Street and San Jose projects. The calculated cost for street flushing and capture was higher than the other sediment management practices at about $11/mg

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[48] Cost adjusted to 2011 dollars *(*www.usinflationcalculator.com). Unit cost includes labor, handling and disposal costs.

PCBs removed, but included disposing of sediment as hazardous waste due to elevated lead concentrations. It is unknown whether concentrations of lead would be similarly elevated in other Bay Area locations.

Table 10 compares cost-benefit calculations for inlet cleanout, street flushing and capture, storm drain flushing and street sweeping (based on sweeping 12 times per year). It should be noted that these calculations are based on limited data and there are many uncertainties in the results, but they can serve as a starting point for the comparison of the cost-benefit of municipal operations and maintenance activities until more information becomes available.

Table 9. Street sweeping - estimated range in costs to collect PCBs and mercury ($/mg) for areas having concentrations in the 10th percentile of concentrations as provided in the SFEI Proposition 13 project database (SFEI 2010).

	Constituent Mass Collected[1] (kg)							Cost/Mass ($/mg)		
Constituent	**Low**	**Best**	**High**	**Road Length Swept (km)**	**Number of Sweepings Per Year**	**Cost per Km[2] ($/km)**	**Total Cost[3] ($)**	**High[4]**	**Best[4]**	**Low[4]**
PCBs	0.04	0.06	0.11	10	12	$24	$43,200	1.29	0.78	0.45
	0.46	0.75	1.31	20	24	$24	$172,800	0.43	0.26	0.15
Mercury	0.03	0.05	0.12	10	12	$24	$43,200	1.77	1.09	0.40
	0.33	0.54	1.45	20	24	$24	$172,800	0.59	0.36	0.13

1. See Table 7 for details on mass calculations.
2. Corresponds to approximately $40 per curb mile based on information from literature review
3. Equals cost per km times the total number of kilometers swept in one year (road length swept times frequency) times number of sites
4. High cost estimate corresponds to low mass collected, low cost estimate corresponds to high mass collected, and best cost estimate corresponds to best mass collected.

Table 10. Comparison of estimated costs to remove PCBs and mercury ($/mg) by sediment management practices.

	Inlet Cleanouts at Areas with Elevated Concentrations[1] ($/mg)			Street Flushing and Capture at Areas with Elevated Concentrations[2] ($/mg)	Storm Drain Flushing at Areas with Elevated Concentrations[3] ($/mg)		Monthly Street Cleaning at Areas with Elevated Concentrations[4] ($/mg)		
	High	**Best**	**Low**		**High**	**Low**	**High**	**Best**	**Low**
PCBs	$0.62	$0.33	$0.30	$11	$6.2	$0.36	$1.3	$0.78	$0.45
Mercury	$0.68	$0.43	$0.35	N/A	N/A	N/A	$1.8	$1.1	$0.40

1. See Table 8 for details on cost calculations.

2. Cost data from Kleinfelder (2006) used to calculate unit cost. Study results showed it cost $100,000 to and dispose of approximately 20 tons of sediment containing 0.009 kg of PCBs from 921 linear feet.

3. Cost data from City of Jose (Dunlavey 2011, personal communication) was used to calculate unit cost. Study results showed that it cost $25,000 to remove 3,500 kg of solids with approximately 0.004 kg (min.) - 0.07 kg (max.) of PCBs based on the range of PCB concentrations previously measured in Leo Ave storm drain line sediments.

4. See Table 9 for details on cost calculations.

9. DATA GAPS

Based on the results of the literature review, the following key data gaps were identified with respect to evaluating the effectiveness of sediment management practices in reducing PCB and mercury loads to San Francisco Bay.

Effectiveness Studies Do Not Address PCBs and Mercury - Although there have been a few Bay Area studies that characterized PCBs and mercury concentrations in materials collected from streets, stormwater conveyance systems and in street sweeper hoppers, there is a lack of information addressing the effectiveness of sediment management practices to reduce loads of PCBs and mercury. One particular concern is the lack of information on the buildup of PCBs and mercury on street surfaces, which can affect the frequency at which sweeping would be most effective. Thus, it is necessary to infer the effectiveness of street sweeper studies based on the effectiveness of sweepers to remove dust and dirt (<2 mm) and in particular the finer fractions of dust and dirt (less than 63 µm). In addition, information is lacking in regards to the amount of sediment that accumulates in inlets, particularly in industrial areas with elevated pollutant concentrations, and the concentrations of PCBs and mercury in that sediment. In addition, very limited information is available on how PCB and mercury mass is distributed among various particle sizes.

Few Effectiveness Studies are Conducted in Semi-Arid Climates - Most reviewed street sweeper effectiveness studies that evaluate advanced sweeper types designed to improve water quality benefits were not carried out in semi-arid climates like the Bay Area. Moreover, a number of studies were conducted where road abrasives are applied during the winter, and this can cause results to be even less representative. There are even fewer studies for inlet cleaning, and only one local study was found that evaluated the effect of cleaning frequencies on the effectiveness of sediment removal.

Few Effectiveness Studies Document Water Quality Improvements - A number of studies have attempted to measure the potential improvement in water quality associated with street sweeping; however, very few studies indicated a statistically reliable improvement in water quality. A recent paper (Kang et. al 2009) indicates that most street sweeping study designs do not have sufficient statistical power to measure a change given the variability in runoff water quality. One inlet cleaning study attempted to measure water quality improvements based on a semi-annual cleaning frequency; however, it was determined that the number of samples collected was insufficient to characterize the improvements (Neely et al. 2008).

No Local Street Sweeping Studies that Evaluate Recent Improvements in Technology - No recent studies were found conducted in Bay Area that evaluate the effectiveness of equipment that reflects improvements in street sweeper technology in approximately the last decade.

Confounding Factors Make it Difficult to Compare Effectiveness Results Across Studies - Most street sweeper effectiveness studies are affected by confounding factors that affect effectiveness, including climate, particle loadings, street texture, moisture, parking car conditions, equipment operating conditions, and frequency of cleaning and also differ in terms of study design such that it is difficult to compare results amongst different studies. Thus, the best comparison amongst sweeper types is limited to the same study and study conditions. There are also factors that confound comparisons among the results of inlet cleaning effectiveness studies, including variations in rainfall patterns, particle size distributions of local sediments collected, configurations of inlet structure, and cleanout frequency.

Most Studies Address Effectiveness of Catch Basins Rather than Drop Inlets – The majority of studies found during this literature review addressed catch basins (with sumps) rather than drop inlets (without sumps). Drop inlets are believed to be the predominant type of inlet in the Bay Area. Since catch basins tend to accumulate more sediment than drop inlets, these studies have limited applicability to the effectiveness of inlet cleaning in the Bay Area.

Limited Information was Found on the Effectiveness of Stormwater Conveyance System Cleaning Enhancements - Only limited information was found on the effectiveness of storm drain inlet cleaning (and especially how effectiveness varies with frequency of cleanout) and storm drain line and street flushing.

Cost-Benefit Information is Not Adequately Addressed - There was 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).

10. RECOMMENDATIONS

Based on the results of the literature review, this section presents general recommendations regarding the design of future studies that evaluate the effectiveness of municipal sediment management practices in relation to reducing PCB and mercury loads to San Francisco Bay. In general, these studies should:

- Be conducted in Bay Area industrial areas known to have elevated concentrations of PCBs in street and storm drain system sediments.
- Measure concentrations of PCBs and mercury and particle size distributions in sediments. Evaluating effectiveness via water quality monitoring is likely to be challenging. For example, Kang et al. (2009) examined why most studies could not document an effect of street sweeping on water quality and concluded that most monitoring studies do not have sufficient statistical power to distinguish the effect of sweeping given the variability in runoff water quality.
- Be conducted at appropriate spatial and temporal scales to optimize what can be learned within resource constraints. This may require implementation at relatively small scales.
- Document rainfall totals and intensities in the study area over the course of the study.
- Gather the appropriate data and conduct cost-benefit analyses.
- Incorporate working with municipal maintenance staff to document practical lessons learned (e.g., successes, failures, challenges) and thereby facilitate future training of maintenance staff if enhanced practices are implemented on a more widespread basis.

As new information is generated by future Bay Area studies on municipal sediment management practices, the spreadsheet models developed during the SFEI Proposition 13 study (Mangarella et al. 2010) should be adapted and refined to incoroporate available data on costs and benefits, including estimated load reduction projections based on regional implementation scenarios and associated cost-benefit analyses.

Recommendations specific to street sweeping and stormwater conveyance system cleaning are provided below.

10.1. STREET SWEEPING

Based on the results of the literature review, consider conducting street sweeper effectiveness studies on road segments containing elevated levels of PCBs and mercury that focus on one or more of the following:

- Establishing a baseline for sweeper effectiveness and costs for removing sediment (fine and coarse) and associated PCBs and mercury;
- Evaluating the effect of increasing frequency on sweeper effectiveness and costs;
- Evaluating the effects of utilizing advanced street sweeper equipment on sweeper effectiveness and costs;
- Documenting the effects of site-specific confounding factors that affect sweeper effectiveness and costs; and
- Conducting marginal cost benefit analysis for modifying sweeper programs.

Particular care should be taken to take into account confounding factors. Experience has shown that studies that consider controls, differences in surface loadings on different streets, statistical study design (a sampling plan that is sufficient to distinguish the changes anticipated), and quality assurance and control are likely to be more successful. In evaluating sweeper types, it is critical that the testing ensure that the sweepers alternatively operate on the same roadway segments so that the surface loading on the streets is the same for each type of equipment. General guidance on conducting street sweeping programs can be found in the literature (e.g., Selbig and Bannerman 2007).

10.2. Stormwater Conveyance System Cleaning

Based on the results of the literature review, consider conducting three general types of stormwater conveyance system cleaning studies:

1. Evaluating the effect of increasing storm drain inlet cleanout frequency on PCB/mercury load reduction benefits and costs.
2. Evaluating costs and PCB/mercury load reduction benefits of street sediment removal including flushing and capture of wash water.
3. Evaluating costs and PCB/mercury load reduction benefits of storm drain line flushing with capture of wash water.

These studies should include working with municipal staff to develop inventories and maps within the study area of storm drain facilities and other pertinent drainage characteristics, including:

- Types and locations of inlet structures (e.g., drop inlet vs. catch basin) and condition.
- Types and locations of piping and condition.
- Sources of sediment to the storm drain system.
- Specific points within the storm drain system where sediment accumulates (e.g., certain inlets and any "sag" points in piping).

CCTV inspection is one potential tool to assist with developing the inventory and maps.

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

Reference	Sweeper Type[1]	Sweeper Frequency	Location	Period	Land Use And Site Information	Pollutants	Study Design[2]	Effectiveness					Costs (2011)[3]	Summary/Benefits
								Pre Sweeping Dust/Dirt Street Load (lbs/curb mile)	Post Sweep Street Load (lbs/curb mile)	Pre-Post Street Load (lbs/curb mile)	Percent Reduction Street Load (%)	Percent Reduction Fines (<63µm)		
Bay Area Studies														
Sartor & Boyd 1979	M		San Jose, Phoenix, Baltimore, Milwaukee, Atlanta, Seattle, Tulsa	1970-1971	Residential, commercial, industrial	Solids, BOD/COD nutrients, pesticides, metals, PCBs, Mercury	1	370 (M)[6] 710 (M) 1303 (M) 450 (M) 1550 (M) 504 (M)	146 (M)[6] 160 (M) 540 (M) 330 (M) 870 (M) 320 (M)		60% (M)[7] 78% (M) 58% (M) 36% (M) 44% (M) 36% (M)			Current street sweeping practices are essentially for aesthetic purposes, and even under well-operated and highly efficient street sweeping programs, their efficiency in the removal of the dust and dirt fraction of street surface contaminants is low.
Pitt 1979	M	Generally daily or weekly for period of 4-6 weeks	San Jose, CA	1976-1977	3 sites (Downtown, Keyes St., Tropicana)	Solids, BOD/COD nutrients, pesticides, metals, FIB, PCBs	2	240 (M)[3] 400 (M) 230 (M)	160 (M) 280 (M) 120 (M)	120 (M) 120 (M) 110 (M)	34% 33% 43%	15-30% (M)	$41 per curb mile swept[12]	Road conditions are more important than the type of broom sweeper in determining effectiveness. Broom sweepers are only about 20% effective at removing smaller particles (<45 um).Water quality benefits from sweeping with broom sweepers require daily frequency.
Pitt and Shawley 1981	M,R	5 times per week for 1 month	Castro Valley, CA	1978-1980	3 study areas (lower, middle, upper)	Solids, BOD/COD nutrients, pesticides, metals, hydrocarbons	2	850 (M) 700 (M) 400 (M) 850 (R) 700 (R) 400 (R)	310 (M) 260 (M) 190 (M) 260 (R) 225 (R) 155 (R)		64% (M) 62% (M 53% (M) 69% (R) 68% (R) 61% (R)	36-61% (M) 55-74% (R)	$24 per curb mile swept[12]	Recommend period of more frequent street sweeping prior to wet season. Street sweeping cannot reduce street surface loadings below 200 lbs/curb mile. Three passes/week is point of diminishing returns. Regenerative air slightly (5-10%) more efficient than broom sweeping especially if streets are initially cleaner.
Woodward Clyde 1994	M,R	Once every 2 weeks	San Jose	1994	Commercial, industrial,	Metals, TOC, O&G, TPH, PAHs, pesticides, PCBs	1			180 (M)[5] 200 (M) 290 (M) 300 (R) 230 (R)				Copper concentrations on streets and in hoppers were about 150 µg/kg in particle range <75um, compared to abut 50 µg/kg for particles > 700 um. The majority of the mass collected by the sweepers were >170um.
EOA 1990	M	Varied generally from weekly to monthly depending on agency and land use	Alameda, Alameda County, Berkeley, Hayward, Livermore, Newark, San Leandro, Union City	1991-1997	Residential, commercial, and industrial	Solids				260-540[8]				EOA compared reported street sweeper collection data in cy and miles swept in commercial, industrial and residential areas from 9 participating agencies in Alameda County. Statistical analysis was unable to show any significant trends although removal rates tended to be lower in commercial areas compared to industrial. This could reflect the tendency to sweep streets more often in commercial areas.

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

Reference	Sweeper Type[1]	Sweeper Frequency	Location	Period	Land Use And Site Information	Pollutants	Study Design[2]	Effectiveness					Costs (2011)	Summary/Benefits
								Pre Sweeping Dust/Dirt Street Load (lbs/curb mile)	Post Sweep Street Load (lbs/curb mile)	Pre-Post Street Load (lbs/curb mile)	Percent Reduction Street Load (%)	Percent Reduction Fines (<63µm)		
Salop 2004	M,R,V					PCBs, mercury								Desktop analysis of available information. Assigned efficiency factors for different types of sweepers based on modeling studies conducted by Sutherland, and then applied these to MS4s in Alameda County based on mix of sweepers used in their sweeper fleet.
EOA 2006			Fairfield, Suisun City	2005	Residential (2 sites) Commercial (2 sites)	Metals, hydrocarbons pesticides, PCBs								Primarily a street sweeping characterization study based on 4 samples of street sweeping materials collected in 2 sites in each city. PCBs were below detection (<0.2 mg/kg). Three of four mercury samples were above detection (<0.02 mg/kg) and ranged from 0.03 to 0.05 mg/kg.
Salop 2006	M,R,V	One pass only	Berkeley, Hayward, Newark, Pleasanton, Livermore	2005	Residential, Mixed, industrial	PCBs, mercury, TOC, PSD								Street sweeping characterization and load reduction study based on analysis of 13 samples taken from hoppers of various types of sweepers in 5 municipalities in Alameda County. Found that highest concentrations and load reduction occurred in northern portion of county which has older developments.
EOA 2007a			Contra Costa County	2006	Residential, Mixed, industrial	Metals, hydrocarbons pesticides, PCBs								EOA collected and analyzed street sweeping materials from 17 routes in seven cities in Contra Costa County. Results indicated that PCBs, total recoverable mercury, copper, nickel, and PBDEs were consistently detected in street sweeping material.
EOA 2007b			Richmond, CA	2001-2007	Industrial Residential (47 sites)	PCBs								EOA collected and analyzed 18 sediment samples from streets in primarily southwestern portion of the City of Richmond. Concentrations of PCBs in street sweeping samples varied from below detection (5 samples) to 900 µg/kg. The mean of the 13 samples above detection was 262 µg/kg.
Studies Outside the Bay Area														
Pitt 1985	M,R	3 times/ week	Bellevue, Washington	1980-1983	Residential sites (2)	Solids, metals, nutrients, PSD	2,3	650 (R) 425 (R) 275 (R) 225 (R) 160 (R)	250 (R) 200 (R) 125 (R) 85 (R) 90 (R)	400 (R) 225 (R) 150 (R) 140 (R) 70 (R)	60% 53% 54% 62% 44%		$42 per curb mile swept[12]	Study involved extensive monitoring (400 storm events) to evaluate water quality benefits of street sweeping. Intensive 3 times/week sweeping did not show statistical change in water quality. Standard and regenerative air sweepers were more effective at removing fine particulates than mechanical sweepers.
Blosser 2000														Report for the City of Olympia, Washington discussing pros and cons of utilizing advanced sweeper in lieu of structural treatment, and need for operator training and vendor support to facilitate transition from mechanical to advanced sweeping technology.

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

Reference	Sweeper Type[1]	Sweeper Frequency	Location	Period	Land Use And Site Information	Pollutants	Study Design[2]	Effectiveness					Costs (2011)	Summary/Benefits
								Pre Sweeping Dust/Dirt Street Load (lbs/curb mile)	Post Sweep Street Load (lbs/curb mile)	Pre-Post Street Load (lbs/curb mile)	Percent Reduction Street Load (%)	Percent Reduction Fines (<63μm)		
Pitt, Williamson, Voorhees, Clark 2004														Review article adressing buildup-washoff data that indicated that median particle size in runoff from typical storms tends to be in 15-50 um range. This fine fraction may only account for 10-20% of the dust and dirt mass on a roadway. Typical storms may remove up to about 50% of this fraction during a storm event.
Pitt, Bannerman and Sutherland 2004	V		Milwaukee Wisconsin		freeway		2	500 (V) 100 (V)	250 (V) 0	250 (V) 0	50% 0%			Review article that includes discussion of results from tests conducted using Sshwarze Industries Enviro Whirl I vacuum type sweeper.
Breault et al. 2005.	M,V		New Bedford, Mass.	2003-2004	Residential	Trace metals, PAHs	1				20-31% (M) 60-92% (V)	13% (M) 39-81% (V)		Controlled sweeper effectiveness tests, which included seeding streets with prescribed amount of graded dirt, indicated vacuum sweeper efficiencies consistently greater (by 1.6 -10 times) than mechanical sweeper for all particle sized ranges.
Shilling 2005													$40 per curb mile (M) $20 per curb mile (V)	A review report that included more extensive analysis of costs, including capital cost estimates of $100,000 for mechanical broom sweepers and $200,000+ for vacuum assisted. Expected life of each was 5 years for mechanical and 8 years for vacuum.
Selbig and Bannerman 2007	M,R,V	Weekly for at least a year	Madison, Wisconsin	2001-2006	Residential (3 sites)	Solids, PSD, metals, nutrients	2,3	558 (M) 776 (R) 776 (V)	456 (M) 340 (R) 116 (V)	102 (M) 436(R) 660(V)	20% (M)* 76% (R)* 63% (V)*	-25% (M)[4] -50% (R)[4] 10% (V)		Street sweepers significantly reduced the dust and dirt loading on streets, with larger reductions achieved with vacuum assisted or regenerative air sweepers. Mechanical broom sweepers more effective when street dirt yield approaches 1000 lbs/curb mile. Statistical comparisons of Event Mean Concentrations (EMCs) and loads between test catchment and control catchment indicated no statistical difference regardless of street-sweeper type.
Rochfort et al. 2007	M,R		Toronto, Canada	2004-2006	1 site	Solids, metals, nutrients, hydrocarbons TOC	1	484 (M) 100 (R)[9] 907 (R)[10]	302 (M) 100 (R) 280 (R)	182 (M) 0 (R) 627 (R)	37% (M) 0% (R) 70% (R)*	75% (R)*		New regenerative air sweeper tested on both north and southbound lanes was effective in reducing dust and dirt loading only in southbound lane because of higher surface loading. Regenerative air sweeper also able to reduce loadings of fines from 40 lbs/curb mile to 10 lbs/curb mile or 75%.

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

Reference	Sweeper Type[1]	Sweeper Frequency	Location	Period	Land Use And Site Information	Pollutants	Study Design[2]	Effectiveness	Costs (2011)	Summary/ Benefits	Reference	Sweeper Type[1]	Sweeper Frequency	Location
								Pre Sweeping Dust/Dirt Street Load (Lbs/Curb Mile)	Post Sweep Street Load (Lbs/Curb Mile)	Pre-Post Street Load (Lbs/Curb Mile)				
Law et al. 2008	M,R,V	Weekly, monthly	Baltimore, Maryland	2006-2008	Residential (2 sites)	Solids, nutrients	1	645(V)	553(V)	92(V)	14%(V)			Vacuum sweeper tested on 2 sites in Baltimore, Maryland. Street Particulate Matter (SPaM) shown is for Catchment O where frequency of sweeping increased to twice/week on all streets from baseline of once or twice per week.
Herrera 2009	R	biweekly	Seattle, Washington	2006-2007	Residential sites (2) Industrial (1)	Solids, metals, PAHs	3	1110 (R)[13] 1010 (R) 790 (R)	240 (R) 150 (R) 350 (R)		74% 90% 48%		$43 ($44) per curb mile swept[11]	Study investigated effectiveness of street sweeping and also relationship between street sweeping and catch basin cleaning frequency. Tests did not indicate a statistically significant change in the accumulation of sediments in catch basins between the test road segments and the control road segments.
Weston 2010	M,R,V	Weekly, bi-weekly	San Diego	2007-2009	Residential, commercial (3 sites total)	Solids, metals,	1			Route 3J 37(M) 54(R) 82(V) Route 103 133(M) 135(R) 157(V) Route 617 96(M) 110(R)				Debris removal rates (lbs/curb mile) varied between routes and temporally within each route, but generally were higher with vacuum assisted sweepers. Vacuum assisted and regenerative air sweepers removed finer material than mechanical sweepers on flatter route (Route 3J) whereas less difference in steeper routes (Routes 1C, 103). Chemistry results for most pollutants indicated that increasing frequency of sweeping from once to twice per week indicated no discernable difference in the effectiveness of constituent removal. (In other words, the pollutant removal did not decrease with increased frequency.)

* Statistically Significant
Note: no entry indicates report did not address

1. M = mechanical sweeper, R = regenerative air, V = vacuum assisted.
2. Study designs: (1) single road segment(s) subjected to before and after sweeping, (2) single road segment(s) with period of no sweeping followed by period of sweeping, (3) paired testing involving control (unswept) and test (swept) road segments.
3. Costs are adjusted for 2011 dollars (http://www.usinflationcalculator.com/).
4. Data illustrated in order by Downtown, Keyes, and Tropicana sites, all good condition asphalt.
5. Authors suggest that increase in fines may be related to abrasive action of wire bristles attached to gutter brooms for mechanical sweepers, also state that mechanical brooms and regenerative air sweepers were unable to pick up particles less than 250 um and 125 um, respectively.
6. All estimates of pre vs post dust/dirt load for this study based on material collected in sweeper hopper.
7. San Jose controlled tests using synthetic street surface contaminant, reported units are in grams over test area that averaged 50 feet long and 8 feet wide.
8. Data are organized by sweeper type, with first four entries Mobil-TE-3 broom sweeper, and last 2 entries are Tymco-300 broom sweeper.
9. Based on hopper volume data compiled and reported by the cooperating agencies; includes trash and vegetative debris, and density of 6.43 lbs/gallon.
10. Northbound side of test road segment.
11. Southbound side of test road segment.
12. Actual sweeping costs, does not include solids handling (estimated at $34/wet ton) and disposal ($43/wet ton).
13. Does not include capital costs, but includes O&M, supplies, equipment depreciation, and disposal.
14. Median effectiveness estimates ordered by site: West Seattle (residential), Southeast Seattle (residential), and Duwamish (industrial).

Appendix B. Summary of Reviewed Stormwater Conveyance System Characterization and Effectiveness Monitoring Studies

Reference	Location	Period	Land Use and Site Information	Pollutants	Study Design	Cleaning Frequency	Effectiveness			Particle Size Distribution	Costs (2011)[1]	Summary/Benefits
							Sediment Load Removed (lbs)	% Reduction in Pollutant Concentrations	Pollutant Load Removed (lbs)			
Bay Area Studies												
Sartor and Boyd 1972	San Francisco, CA	1972	Residential		Controlled tests to evaluate effectiveness of empty catch basins and partially-filled catch basins							For a simulated heavy rainfall intensity (1/2 in/hr.), the empty catch basin was reasonably effective in removing solids with a diameter larger than 246 µm, and ineffective at removing fine solids. For a partially-filled catch basin, the results indicated that most of the material originally contained in the catch basin appeared to remain, regardless of the runoff volume.
Pitt 1979	San Jose, CA	1979			Fluorescent tracer experiment to determine movement of sediment from a constructed catch basin and through the storm drain pipes to creek outfall.							The particles located at the bottom of the catch basin were discharged into the stormwater conveyance system during larger storms. Overall depth of material in the catch basin decreased approximately 20%.
Pitt and Shawley 1981	Alameda County, CA	Sept. 1979	Residential		Accumulation measured in 20 inlets after being cleaned every 1 or 2 years		60 lbss of dry particulates /inlet			Median inlet particle size - 2300 µm; median street particle size - 500µm	\$0.31 - total solids[2]	Based on these sediment in 20 inlets, authors estimated that about 12,000 pounds of dry particulates were present in a total of approximately 200 inlets in the Castro Valley area.
Mineart and Singh 1994	Alameda County, CA	Dec. 1992-Oct. 1993	20 inlets each in residential, commercial and industrial areas	Metals (lead, zinc and copper), petroleum hydrocarbons, and polynuclear aromatic hydrocarbons (PAHs)	Sediment accumulation in inlets based on cleaning frequencies	1. Monthly 2. Quarterly 3. Semi-annually 4. Annually	1. 9 2. 18 3. 30 4. 24[3]		1. 270 2. 38 3. 19[4]	A grain size analysis indicated that over 80% of all inlet sediments were sand (within the range of 62-2,000 microns)		Study showed that for all land uses monthly inlet cleaning removed the most sediment on an annual basis (3-5 cubic feet) and greatest mass of pollutant. For industrial land use, there was a clear decrease in sediment volume and mass removed with decreased frequency. Increasing the cleaning frequency to monthly appeared to significantly increase the removal of copper.
Salop 2004	Alameda County, CA	2004	Various (pre-1950s urban, mixed urban, and recent urban)	PCBs and mercury	Desktop evaluation of inlet cleaning	Annual and semi-annual		Potential decrease of 0.2% PCBs and 43% mercury if inlet cleaning increased from annual to semi-annual			\$355,000 (disposal costs)	Desktop analysis using available MS4 information. Estimated mass of PCBs and mercury removed by annual inlet cleaning and increased cost of increasing frequency to semi-annual cleaning.

Appendix B. Summary of Reviewed Stormwater Conveyance System Characterization and Effectiveness Monitoring Studies

Reference	Location	Period	Land Use and Site Information	Pollutants	Study Design	Cleaning Frequency	Effectiveness			Particle Size Distribution	Costs (2011)[1]	Summary/Benefits
							Sediment Load Removed (tons)	% Reduction in Pollutant Concentrations	PCB Load Removed (g)			
Salop 2004	Alameda County, CA	2004	Mixed (various MS4s)	PCBs and mercury	Desktop evaluation of channel de-silting				10.2 of PCBs and 77.6 of mercury[5]		$1.2-22.5 million	Desktop analysis using available MS4 information. Estimated mass of PCBs and mercury removed by increasing channel de-silting rates from the period 1990-2004 to those of the period 1979-89.
Salop 2006	Alameda County, CA	2006	Various (pre-1950s urban, mixed urban, and recent urban)	PCBs and mercury	Assessed additional removed sediment among a combination of inlets and catch basins across different land use types with an additional wet season cleanout	Two wet season cleanouts			0.2 of PCBs and 0.2 of mercury with an additional wet season cleanout	5% of the total dry mass was in the <63 µm particle size fraction, 63% in the 63-2000 µm fraction and 32% in the >2000µm[6]		Conducted targeted studies to confirm previous 2004 estimates. Less than an estimated 0.1 kg mass each of PCBs and mercury would be collected with an additional wet season cleanout. Salop noted that a catch basin with a sump had greater storage capacity.
Salop 2006	Alameda County, CA	2006	Industrial/ commercial	PCBs and mercury	Collected samples from two pump stations for characterization					% fines in the < 2mm fraction were 2% at Ettie Pump Station and 5% at Pleasanton pump station		Collected samples from two pump stations to determine volume of material and pollutant mass removed. Salop noted that estimates of pollutant mass contained within a pump station can vary greatly based upon pollutant concentrations measured at any one point in time.
Mangarella et al. 2010	Bay Area	2010		PCBs and mercury	Desktop evaluation of inlet cleaning	Quarterly			0.9 lbs/yr PCBs 10.2 lbs/yr mercury[7]			Desktop Evaluationto found the 'unit loading[8]' for both mercury and PCBs were found to be highest for industrial and commerical areas. Application of these street sweeping and inlet cleaning in elevated industrial areas were thought to result in relatively higher PCB load reductions. Street washing was found to result in low load reductions.
Studies Outside Bay Area												
Grottker 1990		1990	Unknown		Simulation model based on data collected from 200 gully pots							Correlation analysis results confirmed that the pollutant removal effectiveness of a gully pot was mainly dependent on the flow rate. Average annual dry weight of the collected material was about the same as that of a pollutant load of a single storm. Thus, the removal efficiency of the gully pots appeared to be minimal.

Appendix B. Summary of Reviewed Stormwater Conveyance System Characterization and Effectiveness Monitoring Studies

Reference	Location	Period	Land Use and Site Information	Pollutants	Study Design	Cleaning Frequency	Effectiveness			Particle Size Distribution	Costs (2011)[1]	Summary/Benefits
							Sediment Load Removed (tons)	% Reduction in Pollutant Concentrations	PCB Load Removed (g)			
Herrera 2009	Seattle, WA	1. Two sites, June 2006-June 2007 (1 yr.); 2. One site, Nov. 2006-June 2007 (8 mths.)	1.Two residential sites 2. One industrial site	Solids	Monitored sediment accumulation in 12 catch basins located in the three sites to assess effect of periods of sweeping and no sweeping.	Sediment accumulation monthly from swept (once every two weeks) and non-swept sites	Swept sites: 1. 1,160 and 1,260 2. 400 Unswept sites: 1. 1,120 2. 520 3. 280[9]			Swept sites: 1. 14-48% 2. 24-44% Unswept sites: 1. 17-29% 2. 26-51%[10]	$0.44/ wet kg sediment and $0.78/ dry kg sediment[11]	Tests did not indicate a statistically significant change in the accumulation of sediments in catch basins between the swept and non-swept sites. Most of the catch basins monitored were less than 10% full at the end of the study period in both swept and non-swept areas.
Jartun et al. 2008	Bergen, Norway	Oct.-Nov. 2004	Urban harbor area	PCBs, PAHs, total organic carbon, and heavy metals	Source and pathway identification of sediment pollution in 68 stormwater traps					21 sediment samples ranged from mostly clay and silt to a main fraction of coarse sand. The median grain size ranged from 23–646 µm, with diameters 250–300 µm being the most frequent.		A Principal Component Analysis of the investigated components indicated a correlation between TOC, PCBs, PAHs and mercury. The authors explained the correlation by a strong sorption between PCBs and PAHs to soil organic matter (Krauss et al. 2000) and the relationship between organic matter and mercury as described by Sanei and Goodarzi (2006).
Law et al. 2008	Baltimore, MD	Jan. 2006 – July 2007	1. High density residential 2.Industrial/ commercial	Total solids, nutrients and metals	Monitored sediment accumulation in an area with biweekly street sweeping	Sediment accumulation measured monthly between a spring and fall cleanout	1. 13.4 lbs/yr 2. 2. 53.7 lbs/yr[12]	Total solids: 18%, annual cleanouts 35%, semi-annual cleanouts		1. 22-41% 2. 33-39%[13]		Daily accumulation rates were found to be statistically significant for both land use types, with residential land use, 0.001-0.005 ft^3/day, and commercial/industrial land use, 0.011-0.013 ft^3/day. The particle size distribution for the inlet material was similar to that of the street dirt.

Appendix B. Summary of Reviewed Stormwater Conveyance System Characterization and Effectiveness Monitoring Studies

Reference	Location	Period	Land Use and Site Information	Pollutants	Study Design	Cleaning Frequency	Effectiveness			Particle Size Distribution	Costs (2011)[1]	Summary/Benefits
							Sediment Load Removed (tons)	% Reduction in Pollutant Concentrations	PCB Load Removed (g)			
Pitt and Field 2004[14]	1.Bellevue, WA 2. Stafford Township, NJ	1. 1980-83 2. 1994	1. Two mixed, medium density residential and commercial areas 2. Residential area	1. Solids, chemical oxygen demand, nutrients (nitrogen and phosphorus), and metals (lead and zinc) 2. Solids	1a. 4 conditions examined in two study areas: no controls, street cleaning alone, catch basin cleaning alone and both street and catch basin cleaning together; 1b. Sediment accumulation in more than 200 inlets after a single cleaning over two-year period. 2. Paired samples of inflow and outflow of inlet devices analyzed.			1. 10-25% in lead and solids and 5-10% in zinc 2. 20% of total solids and 30% of suspended solids				Two studies were reviewed regarding sediment accumulation in catch basins with sumps and storm drain pipes. Catch basins removed up to 30% of the suspended solids load that entered the structures. Much of this material was relatively coarse and may lack mobility and have relatively low pollutant concentrations. Catch basins accumulated sediments until reaching approximately 60% of the total sump capacity, when the sediment reached equilibrium (i.e., scour balancing new deposition). A one-time survey found that pipes that had significant amounts of sediment were either sloped less than 1.5% or located close to a source of sediment.

Note: no entry indicates report did not address

1. Costs are adjusted for 2011 dollars (http://www.usinflationcalculator.com/).
2. Unit costs to remove a pound of constituent, based on one inlet cleaning. This figure is based on limited data, and it is not known what is included in this cost.
3. Median mass collected per inlet by frequency (values listed according to order of frequency in respective column).
4. Annual copper loads reduced based by frequency (values listed according to order of frequency in respective column).
5. Increased removed mass of PCBs if channel de-silting was increased to rates from the period 1990-2004 to that of 1979-89.
6. Based on particle size distribution of annual sediment samples
7. Projected load rates are presented as Individual mass values were not given. Results given are for industrial land use; commercial area did not show an estimated change, and residential areas showed a decrease in loads.
8. Unit loading was calculated by dividing the annual loads from each land use by the area of that land use.
9. Sediment mass removed from inlets at swept and unswept sites. Values presented respective to land use types.
10. Percentage of fines represent particle sizes < 250µm (fine sand and silt/clay)
11. Inspection, cleaning, material handling, and disposal costs were included in the estimate. Cleaning estimates increased with decreased moisture content.
12. Rates are presented as individual mass values were not given.
13. Percentage of fines represent particle sizes < 250µm (fine sand and silt/clay). Values presented respective to land use types. Range in percent fines for residential land uses likely due to different physiographic
14. Pitt and Field (2004) review two past studies regarding 1) sediment accumulation and pollutant concentrations in catch basins with sumps and storm drain pipes and 2) compared effectiveness of catch basin to others with filters. Entries in the table correspond to both studies.

Appendix C. Summary of Reviewed Street and Storm Drain Flushing Characterization and Effectiveness Monitoring Studies

Reference	Location	Period	Land Use and Site Information	Pollutants	Study Design	Effectiveness			Particle Size Distribution	Costs (2011)[1]	Summary/Benefits
						Sediment Load Removed (lbs)	% Reduction in Pollutant Concentrations	PCB Load Removed (lbs)			
Bay Area Studies											
Dunlavey 2011, Personal Communica-tion	San Jose	2000-2006	Single street in Industrial/ Commercial	PCBs	Source identification and abatement on single street		7,000		0.0008-0.14 of PCBs		$27,700[2]
Kleinfelder 2006	Oakland, CA	June 2004-June 2006	Industrial /Commercial (Ettie St. Pump Station Watershed)	PCBs and mercury	Source identification and abatement of two priority areas, each a block long	Area 1 – 2,177 Area 2 – 33,929		Area 1 – 0.0056 Area 2 – 0.0114		$111,000 to remove 20 tons of sediment containing 9g of PCBs from 921 ft ($5,500 to remove 0.4g PCBs/ton sediment)[3]. Est. cost to abate remaining 9 identified priority areas - $930,000 for 7,990 ft with an est. amount of 47 g of PCBs.	Report summarized a project to further investigate, identify, and abate sources of PCB-containing sediment in the watershed. Two of 11 priority areas were high-pressure washed after excess dry sediment was removed using a Bobcat excavator or a brush and shovel. Sediment and wash water were vacuumed into a self-contained vacuum truck with a capacity of 3,000 gallons.
Kleinfelder 2007	Oakland, CA	May 2007	Industrial /Commercial (watershed focus)	PCBs and mercury	Effectiveness evaluation of abated areas		Area 1 @ 2 sites – 42%, 75% and Area 2 @ 3 sites – 94%, 83% and 27%				The two areas abated in Kleinfelder (2006) were resampled to determine effectiveness. Findings found significant reduction in PCB concentrations.
Salop 2007	Oakland, CA	May 2007	Industrial /Commercial (watershed focus	PCBs and mercury	Evaluation of non-treated areas (controls)		Little to no change				Sampling sites (to supplement Kleinfelder 2007) were chosen from the list of high priority sites in Kleinfelder's 2006 report. The concentrations from pre- and post-abatement periods were relatively similar at each sampling site.
Studies Conducted Outside of the Bay Area											
Amato et al. 2010											Review of research on the effects of street cleaning and washing in the abatement of PM[4] emissions. Results indicated that, in general, a combination of street sweeping and subsequent washing was a reliable control measure to mitigate PM emissions from road dust re-suspension.

Appendix C. Summary of Reviewed Street and Storm Drain Flushing Characterization and Effectiveness Monitoring Studies

Reference	Location	Period	Land Use and Site Information	Pollutants	Study Design	Effectiveness			Particle Size Distribution	Costs (2011)[1]	Summary/Benefits
						Sediment Load Removed (lbs)	% Reduction in Pollutant Concentrations	PCB Load Removed (lbs)			
Gromaire et al. 2000	Paris, France	2000	Three single streets in a densely-populated residential and commercial district with a combined sewer system	Solids and metals	Before and after street washing						

Note: no entry indicates report did not address

1. Costs are adjusted for 2011 dollars (http://www.usinflationcalculator.com/).
2. The cost for Clean Harbors to perform the one-day cleanout and dispose of the collected material at the hazardous waste facility. Although this amount includes Clean Harbors' field crew and transport and disposal of the material, it does not include San Jose staff time, analytical testing costs, and cost to video the storm drain line before and after the line cleaning. San Jose estimated that the amount could increase to $50,000 if these latter costs are considered.
3. This amount included disposal of the sediment at a Class I Hazardous Waste landfill as a result of elevated concentrations of lead. Kleinfelder (2006) also reported on the amount of sediment removed by the Alameda County Public Works Agency (ACPWA) at the Ettie Street Pump Station between 2001 and 2006. ACPWA estimated it cost $27,500 to remove 70 tons of sediment with 19.1 g of PCBs in 2006. This cost only included labor, as the County disposed of the sediment at its own facility.
4. Atmospheric particulate matter (PM) is a complex mixture of components arising from a number of emission sources (anthropogenic and natural) and atmospheric processes (secondary PM). Two common categorizations of PM are PM10 (particles with mean aerodynamic diameter <10 µm) and PM2.5 (particles with mean aerodynamic diameter <2.5 µm), which is considered the fine fraction (Amato 2010).