Street Dust: Implications for Stormwater and Air Quality, and Environmental Management Through Street Sweeping

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Contents

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D.M. Whitacre (ed.), *Reviews of Environmental Contamination and Toxicology Volume 233*, Reviews of Environmental Contamination and Toxicology 233,
DOI 10.1007/978-3-319-10479-9_3

1 Introduction

Street dust is composed of particles that arise from motor vehicles (e.g., tire debris, emission-related particulates), local soils, and road pavement (Yeung et al. 2003). These materials are commingled with larger debris, including discarded trash, lawn clippings, fallen leaves and branches, and other detritus (Fig. 1). The nature and composition of street dust is expected to vary widely based on local climate, geology, population and traffic density, infrastructure, and other factors. Maintenance sand or road salt used in inclement weather is a source of primary granular material and can contribute to street dust through mechanical abrasion of the road surface (Kupiainen et al. 2003; Gertler et al. 2006. Kuhns et al. 2003; USGS 2013).

High levels of organic and inorganic contaminants in street dust represent a source of dual potential risk to stormwater and air quality. For example, runoff of street dust to local watersheds can degrade water quality and impact sediment (Buckler and Granato 1999; Sartor and Boyd 1972; Walker et al. 1999). It is also clear that many contaminants exist at higher concentrations in the smallest particles, which are most likely to be mobilized by runoff (Breault et al. 2005; Herngren et al. 2006; Zhao et al. 2009a). Further, studies have indicated that as much as 85 %

Fig. 1 Bulk materials gathered through street sweeping in Waco, Texas, USA

of ambient airborne particulate matter (PM_{10}), exposure to which is associated with several adverse health effects, can arise from accumulated street dust (Amato et al. 2010a).

Many large municipalities coordinate the sweeping of streets on a regular basis, and these efforts are at least partly driven by concerns about the impacts of stormwater runoff to the local environment (Brinkmann and Tobin 2001). Street cleaning is considered to be a best management practice (BMP) for storm water management by the U.S. Environmental Protection Agency (USEPA 2012). A number of different strategies and technologies are available to manage and collect street dust, including flushing, mechanical broom, vacuum and regenerative air systems. The mass of materials diverted from stormwater runoff by street cleaning can be significant. For example, more than 2,000 tons of materials per year are removed by street cleaning in the city of Waco, Texas, USA, which correspondingly has maintained a model compliance record for stormwater management (City of Waco Utilities, personal communication). Furthermore, street cleaning is increasingly studied to determine its utility in improving ambient air quality (Amato et al. 2010a, b).

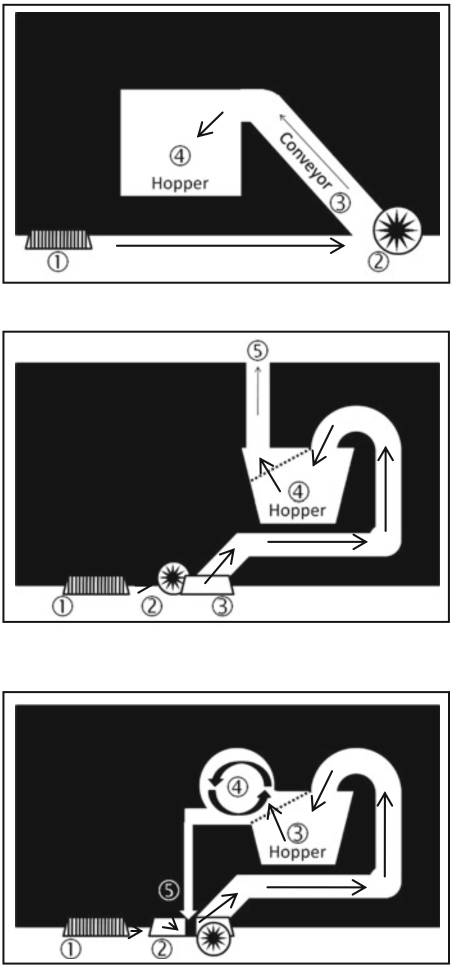
The purpose of this study was to critically review and summarize the available data on the effectiveness of various street cleaning technologies and practices for improvement of stormwater and air quality. As such, we examined the available literature that addressed street dust and its potential impacts on stormwater and air quality, and related the relative efficacy of multiple street sweeping technologies to the context of environmental/ecological and human health risk. During this exercise, 1,187 journal articles from the peer reviewed literature were compiled by searching for the following terms: “street dust,” “road dust,” “urban dust,” “roadway sediments,” etc. Of these, 89 papers contained the phrases “street sweeping,” “street cleaning,” “road sweeping,” or “road cleaning.” Only two peer-reviewed articles provided quantitative data on the comparative efficacy of multiple sweeping technologies on gathering street dust (Amato et al. 2010a; Tobin and Brinkmann 2002). Unfortunately, authors of many studies failed to sufficiently describe the specific street cleaning apparatus used in the studies they performed. In several government documents from the United States and Canada, there were attempts to assess the comparative efficacy of street cleaning across available technologies. To date, no published journal articles or government reports have characterized comparative margins of safety and/or relative risk to human health and the environment, in the context of multiple modern street sweeping technologies and strategies for street dust management. In Table 1, we summarize the available literature for which street cleaning technologies and constituents have been measured.

Most modern street sweepers fall into one of three categories: mechanical, vacuum, and regenerative air (Fig. 2). The majority (about 41 %) of sweepers in the United States are mechanical broom sweepers (Schilling 2005a, b). These sweepers remove debris with a large rotary brush fitted at the rear of the sweeper that directs collected material onto a conveyor. This conveyor leads to the hopper, where collected materials are stored until disposal. Mechanical sweepers are

Table 1 A summary of published scientific studies related to street cleaning

		Sweeper technology						Constituents analyzed						
		Standard			High efficiency									
Reference	Study type	Mechanical	Vacuum	Regen. air	Mechanical	Vacuum	Regen. air	Metals	Organics	Solids	Nutrients	Particle size	PM10	PM2.5
Amato et al. (2009)	Empirical		×					×					×	
Amato et al. (2010a)	Simulated	×	×	×						×		×	×	
Amato et al. (2010b)	Empirical		×					×					×	
Bender and Terstreip (1984)	Empirical	×						×		×	×			
Berretta et al. (2011)	Empirical	Unspecified								×	×			
Brinkmann and Tobin (2001)	Empirical	×		×				×	×	×	×			
Bris et al. (1999)	Empirical							×	×	×				
Calabro (2010)	Empirical	×						×		×		×		
Chang et al. (2005)	Empirical			×			×						×	
DeLuca et al. (2012)	Empirical						×						×	
ETV (2011, 2012a, b, c)	Empirical				×		×						×	×
Gasperi et al. (2005)	Empirical								×					
German and Svensson (2002)	Empirical		×					×				×		
Gertler et al. (2006)	Empirical	×											×	×
Gromaire et al. (2000)	Empirical							×		×				
Horwatich and Bannerman (2009)	Empirical		×									×		
Jang et al. (2009)	Empirical	Unspecified						×						
Kang et al. (2009)	Simulated	×	×	×				×		×			×	
Kuhns et al. (2003)	Empirical	×	×										×	
Law et al (2008)	Empirical		×					×		×	×	×		
Norman and Johansson (2006)	Empirical	×											×	

NRDL (1959)	Empirical	×	×										
NWRI (2007)	Empirical	×		×			×	×	×	×	×	×	
Sartor and Gaboury (1984)	Simulated	×	×					×		×	×		
Seattle Public Utilities and Herrera EC (2009)	Empirical			×				×	×	×	×		
Sutherland and Jelen (1997)	Simulated	×		×		×						×	
Sutherland et al. (1998)	Simulated	×		×		×		×	×	×	×	×	
Sutherland (2009)	Empirical		×	×	×		×					×	
Tandon et al. (2008)	Empirical							×			×		×
Terstriep et al. (1982)	Empirical	×						×		×	×		
Tobin and Brinkman (2002)	Empirical	×		×				×	×		×	×	
USEPA (1972)	Simulated	×	×	×				×	×	×	×	×	
USEPA (1979)	Empirical	×	×					×	×	×	×	×	×
USEPA (1983)	Simulated	Unspecified						×		×	×		
USEPA (1985a)	Empirical	×		×						×			
USEPA (1985b)	Empirical	×		×									
USGS (2002)	Empirical	×						×	×	×	×	×	
USGS (2005)	Empirical	×	×					×	×			×	
USGS (2007)	Empirical	×	×	×				×		×	×	×	
USGS (2013)	Empirical	×	×				×	×		×	×	×	
Weston Solutions (2010)	Empirical	×	×	×				×	×	×	×	×	
Wilber and Hunter (1979)	Empirical	Unspecified						×		×			
Wu et al. (2010)	Empirical		×									×	



A. Mechanical Broom Sweepers

1. A rotating gutter broom directs dirt and debris from the curb into the path of a large rotating cylindrical broom.
2. The main broom flicks dirt and debris onto a conveyor.
3. The conveyor carries dirt and debris to a hopper.
4. The conveyor drops dirt and debris into a hopper.

B. Vacuum Sweepers

1. A rotating gutter broom directs dirt and debris from the curb into the path of the vacuum nozzle.
2. A windrow broom is often used to direct dirt debris into the path of the vacuum nozzle.
3. The debris-laden air stream is pulled into a hopper, at the opposite side of the suction inlet where the air loses velocity and the larger debris drops to the bottom.
4. Dirt and debris settle in hopper and lighter debris is blocked by a screen.
5. Air is exhausted from hopper.

C. Regenerative Air Sweepers

1. A rotating gutter broom directs dirt and debris from the curb into the path of the pick-up head.
2. Within the pick-up head, a blast of air dislodges and suspends dirt and debris. A broom within the pick-up head is sometimes used to dislodge stuck-on debris.
3. The debris-laden air stream is pulled into a hopper, at the opposite side of the suction inlet where the air loses velocity and the larger debris drops to the bottom.
4. Dirt passes through a centrifugal dust separator
5. Clean air returns to the blast orifice of the pick-up head.

Fig. 2 Process flow diagrams for three primary street sweeping technologies

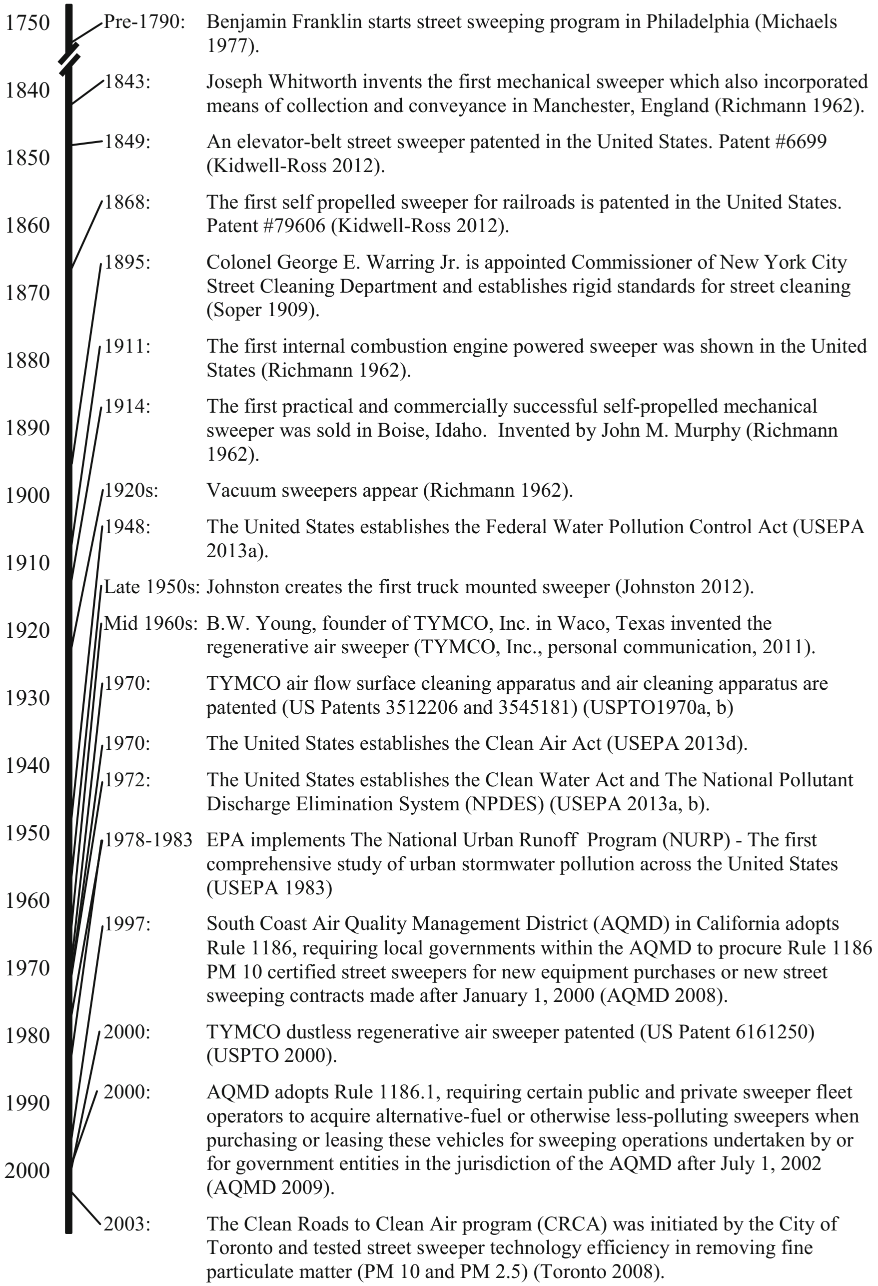
effective at picking up wet vegetation, gravel and coarse sand, but are less efficient at removing fine particles, especially those below 250 μm (Kang et al. 2009; Schilling 2005a). Vacuum street sweepers have gained popularity because of their ability to remove fine dust more effectively than mechanical sweepers USGS 2007). They use a rotary brush called a windrow boom to push dirt and debris toward the path of the suction nozzle (Fleming 1978; Sutherland 2011). Vacuum street sweepers are comparable to household vacuums, in that they suck in air with a fan, collect dust and debris, and then exhaust the air (Sutherland 2011). In general, these units have difficulty removing wet vegetation and large road debris (Schilling 2005a). The newest street sweeping technology, regenerative air, is similar to a vacuum unit, in that it uses a fan called a blower to suck in dirt and debris from the street surface; rather than just a vacuum nozzle, it uses a pick-up head with a blast orifice, which directs a strong blast of air onto the street that suspends dirt and debris with the pick-up head enclosure. Ambient air is then sucked into the hopper where larger volume forces the heavier dust and debris to fall. Some regenerative air sweepers use a centrifugal dust separator to remove the lighter dust (Schilling 2005a). Cleaned air is then returned to the blower, making it a closed-loop system with no air or dust exhausted to the atmosphere (Fleming 1978).

2 Street Cleaning, Sweeping and Mitigation

For hundreds of years street sweeping has been used as a means for municipalities to remove litter, dirt, horse droppings, and vegetation for aesthetic and sanitation purposes (Schilling 2005a; Fig. 3). Before the introduction of the mechanical sweeper, street sweeping was done manually, using a broom, shovel, and either push or horse-drawn carts (Schilling 2005a). The earliest account of street cleaning in the United States may have appeared (Fleming 1978; Michaels 1977) in Benjamin Franklin's *Autobiography*. Franklin wrote about hiring a man to sweep a paved market area in Philadelphia more than 200 years ago:

> This, for some time, gave an easy access to the market dryshod; but, the rest of the street not being paved, whenever a carriage came out of the mud upon this pavement, it shook off and left its dirt upon it, and it was soon covere'd with mire, which was not remov'd, the city as yet having no scavengers. After some inquiry, I found a poor, industrious man, who was willing to undertake keeping the pavement clean, by sweeping it twice a week, carrying off the dirt from before all the neighbour's doors, for the sum of six-pence per month, to be paid by each house (as quoted in Michaels (1977), and Fleming (1978)).

Street cleaning in New York City was conducted by the police department, until it became its own administrative branch in 1881. Colonel George E. Waring Jr. was appointed as Commissioner of Streets in 1895 (Armstrong et al. 1976; Fleming 1978; Richmann 1962; Soper 1909). Drawing from his military experience as a volunteer in the Missouri Cavalry during the Civil War, Waring outfitted street sweeping workers with white uniforms, earning them the nickname "White Wings" (Armstrong et al. 1976). Waring's efforts appeared to produce a decline in sickness, to wit, declines in diarrheal diseases and the death rate in New York City (from 26.8 per 1,000 from 1882 to 1894, to 19.6 per 1,000 in 1897) (Richmann 1962), and established New York City as a model for other cities throughout the United States (Armstrong et al. 1976).



Pre-1790: Benjamin Franklin starts street sweeping program in Philadelphia (Michaels 1977).

1843: Joseph Whitworth invents the first mechanical sweeper which also incorporated means of collection and conveyance in Manchester, England (Richmann 1962).

1849: An elevator-belt street sweeper patented in the United States. Patent #6699 (Kidwell-Ross 2012).

1868: The first self propelled sweeper for railroads is patented in the United States. Patent #79606 (Kidwell-Ross 2012).

1895: Colonel George E. Warring Jr. is appointed Commissioner of New York City Street Cleaning Department and establishes rigid standards for street cleaning (Soper 1909).

1911: The first internal combustion engine powered sweeper was shown in the United States (Richmann 1962).

1914: The first practical and commercially successful self-propelled mechanical sweeper was sold in Boise, Idaho. Invented by John M. Murphy (Richmann 1962).

1920s: Vacuum sweepers appear (Richmann 1962).

1948: The United States establishes the Federal Water Pollution Control Act (USEPA 2013a).

Late 1950s: Johnston creates the first truck mounted sweeper (Johnston 2012).

Mid 1960s: B.W. Young, founder of TYMCO, Inc. in Waco, Texas invented the regenerative air sweeper (TYMCO, Inc., personal communication, 2011).

1970: TYMCO air flow surface cleaning apparatus and air cleaning apparatus are patented (US Patents 3512206 and 3545181) (USPTO1970a, b)

1970: The United States establishes the Clean Air Act (USEPA 2013d).

1972: The United States establishes the Clean Water Act and The National Pollutant Discharge Elimination System (NPDES) (USEPA 2013a, b).

1978-1983 EPA implements The National Urban Runoff Program (NURP) - The first comprehensive study of urban stormwater pollution across the United States (USEPA 1983)

1997: South Coast Air Quality Management District (AQMD) in California adopts Rule 1186, requiring local governments within the AQMD to procure Rule 1186 PM 10 certified street sweepers for new equipment purchases or new street sweeping contracts made after January 1, 2000 (AQMD 2008).

2000: TYMCO dustless regenerative air sweeper patented (US Patent 6161250) (USPTO 2000).

2000: AQMD adopts Rule 1186.1, requiring certain public and private sweeper fleet operators to acquire alternative-fuel or otherwise less-polluting sweepers when purchasing or leasing these vehicles for sweeping operations undertaken by or for government entities in the jurisdiction of the AQMD after July 1, 2002 (AQMD 2009).

2003: The Clean Roads to Clean Air program (CRCA) was initiated by the City of Toronto and tested street sweeper technology efficiency in removing fine particulate matter (PM 10 and PM 2.5) (Toronto 2008).

Fig. 3 A timeline of usage and technological development in street sweeping

2.1 Street Cleaning Technologies

2.1.1 Manual

Manual cleaning represents the oldest form of street cleaning in the U.S., and is still selectively practiced today. Though it has been largely replaced by modern methods, it retains several advantages, including low initial and maintenance cost of equipment; manual push brooms can reach into places inaccessible to mechanical sweepers such as areas harboring parked cars, small alleyways, and busy city areas, no matter the time of day, level of traffic, or weather conditions (Fleming 1978).

2.1.2 Mechanical

The first mechanical sweepers were horse drawn with a rotary broom at the rear, which would push dirt from the center of the street to the curb. Dirt would then be pushed into piles, and then shoveled on carts by workers (Richmann 1962). Such horse drawn sweepers were used in New York City as early as 1882 (Armstrong et al. 1976). Because these early mechanical sweepers created a great deal of dust, tanks were added to sprinkle water onto the street. Later, more powerful high capacity sprinkling wagons would follow the sweeper (Richmann 1962).

The first mechanical sweeper that integrated collection and conveyance was invented by Joseph Whitworth and was used in Manchester, England in 1843 (Richmann 1962). In the United States, Charles B. Brooks is often credited with patenting the first elevator-belt mechanical street sweeper in 1896; however, other sources cite his system as just one of many around the same time. Over 300 US patents for street sweepers were issued prior to 1900, the earliest of which may be an elevator-belt sweeper (1849) (Kidwell-Ross 2012).

Among those systems invented prior to 1900 was the first self-propelled sweeper patented in the United States in 1868, which was intended for cleaning railroad tracks. In 1891, a self-propelled steam-powered sweeper, designed to clean roads, was also patented (Kidwell-Ross 2012). An electrically-powered street sweeper was used in Berlin, Germany in the early 1900s (Soper 1909). In 1911, the first internal combustion-engine-powered sweeper was demonstrated in the United States, but was not widely accepted because it lacked maneuverability; moreover, its pan-type shelf was only large enough to hold sweepings from one side of a single block, and its engine could not supply power to both the sweeping apparatus and provide mobility for the unit (Armstrong et al. 1976; Richmann 1962). The first practical and commercially successful self-propelled mechanical sweeper was sold in Boise, Idaho in 1914. It was invented by John M. Murphy in a partnership with American Tower and Tank Company, which would later become Elgin Sweeper Company (Armstrong et al. 1976; Fleming 1978; Richmann 1962).

Modern mechanical broom sweepers use a large rotary brush that is as wide as the sweeper, and which flicks dirt and debris onto a conveyor that then carries dirt and debris to a hopper (Schilling 2005a; Sutherland 2011). Water is often sprayed for dust suppression (Kang et al. 2009) and gutter brooms may be used to move dirt and debris from the gutter to the path of the brush (Schilling 2005a; Sutherland 2011). Mechanical sweepers remain the main type of sweeper used by municipalities, despite advances in alternative sweeper technologies (Sutherland 2011). According to a survey conducted in 2005, about 41 % of municipalities in the United States and Canada still use traditional mechanical broom sweepers, rather than vacuum and regenerative air varieties (Schilling 2005a). A survey conducted in 2001 shows that 81 % of cities having populations greater than 250,000 use mechanical sweepers, with only 5 % that use vacuum or regenerative air sweepers (Brinkmann and Tobin 2001).

Mechanical sweepers are effective at picking up wet vegetation, coarse sand, and heavy material such as gravel, but they are less efficient at removing finer particles (60 μm and smaller) left behind in cracks and uneven pavement. In a sense, mechanical sweepers may actually contribute to storm water-related pollution, because the rotary action of the broom breaks down large particles to smaller ones that are then transported by surface runoff (Schilling 2005a; Sutherland 2011). Mechanical sweepers can also increase airborne dust in dry weather despite the use of water to suppress it (Sutherland 2011). Use of too much water, of course, turns street dirt to mud, making its removal difficult.

2.1.3 Flushing

Historically, another method of removing street dust was simply to flush it into runoff drains. Early flushers used gravity to discharge water. With the development of the gasoline engine, high pressure water pumps were added to facilitate flushing. Water was sprayed with high pressure at an angle on the street that created a "chisel" action, removing stuck-on dirt and debris, which could then be washed to the curb or introduced to the stormwater system (Richmann 1962).

Street flushing is no longer common practice in the United States, because dirt was frequently flushed to the gutters rather than being removed. Water quality implications of street dust intentionally washed to streams and reservoirs also detracted from the utility of street flushing operations, as did the damage it caused to pavement (Richmann 1962). Though flushing is no longer a common practice in the United States, it remains so in other countries. For example, Amato et al. (2009) evaluated the effectiveness of flushing as a street cleaning method in Spain, Chang et al. (2005) used a street washer in Taiwan, and Bris et al. (1999) assessed the effectiveness of a water-jet cleaning procedure in France.

2.1.4 Vacuum

Vacuum sweepers were first used in the 1920s to remove fine dust left behind mechanical sweepers (Armstrong et al. 1976; Fleming 1978; Richmann 1962). A primary advantage of early vacuum sweepers is that they operated in freezing weather without water use; a disadvantage of these systems was that they were noisy and unreliable (Richmann 1962). In the early 1970s, several sweeper manufacturers reintroduced vacuum sweepers to the market, and again, their primary function was to remove fine particulate matter left behind by mechanical sweepers (Armstrong et al. 1976).

Modern vacuum sweepers use an engine powered fan to create suction. Vacuum sweepers are frequently designed with the vacuum nozzles typically placed on one side of the sweeper (Sutherland 2011) or on both sides with one suction nozzle operating at a time. Most vacuum sweepers use gutter brooms and a rotary brush called a windrow boom to push dirt and debris in the path of a suction nozzle (Fleming 1978; Sutherland 2011). An inherent problem with the windrow broom is that it tends to brush dirt and debris into street cracks. This results from pavement irregularities, which may contribute to inefficient collection of street dust across all technology types (Sutherland 2011). The abrasive nature of the brooms used may also produce finer size particles that are more easily transported by surface runoff (Schilling 2005a).

Vacuum sweepers may use a filtration system or water for dust suppression (USGS 2005; Fleming 1978; Zarriello et al. 2002). Typically, used air is exhausted from the sweeper, releasing a large amount of particulate matter into the atmosphere (Sutherland 2011). Vacuum sweepers are not as effective as mechanical sweepers when picking up wet vegetation or large debris (Schilling 2005a). Several studies have shown that vacuum sweepers are more effective than mechanical sweepers at picking up smaller particles. When comparing an Elgin Pelican (mechanical sweeper) to a Johnston 605 Series (vacuum sweeper), USGS (2005) found that the vacuum sweeper was at least 1.6–10 times more efficient than the mechanical sweeper for vacuuming all particle-size ranges. In addition, they found that vacuuming efficiencies for particle sizes between 2 mm and 250 μm (or coarse sand) were at least 1.5–5 times greater for the vacuum, than for the mechanical sweepers.

When comparing an Elgin Pelican (mechanical sweeper) to an Elgin Crosswind (regenerative air sweeper) and an Elgin Whirlwind (vacuum sweeper), USGS (2007) found that regenerative air and vacuum sweepers had similar pickup efficiencies of 25 and 30 %, compared to ~5 % of street-dirt yield for the mechanical sweeper.

2.1.5 Regenerative Air

Regenerative air sweepers were invented by a road construction contractor, B.W. Young of Young Brothers Construction Company in Waco, Texas, U.S.A. during the mid-1960s. These units were designed to sweep dirt from pavement cracks to achieve better bonding of Slurry Seal, an emulsified mixture of asphalt and sand used to repair broken pavement and restore asphalt roads (TYMCO 2012a, b, c, d).

Regenerative air sweepers use an engine to power a blower, which pushes air forward through a blast orifice across the entire width of a pick-up head onto the street surface and into the cracks in the street. The pick-up head extends across the entire width of the sweeper and uses rubber curtains on the front and back to create a seal on the road surface (Fleming 1978). The blast of air forces dirt and debris to become suspended (TYMCO 2012b). This debris-laden air is then sucked into the sweeper's hopper via a suction inlet. The larger air volume in the hopper slows the air, allowing heavier debris to fall. Lighter debris such as paper, plastic bags and leaves is trapped by a screen, while the lighter particulates are removed by a centrifugal dust separator (Fleming 1978). The cleaned air is then returned to the blower to restart the process. This closed-loop system prevents air from being exhausted to the atmosphere (Fleming 1978). Regenerative air sweepers are commonly grouped with vacuum sweepers (Brinkmann and Tobin 2001; USEPA 1985a). As with other sweeper types, gutter brooms may be used to direct dirt and debris to the path of a pick-up mechanism and a water spray mist may be used to suppress dust during the entire process (Sutherland 2011). Some pick-up heads may also contain a rotary brush to dislodge stuck-on dirt and debris (Elgin Sweeper 2012a; TYMCO 2012c).

Regenerative air sweepers are considered to be more environmentally friendly than mechanical and vacuum sweepers, because of their ability to sweep a wider path than vacuum sweepers, remove larger materials (viz., trash, road debris, and vegetation) and small and coarse particles found in cracks and uneven pavement, and to minimize the resuspension of particulate matter (Schilling 2005a; Sutherland 2011).

Uneven pavement may create fugitive dust losses from the pick-up head, but this loss is much less than from a typical vacuum sweeper (Sutherland 2011). Regenerative air sweepers generally do not remove wet vegetation or large road debris as well as mechanical sweepers. The requirement for pick-up head curtains to reinforce surface suction may cause larger materials to be pushed aside unless a pressure bleeder is used. Moreover, like all sweeper types, gutter brooms and the pick-up head broom may expose finer sized-particles for easy transport in stormwater (Schilling 2005a).

2.1.6 High-Efficiency Sweepers

High-efficiency sweepers are represented by any of the three main types (mechanical, vacuum, or regenerative air), provided they are modified to control the loss of fugitive dust smaller than 60 μm with the use of media particulate filters (Sutherland 2011). Most high-efficiency sweepers have the ability to suppress dust without using water (Sutherland 2011).

Sutherland credits himself for coining the term "high-efficiency" in 1997, when describing what he thought was the first sweeper to use a filtration system, and which would only exhaust particles with diameters less than 2.5 μm (Sutherland 2011). The device he described as being "high efficiency" was a vacuum sweeper developed in 1995 by EnviroWhirl Technologies in Centralia, IL, which was acquired by Schwarze Industries in 1999, and whose technology was then used in their EV-series, i.e., in their EV1 and EV2 models (Sutherland 2011).

In a computerized simulation comparing the EnviroWhirl sweeper with an Elgin Crosswind (regenerative air), and 1988 Mobil (mechanical), the EnviroWhirl reduced mean total suspended solids (TSS) by more than 80 %, followed by about 70 % for the Crosswind, and 20–30 % for the Mobil (Sutherland and Jelen 1997). Though the EV-series performed well in the simulation and was useful for waterless applications such as hazardous material cleanup, its high cost and limited maximum non-sweeping speed of 25 mph hindered its acceptance by the municipal market. The EV-series has since been discontinued (Sutherland 2011).

Several sweepers in the late 1970s were fitted with filters in an effort to control fugitive dust emissions; the filtration units on these had technical issues which led to loss of suction. Beginning in the early 1980s, the TYMCO Model 600DC (the predecessor to the DST-6), used media filters inside its hopper to control $PM_{2.5}$ emissions (TYMCO Inc. 2011, personal communication). TYMCO's DST-6 and DST-4 models clean all of the air by employing a centrifugal dust separator. After passing through the centrifugal dust separator, a small percentage of the air is exhausted to atmosphere after it is diverted to an external module containing filter cartridges, which are designed to remove particles as small as 0.5 μm. This causes an increase in suction around the pick-up head, thereby reducing fugitive emissions (Sutherland 2011; TYMCO 2012c).

Elgin Sweeper Company has three models that may be called "high-efficiency" sweepers: the Waterless Eagle and Waterless Pelican (mechanical) and the Crosswind NX (a regenerative air sweeper, which is no longer listed on Elgin's website) (Elgin Sweeper 2012b; Sutherland 2011). The waterless mechanical sweepers use a vacuum fan to siphon dust out of the hopper, shrouded gutter brooms, and a shrouded rotary broom. A filter in front of the fan traps dust and the cleaned air is exhausted (Sutherland 2011). The Crosswind NX is similar to the TYMCO DST-6 in that it siphons air from the hopper to an outside container. Rather than filter cartridges, the Crosswind NX use a series of filter bags, which purportedly remove over 99 % of particles as small as 0.5 μm (NAS 2012).

Schwarze Industries also has a high efficiency waterless model called the DXR, which uses a series of filter cartridges within the hopper, channeling 100 % of the air flow through a cartridge filter before it enters the blower. The DXR also employs shrouded gutter brooms with suction tubes to capture fugitive dust (Sutherland 2011). The DXR is not currently featured on Schwarze's website, and may have been discontinued.

2.2 Street Cleaning Purposes and Strategy

A survey of several municipalities across the United States suggests that street sweeping policy is dictated more by cleanliness and aesthetics than by potential water quality impacts. In communities with populations greater than 250,000, 11 %

were concerned about stormwater quality, 36 % were concerned about cleanliness, and 36 % were concerned about both categories (Brinkmann and Tobin 2001). Furthermore, the same survey disclosed that few cities have done research to assess their street sweeping practices or the effectiveness of their street cleaning program. Only 7 % of communities with populations of 5,000–25,000, 17 % of communities with populations of 25,000–100,000, and 24 % communities with populations >250,000 had done so (Brinkmann and Tobin 2001).

Several cities have implemented changes in street cleaning technologies as part of environmental management efforts. For example, the City of San Angelo, TX has implemented several changes to its street sweeping program to improve water quality of the North Concho River, including the use of 5 TYMCO Model 600 regenerative air sweepers, and using geospatial technology to record sweeping times and frequency. These changes resulted in pickup of 400–450 tons of material per year vs. the pre-change amounts of 200–250 tons of material per year (Talend 2012). Similarly, the City of Tacoma, Washington replaced its fleet of mechanical sweepers with 4 TYMCO Model 500x regenerative air sweepers and now uses geospatial technology to track sweeping implementation and to mark catch basins that require cleaning; this new strategy reduced the solids entering Commencement Bay via the Foss Waterway by more than half (Talend 2012). The City of Hamilton, Ontario, Canada and cooperative industry groups reduced ambient PM_{10} from 114 to 73 $\mu g/m^3$ by implementing several control measures, including street sweeping with TYMCO Model DST-6 high-efficiency regenerative air sweepers (DeLuca et al. 2012).

The California Stormwater Quality Association lists several suggested protocols for street sweeping and cleaning (CSQA 2003). These protocols include sweeping monthly at a minimum, sweeping in dry weather, avoiding flushing, increasing sweeping frequency in high traffic areas before the wet season, in special problem areas, at special events and in high litter zones, maintaining equipment in good order, and replacing older technologies with newer ones, preferably regenerative air (CSQA 2003).

A simulated study by the U.S. Geological Survey (USGS) suggested that solids and lead removal efficiency noticeably increased at sweeping frequencies of <7 days (Zarriello et al. 2002). A Florida study suggested that the optimum sweeping frequency for reducing street sediment for mechanical sweepers is once per week, the optimum frequency for reducing constituent loading in stormwater runoff is twice per week, and maintaining a frequent sweeping schedule is more important than storm intensity and duration in reducing sediment and pollutant loadings (Brinkmann and Tobin 2001). In contrast, a modeled USGS study of a commercial area indicated that sweeping once a month with a regenerative air sweeper is more effective than sweeping three times a week with mechanical or vacuum sweepers, judging by modeled reductions in the totals for solids, particulate solids, total phosphorus, and to particulate phosphorus (USGS 2013). Notwithstanding these commentaries, peer-reviewed empirical data supporting such management activities are not available.

2.3 Early Street Sweeper Studies

The earliest street sweeper studies were conducted by the U.S. Naval Radiological Defense Laboratory (NRDL) in the late 1950s and early 1960s to compare mechanical, vacuum, and flusher effectiveness at removing dry particulate matter (dry fallout material) from paved areas (Lee et al. 1959; Sartor and Boyd 1972). Sartor and Boyd (1972) reviewed the early studies by NRDL, along with other published data and information from street cleaning manufacturers, and performed an *in situ* evaluation of several U.S. cities, and conducted controlled tests using a simulated street surface contaminant. The NRDL data review showed that vacuum sweeping is more effective than mechanical sweeping for a "level of effort," as defined by the ratio of minutes of equipment operation to the surface area swept. The *in situ* evaluation indicated removal efficiencies ranging from 11 to 62 % for various mechanical sweepers, and the controlled study showed removal efficiencies of 26.5–77.7 % for a Mobil-TE-3 mechanical sweeper, and 36.0 and 44.2 % for a TYMCO Model 300 regenerative air sweeper (Sartor and Boyd 1972).

Axetell and Zell (1977) evaluated measures to control particulate air quality for the EPA. The capacity of mechanical, vacuum, and regenerative air sweepers (with and without flushing) to prevent re-entrainment of particulate matter was tested in a commercial area of Kansas City, Missouri and a residential area of Cincinnati, Ohio. After evaluating flushing and mechanical sweeping in Kansas City, flushing was found to be most effective at controlling air particulates, achieving a reduction of air particulate concentrations of 8–18 μg/m^3 after adjusting for differences in local air quality. The investigators reported that particulate concentrations were higher on the day of flushing and sweeping, but were lower than average on the next few days thereafter. In Cincinnati, flushing, mechanical sweeping, and vacuum sweeping were evaluated with contradictory results. Mechanical sweeping was considered to be the most effective for controlling particulate resuspension, with concentrations 6–20 μg/m^3 less than the other methods tested. Flushing showed no significant reduction, though concentrations were 16 μg/m^3 lower on the days that flushing was practiced and 4 μg/m^3 lower on the day after flushing. Vacuum sweeping was found to be ineffective, with concentrations increasing by 5 μg/m^3 when compared to no street cleaning (Axetell and Zell 1977). A vacuum sweeper was also evaluated in a suburb of Kansas City, and appeared to be effective at removing material from the street surface. However, study results showed no significant difference in air particulate levels compared to a nearby area that was not swept. This outcome may have resulted from low traffic density at the test site (Axetell and Zell 1977).

EPA established the Nationwide Urban Runoff Plan (NURP) in 1978. The program included a five year study designed to quantify the characteristics of urban runoff in different locations to determine the following: differences and similarities, how much urban runoff contributes to water quality problems across the nation, and the effectiveness of management practices for controlling pollutants in urban runoff. Study results showed street sweeping to be largely ineffective, with constituent reductions never exceeding 50 % in event mean concentrations (USEPA 1983).

Robert Pitt is credited with being the first to evaluate the effectiveness of street cleaning to manage storm water runoff by performing monitoring activities in an EPA funded study in San Jose, CA (Sutherland 2011; USEPA 1979). Pitt concluded that street sweepers were more effective at picking up larger size particles than smaller ones, that smaller size particles tended to increase over time, and pollutant concentrations tended to increase with decreasing particle size (USEPA 1979). Pitt also developed sampling procedures for evaluating street cleaning equipment under real-world conditions. The sampling technique utilized an industrial vacuum cleaner with a stainless steel canister. Street dirt was vacuumed along a randomly selected test strip within a test area from the curb to the center of the street before and after sweeping (USEPA 1979). This sampling technique is popular amongst researchers (USGS 2007; Law et al. 2008; DiBlasi 2008), because of its random nature and ease, but drawbacks that have been pointed out by Sutherland (2011) include possible street dirt accumulation if sampling is not done immediately after street sweeping, and parked cars present at the time of sweeping may not be present at the time of sampling and therefore may inhibit the accuracy of the measurements.

EPA tested the performance of a modified TYMCO Model 600 regenerative air sweeper, a standard TYMCO Model 600 regenerative air sweeper, and a Mobil mechanical sweeper. Modifications of the TYMCO Model 600 included partial hoods over the gutter brooms, venting the hoods to the hopper, and venting air out of the regenerative air system to increase suction with a low pressure drop venturi scrubber for dust suppression. Results of the study showed the modified TYMCO Model 600 was able to remove 80 % of solids, followed by 70 % and 20 % for the standard Model 600 and Mobil sweepers, respectively (USEPA 1985a).

2.4 Recent Sweeper Technology Comparison Studies

Though limited peer-reviewed information exists for comparisons of the effectiveness of sweeping methods, several researchers have attempted to compare effectiveness of different sweeper technologies. Evaluating sweeper efficiencies for street dust is difficult, because within the general sweeper technology categories of mechanical, vacuum and regenerative air, different manufacturers' sweeper models include subtle design modifications. In addition to differences amongst manufacturers, parameters in experimental designs may vary, including testing conditions, sampled material (simulated or as found *in situ*), sweeping speed, human error (adherence with standardized protocols, practices, procedures), and other factors. Despite such influencing variables, which inherently introduce uncertainty in environmental assessment and management efforts, we examine these more recent studies below.

Sutherland and Jelen (1997) conducted a simulated model study, in which sweeper test data from EPA's NURP studies of the late 1970s and early 1980s which indicated that sweeping was <50% effective at reducing constituents in runoff, were compared to data developed in the 1990s (USEPA 1983). The sweeper models compared included a ~1978 Mobil (mechanical) sweeper from Pitt (USEPA 1985b), a 1988 Mobil sweeper, a 1988 Mobil and a TYMCO regenerative air sweeper generically labeled as a vacuum, in tandem from HDR (1993), an Elgin Crosswind (regenerative air) sweeper from a test performed in 1995, and an EnviroWhirl (high efficiency vacuum) tested in two separate studies by Sutherland and Jelen in 1995. A comparison of residual dust remaining on the street indicated that most residuals remained after using a NURP era mechanical sweeper, followed by a newer mechanical sweeper, then the 1988 Mobil and TYMCO sweepers in tandem, finally followed by the Elgin Crosswind, and the EnviroWhirl sweepers. Though the EnviroWhirl sweeper was predicted to leave no residual dust on the street for any of the particle size groups examined, its efficiencies were modeled at less than 100 % for all particle sizes; the authors note that the seeming inconsistency in these modeled results arises from predictions for higher quantities of loading beyond the expected baseline. However, 100 % efficiencies were reportedly achieved for the newer mechanical sweeper in the lower particle size ranges <63 – 250 μm, and for the regenerative air sweeper in the 250–2,000 μm particle size ranges (Sutherland and Jelen 1997).

In another simulated study, USGS tested for expected efficiencies of a mechanical sweeper, wet vacuum and regenerative air sweeper, a dry vacuum, and a "best available technology" sweeper. The "best available technology" sweeper was described as having produced the highest efficiencies found in the literature (Zarriello et al. 2002). When averaging the expected removal efficiencies for each sweeper for suspended solids, fecal coliform bacteria, total phosphorus, and total lead, the best available technology was expected to achieve an efficiency of 93 %, followed by 63 % for the dry vacuum, 29 % for the wet vacuum and regenerative air method, and 11 % for the mechanical sweeper (Zarriello et al. 2002). The Florida Department of Transportation evaluated a mechanical sweeper and a regenerative air sweeper, and sweeper effectiveness was determined by measuring material left on the street after the sweeper had passed (Tobin and Brinkmann 2002). Coarse material was defined as material collected after the sweeper had passed, and which was collected by using a whisk-broom and dust pan. Fine material was defined as material collected by a shop-vacuum after the course material was collected. Very fine material was defined as material collected from a sandbag dammed area after flushing. In this study, a mechanical sweeper was more efficient at sediment removal, especially course sediment, than was a regenerative air sweeper. The mechanical sweeper in this study showed an overall effectiveness of 95–98 %, far beyond what has been observed in other studies of similar technologies. The regenerative air sweeper was better at removing very fine sediment (Brinkmann et al. 1999). Two water samples were also collected from the curbside reservoir and one from the water delivery system to serve as a background control (Brinkmann et al. 1999). The test material applied was previously collected street sweepings representative to the area. Each sweeper was evaluated on three test strips on a closed street on a dry, calm day. Each test strip was 1.5 m from the curb, was 10 m long, and had 25 kg of material spread evenly to a depth of 0.5 ± 0.2 cm, and had a minimum width of 1.25 m (Brinkmann et al. 1999).

Among comparative studies in the grey literature, perhaps the most robust was performed by the City of Toronto using Environmental Technology Verification (ETV) Canada General Verification Protocol (ETV 2012a, Toronto 2008). This test protocol evaluated the sweepers' pick-up efficiencies and the sweepers' ability to minimize PM_{10} and $PM_{2.5}$ emissions while sweeping (Toronto 2008). ETV has now verified four high-efficiency sweepers under the City of Toronto's PM_{10} and $PM_{2.5}$ Street Sweeper Efficiency Test Protocol. These studies were conducted in an 80×11 m enclosed tent, in which two 2.75×30 m strips of calcium carbonate powder were distributed onto aged pavement with cracks and potholes. The powder particles had a mean diameter of 3 μm and total weight of about 270 kg. Water was not used for dust suppression by any of the sweepers tested (City of Toronto 2008). The first sweeper, certified in 2005, a TYMCO Model DST-6 (regenerative air) removed >90 % of the test material from the surface. PM_{10} and $PM_{2.5}$ air contamination concentrations were measured as being below the limit of detection (LOD) (ETV 2012a). Comparing testing conducted in 2005 and 2008 is difficult as the limits of detection for PM were lowered in the second trial. Therefore, we will only compare the remaining three sweepers tested (ETV 2011, 2012a, b, c) below.

Of the tests performed in 2008, the Elgin Waterless Eagle and TYMCO Model DST-4 showed similar removal efficiencies of 88 % and 89 %, respectively, followed by the Elgin Crosswind NX with 82 % pick-up efficiency. Total PM_{10} air contamination concentrations were 11, 2.63, and 6.12 mg/m^3-kg for the DST-4, Waterless Eagle, and Crosswind NX, respectively. Total $PM_{2.5}$ air contamination concentrations were 7.5, 1.44, and 4.71 mg/m^3-kg for the DST-4, Waterless Eagle, and Crosswind NX, respectively (ETV 2011, 2012a, b, c). The only mechanical sweeper (the Waterless Eagle) controlled ambient PM better than the Crosswind NX, followed by the DST-4 (ETV 2011, 2012a, b, c). This performance by the Waterless Eagle may be attributed to its use of shrouded gutter brooms that enhanced vacuum suction, a feature not present on the other sweeper models tested. It should be noted that gutter broom shrouds were fastened in an elevated position that allowed the gutter brooms to make full contact with the curb during the test (ETV 2012c). Although shrouded gutter brooms with vacuum suction may be efficient in controlling ambient PM, it is also true that they may push larger debris such as leaves to create a bulldozing effect that prevents sweeping.

The USGS tested an Elgin Pelican Series P (mechanical sweeper) against a Johnston 605 (vacuum sweeper; USGS 2005). Street-sweeper efficiencies ranged from about 20–31 % for the mechanical sweeper and from about 60–92 % for the vacuum sweeper for the particle-size range tested. Efficiencies for particle sizes 2 mm-250 μm were at least 1.5–5 times greater for the vacuum sweeper than for the mechanical sweeper. The vacuum sweeper was at least 1.6–10 times more efficient than the mechanical one for all particle-size ranges examined (USGS 2005).

The USGS performed another study, in which they compared an Elgin Pelican (mechanical sweeper), an Elgin Crosswind (regenerative air sweeper) and an Elgin Whirlwind (vacuum sweeper) (USGS 2007). A regenerative air sweeper was replaced by a vacuum sweeper during this study, because industry representatives considered it to be more effective. These regenerative air and vacuum sweepers had similar pickup efficiencies (i.e., 25 and 30 %) compared to an average of 5 % of street dust yield for the mechanical sweeper. Average reductions in basin street dust yield were compared among three sweepers. A regenerative air sweeper provided the highest reduction (76 %), followed by 63 % and 20 % for the vacuum and mechanical sweepers, respectively. The discrepancy between street dust yield reductions and pick-up efficiencies may be attributed to the abrasive nature of the gutter and rotary brooms that generate smaller particle-size loads. This added load from the brooms may also negate the stormwater quality benefits of street sweeping USGS 2007).

The National Water Research Institute (NWRI) in Canada compared a regenerative air sweeper, a mechanical sweeper and a high efficiency regenerative air sweeper (NWRI 2007). Although the study did not identify brands or models of sweepers, the sweepers pictured appear to be an Elgin Air Bear, which is referred to as "old-technology regenerative air" (ORA), an Allianz 4000, which is referred to as "conventional mechanical" (CM), and a TYMCO Model DST-6, which is referred to as "new-technology regenerative air" (NRA). The ORA sweeper and the CM sweeper were examined at 8–15 km/h in 2004, while the NRA sweeper was tested at 5–8 km/h in 2005. The ORA sweeper was tested in the northbound side of the roadway, the CM sweeper was tested in the southbound, and the NRA sweeper was tested in both (NWRI 2007).

The NRA sweeper was the only sweeper that removed a statistically significant mass of solids from the road surface (48 kg/curb km), and appeared to remove solids to a "background" level (approximately 40–60 kg/curb km), beyond which further removal appeared unlikely. The CM sweeper also removed approximately 40 kg/curb km (on average), but the difference between the swept and unswept streets was not statistically significant. Similarly, the ORA sweeper showed no statistically significant reduction in street dust. Both the CM sweeper and the NRA sweeper provided consistent reductions in the largest size range >2,000 μm in the northbound lanes (58 % and 88 % respectively). The NRA sweeper removed 73 % of the total mass of particles that were >2,000 μm in the southbound lanes, and the ORA sweeper was unable to pick up particles sized >2,000 μm. Only the NRA sweeper was able to significantly pick up particles in the 64–2,000 and <64 μm size ranges (62 % and 35 % removal efficiencies, respectively). The performance difference of the NRA sweeper in the northbound side compared to the southbound side may be attributable to a difference in street dirt accumulation on the surface (NWRI 2007).

Runoff studies using a sealed catch basin insert and dechlorinated tap water from a garden hose equipped with a gentle rain-like spray head, showed that mobilized solids were relatively unchanged by sweeping (NWRI 2007). The study authors also examined the effectiveness of these sweepers on levels of environmental contaminants. Both the ORA and CM sweepers showed slight reductions of solids. The NRA sweeper showed an increase of solids in the northbound side, and only minor reductions in the southbound side. The difference in these results between the 2004 and 2005 tests may be attributed to changes in the test procedure mentioned above, with the higher pressure and acidity dislodging more solids. None of the sweepers showed significant reduction in total metals. Whereas total

Table 2 Efficacy and efficiency of street sweeper technologies

Technology	% Efficiency	Sweeper model	Particle size	Reference
Mechanical				
	13	Elgin Pelican Series P	<63 μm	USGS (2005)
	9–40	Elgin Pelican Series P	63–2,000 μm	USGS (2005)
	20–31	Elgin Pelican Series P	Overall	USGS (2005)
	No significant change	Allianz 4000[a]	<64 μm	NWRI (2007)
	No significant change	Allianz 4000[a]	64–2,000 μm	NWRI (2007)
	55	Allianz 4000[a]	>2,000 μm	NWRI (2007)
	−41 to 46	Elgin Pelican	Overall	USGS (2007)
Vacuum				
	39–81	Johnston 605 Series	<63 μm	USGS (2005)
	31–93	Johnston 605 Series	63–2,000 μm	USGS (2005)
	60–92	Johnston 605 Series	Overall	USGS (2005)
	−2 to 52	Elgin Whirlwind	Overall	USGS (2007)
Regenerative air				
	No significant change	Elgin Air Bear[a]	Overall	NWRI (2007)
	3–51	Elgin Crosswind	Overall	USGS (2007)
High efficiency mechanical				
	88.1	Elgin Waterless Eagle	3 μm mean	ETV (2012c)
High efficiency regenerative air				
	No significant change-35	TYMCO Model DST-6[a]	<64 μm	NWRI (2007)
	No significant change-62	TYMCO Model DST-6[a]	64–2,000 μm	NWRI (2007)
	73–88	TYMCO Model DST-6[a]	>2,000 μm	NWRI (2007)
	90	TYMCO Model DST-6	3 μm mean	ETV (2012a)
	89	TYMCO Model DST-4	3 μm mean	ETV (2011)
	81.8	Elgin Crosswind NX	3 μm mean	ETV (2012b)
	35.7–98.3	TYMCO DST-6	Overall	USGS (2013)

[a] Indicates the sweeper manufacturers and models were not named in the literature; however we have attempted to identify them by their respective photos

zinc showed no change, dissolved zinc showed reductions of 46 % for the ORA sweeper and 56 % for the NRA sweeper. There were no significant changes for polycyclic aromatic hydrocarbons (PAHs) for any of the sweepers (NWRI 2007).

Weston Solutions, Inc. (2010) weighed street dirt material that was collected on sweeping routes for a Johnston 4000 (mechanical), an Elgin Whirlwind (vacuum), and a Schwarze A7000 (regenerative air) street cleaning units and found that the vacuum sweeper was able to pick up 14–45 % more material weight than the regenerative air, and 15–65 % more material weight then the mechanical sweeper. Pick-up efficiency could not be calculated, because the amount of material on the street was not measured before and after the sweeper pass.

Most recently the USGS tested a TYMCO Model DST-6 (high efficiency regenerative air sweeper) on multifamily residential and commercial land use streets in Cambridge, MA (USGS 2013). A computer model was used to determine estimated percent reduction of solids contributing to stormwater with a single pass of the Model DST-6 vs. a mechanical and a vacuum sweeper with previously collected data from other studies at various sweeping frequencies. The model showed reductions of 2.7, 5.2, and 16 % for the mechanical, vacuum and regenerative air sweepers respectively with monthly sweeping. Bimonthy sweeping showed reductions of 3.3, 7.0, and 18 % for the mechanical, vacuum and regenerative air sweepers respectively. Weekly sweeping showed reductions of 4.2, 9.6, and 18 % for the mechanical, vacuum and regenerative air sweepers respectively. Sweeping three times per week showed reductions of 6.0, 14, 19 % for the mechanical, vacuum and regenerative air sweepers respectively. Although there was little improvement with increased sweeping frequency for the Model DST-6, sweeping monthly with it was still more effective than sweeping three times a week with mechanical or vacuum technologies (USGS 2013).

There are a limited number of studies, in which sweeper technologies were compared under well-defined experimental conditions. Differences in numerous study parameters (e.g., local land-uses, local geology and material studied, operational details, etc.), make it difficult to draw defensible conclusions from the literature about which technique or equipment type is optimum for various scenarios. Nevertheless, below, we have attempted to combine efficacy data from various studies to gain a better understanding of technology efficacy differences (Table 2).

Because simulated computer models were used to determine expected efficiencies, the papers by Sutherland and Jelen (1997), USGS (2013) and Zarriello et al. (2002) were excluded. The work of Brinkmann et al. (1999) was also excluded from our analysis, because their study only considered material left behind, which excluded material displaced outside of the sweeper and street. Another deficiency of this latter study is that particle size was not quantifiably defined. Weston Solutions (2010) was also excluded because pick-up efficiency could not be calculated. As expected, efficiencies were much higher for high efficiency sweepers, with an overall efficiency of 82 % for the Elgin Crosswind NX (regenerative air), 88 % for the Elgin Waterless Eagle (mechanical), 89 % for the TYMCO Model DST-4 (regenerative air), and 90 % for the TYMCO Model DST-6 (regenerative air) (ETV 2011, 2012a, b, c).

Table 2 highlights the high degree of variability amongst sweeper experiments performed to date, even when the same sweeper model was tested. For example, the TYMCO Model DST-6 was 90 % efficient in the ETV study, but only up to 35 %

efficient in the test performed by NWRI in the smallest particle size range (<63 μm) (ETV 2012a; NWRI 2007). Efficiency ranged from 36 to 98 % in the study conducted by USGS, which included 72 data points from commercial and residential neighborhoods (USGS 2013). There are several notable differences between these two studies; most notably that the ETV test used a test material with an average diameter of 3 μm in a controlled environment, while NWRI was a "real world" study (material of variable diameter from a non-controlled environment) (NWRI 2007; Rochfort 2012a). Similarly, the Elgin Pelican was up to 31 % efficient in the 2005 USGS test, while in the 2007 USGS test efficiencies ranged widely with the Pelican actually adding to street dirt yield by up to 41 % and reducing the street dirt yield by up to 46 % (Breault et al. 2005; Selbig and Bannerman 2007; Table 2). Interestingly, the vacuum sweeper performed better than the regenerative air sweeper as documented in various studies within the technology categories; however, again, there was a high degree of variability within and between studies, with overall removal efficiencies ranging from 60 to 92 % and -2 to 52 % in two separate USGS studies in which different vacuum sweeper models were evaluated and efficiencies ranging from no change and -3 to 51 % in studies by NWRI and USGS in which two different regenerative air sweeper models were evaluated (USGS 2005; NWRI 2007; Table 2) (USGS 2007).

3 Environmental Regulation in the US

The first major law to address water pollution in the US was the Federal Water Pollution Control Act of 1948 (FWPCA). Eventually, FWPCA was amended by the Clean Water Act (CWA) of 1972 to address public concerns associated with water pollution. The CWA outlined a regulatory structure for pollutant discharges to US waters, set standards for industry discharges and surface water quality, required a permit for point source discharges, established grants for municipal sewage treatment, and identified a planning need for the problems associated with nonpoint source pollution, including that from street surface runoff (USEPA 2013a). Of particular relevance to street cleaning is that point source and nonpoint source stormwater pollution are regulated by the National Pollutant Discharge Elimination System (NPDES) program for municipal separate storm sewer systems (MS4s), construction activities, and industrial activities by permit (USEPA 2013b).

NPDES permits for MS4s fall under two categories: phase I and phase II. Phase I, issued in 1990, requires stormwater discharge permits for medium and large cities, and some counties with populations of 100,000 or greater. Phase II, issued in 1999, requires stormwater discharge permits for small MS4s in and around urbanized areas (USEPA 2013c). NPDES requires six MS4 program elements called "minimum control measures" as follows: (1) public education and outreach (e.g., distribution of educational materials about the impacts of stormwater discharge on water quality); (2) public participation and involvement (e.g., public hearings on stormwater regulations); (3) detection and elimination of illicit discharges; (4) runoff control for construction sites; (5) pollution prevention/good housekeeping with control measures (e.g., regular street sweeping, and; (6) development and maintenance of on-site wastewater treatment systems (USEPA 2005a). To obtain a permit, MS4s operators must submit a Notice of Intent (NOI) including its chosen Best Management Practices (BMPs) and measureable goals for each minimum control measure (USEPA 2005a). BMPs include municipal landscaping, parking lot and street cleaning, storm drain system cleaning, and others (USEPA 2005b).

Another relevant street-cleaning regulation in the US was the Clean Air Act (CAA) of 1970 (USEPA 2013d). The CAA regulates emissions from stationary sources, such as coal fired power plants, and mobile sources, such as vehicles. Under the CAA, EPA sets National Ambient Air Quality Standards (NAAQS) to regulate hazardous emissions for the sake of public health and welfare (USEPA 2013d).

Arguably the NAAQS region most impacted by poor air quality is the South Coast Air Quality Management District (AQMD) covering all of Orange County, California, and the urban portions of Los Angeles, Riverside, and San Bernardino counties in Southern California. In an effort to reduce ambient PM loads from paved and unpaved roads and livestock operations, AQMD adopted Rule 1186 in 1997 (AQMD 2008). Regarding street sweepers, Rule 1186 requires municipal use street sweepers to be certified by the AQMD. Sweepers are required to have a minimum pick-up efficiency of the test material of 80 % (AQMD 2009). Though the original intent of the Rule 1186 sweeper test was to determine which sweepers were efficient at picking up PM_{10}, it has been criticized because the testing procedure never actually measures the particle size of the material removed (Sutherland 2011). In addition, only about 3 % of the test material had diameters of 10 μm or less; hence, with a minimum pick-up efficiency of 80 % a sweeper could easily be certified as compliant without picking up any PM_{10} material (Sutherland 2011).

4 Characteristics of Street Dust

Typical street sweepings consist of soil, sediment, small pieces of pavement, leaves and organic debris, and anthropogenic trash. Several factors may affect variability in the composition of street sweepings, including sweeping method and technology, street surface type, traffic load, geographic area, and weather (Jang et al. 2009). Dust or sediments found in street sweepings typically consist of local crustal material such as eroded rock and soil and anthropogenic materials such as eroded material from bricks, concrete, other building materials, construction trackout, and roadway debris (maintenance/traction sand, automotive debris, exhaust particles, asphalt, sealants, etc.) (Brinkmann and Tobin 2001). Previous studies have indicated that street dust accumulates fairly quickly after cleaning (9 lb per curb mile per day for the first four days after cleaning, and 2 lb per curb mile per day between four and nine days after cleaning), but rates of accumulation can vary widely from location to location (USEPA 1979; WDOT 2009). Seventy-five percent of the mass of street dust lies within 3 ft of the curb, and approximately 90 % within 8 ft (USGS 2007; USEPA 1985a).

Crustal material grain size naturally varies by location, resulting in unique site-specific conditions. For example, soil in Milwaukee, Wisconsin (and much of the northern Midwest to the northeast) tends to contain more clay from glacial tills, whereas materials in Sarasota, Florida contains more sand (Brinkmann and Tobin 2001). Anthropogenic sediment sources are not as prevalent on roadways as natural sources and tend to be coarser in nature (Brinkmann and Tobin 2001).

Particle size is particularly important, because pollutants tend to bind to smaller size particles more than to larger size particles, due to the negative electrical charge of smaller particles and the positive electrical charge of pollutants, and because smaller particles have a higher surface area (Brinkmann and Tobin 2001; Lau and Stenstrom 2005; Liebens 2001). Smaller size particles also have a low density, allowing them to be easily carried by surface runoff (Zhao et al. 2009b).

Herngren et al. (2006) analyzed road-deposited sediments for three different land uses (residential, industrial, commercial) in Queensland, Australia. The highest percentage of total mass collected was consistently in the 0.45–75 μm size range, followed by the 76–150 μm size range. It was found that >90 % of the particles at each site were below 150 μm. In Santa Monica, CA, Lau and Stenstrom (2005) collected street dust samples from 18 locations spanning 5 different land use patterns: industrial, roads (i.e., major intersections), multi-family residential, single family residential, and commercial areas. For combined land uses, 47.7 % of the total mass of street dust collected was in the 100–250 μm size range. In all of the land use areas, the 100–250 μm size range was considered to be the most important, with the exception of the single family residential areas, which showed a larger proportion of mass within the <43 μm size range. However, in Wisconsin it was observed that 75 % of particle mass was in size fractions greater than 250 μm, and that the sizes class smaller than 63 μm contained less than 5 % of the total mass. The variability in granulometry among these different sites is significant; many local factors are expected to contribute to this variability, and as the available technologies for street sweeping have been shown to be most efficacious for certain size classes, a scientific approach to street sweeping must include a characterization of site-specific granulometry.

4.1 Sources of Contaminants in Street Sweepings

Sources of contaminants in street sweepings and roadside sediment include: emissions from vehicles, tire wear components, road wear components, tire control additives, pesticides, fertilizers, and industrial emissions (Jang et al. 2009). From these sources, a number of chemical contaminants arise, including many heavy metals and organic compounds. For instance, manganese and chromium are associated predominantly with brake dust (Tandon et al. 2008), whereas sources of zinc include: exhaust emissions, tire and body wear of vehicles, fluid leakage from vehicles, galvanized steels in road structures, and the weathering of asphalt and concrete (Jang et al. 2009; Lindgren 1996). Sources of nickel include gasoline, oil, asphalt vehicle exhaust, and the weathering of asphalt and concrete (Lindgren 1996; Muschack 1990). Sources of copper include brake linings, tires, alloys in motor vehicles, and the weathering of asphalt and concrete (Jang et al. 2009; Sadiq et al. 1989). Aluminum, potassium, silica, calcium, titanium, and strontium are thought to arise in street dust from local crustal materials (i.e., soil, sand, etc.) (Abu-Allaban et al. 2003; Amato et al. 2010a, b). Organic contaminants, such as PAHs, phthalates, dioxins, furans, and pesticides, are frequently found in street dust. Sources of organics in street dust are obviously numerous, but arise from asphalt, motor oil, gasoline, tire particles, wood soot, and vegetation (USGS 2005). Nutrients are another contaminant of potential concern in street dust. Nutrients in street dust originate from lawns, pet wastes, failing septic systems, and atmospheric deposition from industry and automobile emissions (USEPA 2005c).

In the following sections, we more closely examine available information for these various contaminants in street dust. For example, the USGS examined accumulation rates and chemical composition of street dust in residential areas (USGS 2005). Substantial concentrations of trace metals and PAHs were found in residential areas, with several metals exceeding probable effects concentrations (PEC) for producing adverse biological effects to aquatic organisms within several particle size ranges, and two PAHs exceeding their exposure-based guidelines. The largest mass of heavy metals, including cadmium, chromium, copper, lead, nickel, and zinc made up about 30 % of total mass in the 250–2,000 μm size range, while the sum of parent PAHs made up about 27 %. The largest concentrations of heavy metals and PAHs were found in the smaller particle size range (<63 μm). PAH levels were similar to those measured by the USGS in asphalt and in used motor oil in an unpublished study (USGS 2005).

4.2 Metals

Metals that are prominent in street dust include antimony, arsenic, beryllium, bismuth, cadmium, cobalt, copper, gold, lead, mercury, nickel, palladium, selenium, silver, tellurium, thallium, tin, and zinc (Brinkmann and Tobin 2001; Table 3). In the studies we analyzed, aluminum, cadmium, chromium, copper, lead, nickel, and zinc were quantified most frequently. The geographic locations of these studies spanned Massachusetts and Florida, USA; Xincheng, China; Brisbane, Australia; and Jonkoping and Lulea, Sweden. No trends in amounts found were established based on geography, because the available data are not extensive enough to allow for a systematic evaluation.

In a few studies, the concentrations of contaminants found in street dust were compared to either background levels, soil cleanup target levels, probable effect concentrations or other benchmarks. In Florida, zinc and copper concentrations in street dust were found to be statistically greater ($p < 0.05$) that those found in

Table 3 A summary of metal levels detected in street dust samples

Metal	Concentration (ppm)	Particle fraction (μm)	Geographic location	Sample	Citation
Aluminum					
	7,600	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	9,800	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	18,000	<63	New Bedford, MA, USA	Residential	USGS (2005)
	0.01	<0.45	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.01	<0.45	Brisbane, Australia	Industrial	Herngren et al. (2006)
	0.07	<0.45	Brisbane, Australia	Commercial	Herngren et al. (2006)
	8.80	0.45–75	Brisbane, Australia	Residential	Herngren et al. (2006)
	13.59	0.45–75	Brisbane, Australia	Industrial	Herngren et al. (2006)
	5.51	0.45–75	Brisbane, Australia	Commercial	Herngren et al. (2006)
	8.80	75–150	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.63	75–150	Brisbane, Australia	Industrial	Herngren et al. (2006)
	3.52	75–150	Brisbane, Australia	Commercial	Herngren et al. (2006)
Antimony					
	6	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	6	<63	New Bedford, MA, USA	Residential	USGS (2005)
Arsenic					
	6	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	5	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	9	<63	New Bedford, MA, USA	Residential	USGS (2005)
Barium					
	98	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	110	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	210	<63	New Bedford, MA, USA	Residential	USGS (2005)

(continued)

Table 3 (continued)

Metal	Concentration (ppm)	Particle fraction (μm)	Geographic location	Sample	Citation
Beryllium					
	0.5	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	0.6	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	0.9	<63	New Bedford, MA, USA	Residential	USGS (2005)
Cadmium					
	0.5–1.5	<500	Bordeaux, France	Bridges and highway	Durand et al. (2003)
	1	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	2	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	3	<63	New Bedford, MA, USA	Residential	USGS (2005)
	0.003	<0.45	Brisbane, Australia	Commercial	Herngren et al. (2006)
	0.002	0.45–75	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.002	0.45–75	Brisbane, Australia	Commercial	Herngren et al. (2006)
	0.002	75–150	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.01	75–150	Brisbane, Australia	Commercial	Herngren et al. (2006)
Chromium					
	33–70	<500	Bordeaux, France	Bridges and highway	Durand et al. (2003)
	350	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	300	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	200	<63	New Bedford, MA, USA	Residential	USGS (2005)
	193	<63	Xincheng, China	Street Dust	Zhao et al. (2009a)
	168	125–63	Xincheng, China	Street Dust	Zhao et al. (2009a)
	133	250–125	Xincheng, China	Street Dust	Zhao et al. (2009a)

(continued)

Table 3 (continued)

Metal	Concentration (ppm)	Particle fraction (μm)	Geographic location	Sample	Citation
	0.02	0.45–75	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.06	0.45–75	Brisbane, Australia	Industrial	Herngren et al. (2006)
	0.03	0.45–75	Brisbane, Australia	Commercial	Herngren et al. (2006)
	0.01	75–150	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.003	75–150	Brisbane, Australia	Industrial	Herngren et al. (2006)
	0.02	75–150	Brisbane, Australia	Commercial	Herngren et al. (2006)
	0.01	151–300	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.002	151–300	Brisbane, Australia	Industrial	Herngren et al. (2006)
	0.01	151–300	Brisbane, Australia	Commercial	Herngren et al. (2006)
Cobalt					
	6	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	9	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	11	<63	New Bedford, MA, USA	Residential	USGS (2005)
Copper					
	67–151	<500	Bordeaux, France	Bridges and highway	Durand et al. (2003)
	91	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	140	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	250	<63	New Bedford, MA, USA	Residential	USGS (2005)
	285	<63	Xincheng, China	Street Dust	Zhao et al. (2009a)
	258	125–63	Xincheng, China	Street Dust	Zhao et al. (2009a)
	182	250–125	Xincheng, China	Street Dust	Zhao et al. (2009a)
	0.08	<0.45	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.01	<0.45	Brisbane, Australia	Industrial	Herngren et al. (2006)

(continued)

Table 3 (continued)

Metal	Concentration (ppm)	Particle fraction (μm)	Geographic location	Sample	Citation
	0.12	<0.45	Brisbane, Australia	Commercial	Herngren et al. (2006)
	0.56	0.45–75	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.96	0.45–75	Brisbane, Australia	Industrial	Herngren et al. (2006)
	0.26	0.45–75	Brisbane, Australia	Commercial	Herngren et al. (2006)
	0.48	75–150	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.04	75–150	Brisbane, Australia	Industrial	Herngren et al. (2006)
	0.24	75–150	Brisbane, Australia	Commercial	Herngren et al. (2006)
Iron					
	33,000	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	34,000	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	33,000	<63	New Bedford, MA, USA	Residential	USGS (2005)
	0.01	<0.45	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.96	<0.45	Brisbane, Australia	Commercial	Herngren et al. (2006)
	14.00	0.45–75	Brisbane, Australia	Residential	Herngren et al. (2006)
	43.96	0.45–75	Brisbane, Australia	Industrial	Herngren et al. (2006)
	16.78	0.45–75	Brisbane, Australia	Commercial	Herngren et al. (2006)
	12.80	75–150	Brisbane, Australia	Residential	Herngren et al. (2006)
	2.16	75–150	Brisbane, Australia	Industrial	Herngren et al. (2006)
	9.59	75–150	Brisbane, Australia	Commercial	Herngren et al. (2006)
Lanthanum					
	12	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	18	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	24	<63	New Bedford, MA, USA	Residential	USGS (2005)

(continued)

Table 3 (continued)

Metal	Concentration (ppm)	Particle fraction (µm)	Geographic location	Sample	Citation
Lead					
	96–222	<500	Bordeaux, France	Bridges and highway	Durand et al. (2003)
	420	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	490	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	1,240	<63	New Bedford, MA, USA	Residential	USGS (2005)
	311	<63	Xincheng, China	Street Dust	Zhao et al. (2009a)
	333	125–63	Xincheng, China	Street Dust	Zhao et al. (2009a)
	203	250–125	Xincheng, China	Street Dust	Zhao et al. (2009a)
	0.01	<0.45	Brisbane, Australia	Commercial	Herngren et al. (2006)
	0.04	0.45–75	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.96	0.45–75	Brisbane, Australia	Industrial	Herngren et al. (2006)
	0.34	0.45–75	Brisbane, Australia	Commercial	Herngren et al. (2006)
	0.03	75–150	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.04	75–150	Brisbane, Australia	Industrial	Herngren et al. (2006)
	0.19	75–150	Brisbane, Australia	Commercial	Herngren et al. (2006)
Lithium					
	9	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	12	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	22	<63	New Bedford, MA, USA	Residential	USGS (2005)
Manganese					
	350	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	400	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	440	<63	New Bedford, MA, USA	Residential	USGS (2005)

(continued)

Table 3 (continued)

Metal	Concentration (ppm)	Particle fraction (μm)	Geographic location	Sample	Citation
	0.01	<0.45	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.02	<0.45	Brisbane, Australia	Industrial	Herngren et al. (2006)
	0.27	<0.45	Brisbane, Australia	Commercial	Herngren et al. (2006)
	0.23	0.45–75	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.51	0.45–75	Brisbane, Australia	Industrial	Herngren et al. (2006)
	0.22	0.45–75	Brisbane, Australia	Commercial	Herngren et al. (2006)
	0.20	75–150	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.02	75–150	Brisbane, Australia	Industrial	Herngren et al. (2006)
	0.16	75–150	Brisbane, Australia	Commercial	Herngren et al. (2006)
Molybdenum					
	4	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	4	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	5	<63	New Bedford, MA, USA	Residential	USGS (2005)
Nickel					
	67–151	<500	Bordeaux, France	Bridges and highway	Durand et al. (2003)
	35	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	44	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	55	<63	New Bedford, MA, USA	Residential	USGS (2005)
	165	<63	Xincheng, China	Street Dust	Zhao et al. (2009a)
	135	125–63	Xincheng, China	Street Dust	Zhao et al. (2009a)
	96	250–125	Xincheng, China	Street Dust	Zhao et al. (2009a)

(continued)

Table 3 (continued)

Metal	Concentration (ppm)	Particle fraction (μm)	Geographic location	Sample	Citation
Scandium					
	2.7	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	3.8	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	3.9	<63	New Bedford, MA, USA	Residential	USGS (2005)
Silver					
	0.4	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	1.0	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	1.2	<63	New Bedford, MA, USA	Residential	USGS (2005)
Strontium					
	30	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	36	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	46	<63	New Bedford, MA, USA	Residential	USGS (2005)
Tin					
	12	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	19	<63	New Bedford, MA, USA	Residential	USGS (2005)
Titanium					
	800	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	100	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	1,300	<63	New Bedford, MA, USA	Residential	USGS (2005)
Vanadium					
	36	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	49	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	75	<63	New Bedford, MA, USA	Residential	USGS (2005)
Yttrium					
	11	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	13	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	15	<63	New Bedford, MA, USA	Residential	USGS (2005)

(continued)

Table 3 (continued)

Metal	Concentration (ppm)	Particle fraction (μm)	Geographic location	Sample	Citation
Zinc					
	249–547	<500	Bordeaux, France	Bridges and highway	Durand et al. (2003)
	270	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	320	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	810	<63	New Bedford, MA, USA	Residential	USGS (2005)
	529	<63	Xincheng, China	Street Dust	Zhao et al. (2009a)
	438	125–63	Xincheng, China	Street Dust	Zhao et al. (2009a)
	384	250–125	Xincheng, China	Street Dust	Zhao et al. (2009a)
	0.39	<0.45	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.18	<0.45	Brisbane, Australia	Industrial	Herngren et al. (2006)
	0.83	<0.45	Brisbane, Australia	Commercial	Herngren et al. (2006)
	1.80	0.45–75	Brisbane, Australia	Residential	Herngren et al. (2006)
	2.32	0.45–75	Brisbane, Australia	Industrial	Herngren et al. (2006)
	0.42	0.45–75	Brisbane, Australia	Commercial	Herngren et al. (2006)
	0.72	75–150	Brisbane, Australia	Residential	Herngren et al. (2006)
	0.11	75–150	Brisbane, Australia	Industrial	Herngren et al. (2006)
	0.30	75–150	Brisbane, Australia	Commercial	Herngren et al. (2006)
Zirconium					
	13	125–250	New Bedford, MA, USA	Residential	USGS (2005)
	10	63–125	New Bedford, MA, USA	Residential	USGS (2005)
	7.1	<63	New Bedford, MA, USA	Residential	USGS (2005)

Florida soils (Jang et al. 2009). USGS (2005) tested street dust for metals and found that beryllium and lead concentrations exceeded Massachusetts Department of Environmental Protection exposure-based soil standards by 1.3 and 4.1 times, respectively, in the smallest particle size range (<63 μm). Lead also exceeded exposure-based guidelines for all particle size ranges <250 μm, and its whole sample concentration was 1.1 times greater than its exposure-based guideline.

USGS (2005) compared metal concentrations to PECs for adverse biological effects in benthic organisms. Chromium and nickel exceeded their respective PECs in all particle size ranges except for those >2,000 μm. Cadmium and zinc were higher than their PECs only in the smallest particle-size range (<63 μm), whereas copper exceeded its PEC in the smallest and largest particle size ranges of <63 μm and >2,000 μm, respectively.

Zhao et al. (2009a) analyzed heavy metals (e.g., chromium, copper, nickel, lead, and zinc) in street dust particles in a small town near the Yangtze River delta in China and found that about 63–71 % of their mass resided in particles of the <250 μm size range, which accounted for 40 % of the total mass of material collected from the street. Among land use categories, industrial areas had the highest concentration of metals, followed by main traffic roads, old residential, commercial, and new residential roads, respectively.

In Queensland, Australia, Herngren et al. (2006) analyzed street dust from residential, industrial, and commercial areas for eight heavy metals, and found that the highest concentrations were consistently found in the 0.45–75 μm size range overall. More than 90 % of the total mass of street dust collected was smaller than 150 μm, and half of the total heavy metal concentrations were found in the <75 μm range. For all metals tested, the highest concentrations were found at the industrial site, although cadmium results were usually below the detection limit. The highest concentrations found were usually for iron and aluminum.

In each of the studies examined above, concentrations generally increased with decreasing particle size.

4.2.1 Aluminum

Aluminum in street dust primary arises from local soils (Amato et al. 2010b). The highest concentrations from the selected studies were recorded in New Bedford, Massachusetts where total aluminum concentrations ranged from 6,700 to 18,000 mg/kg, followed by Pensacola and Escambia County, Florida, where concentrations ranged from 1,278 to 17,312 mg/kg (Liebens 2001; USGS 2005). Concentrations in Brisbane, Australia were comparatively lower, ranging from 0.01 to 13.59 mg/kg (Herngren et al. 2006).

4.2.2 Cadmium

Cadmium in street dust arises from vehicle exhaust, tire wear, and industrial emissions (Hood 2006; Legret and Pagotto 1999). In the selected studies, concentrations were the highest (3 mg/kg) in the lowest particle size range (<63 μm) in Massachusetts (USGS 2005). Concentrations detected in other regions were comparatively lower, ranging from below the limit of detection to 1.37 mg/kg in Florida, below the detection limit to 0.01 mg/kg in Australia, and 0.049–0.23 mg/kg in Sweden (Herngren et al. 2006; Liebens 2001; Viklander 1998).

4.2.3 Chromium

Chromium is mainly associated with brake dust (Tandon et al. 2008). There is a high degree of variability in amounts of chromium detected in the various studies. For example, maximum concentrations were as high as 193 mg/kg (Xincheng, China) and 200 mg/kg (New Bedford, Massachusetts) in particles <63 μm, but, elsewhere, levels as low as 0.02–0.06 mg/kg (Brisbane, Australia) were observed for comparable size ranges (USGS 2005; Herngren et al. 2006; Zhao et al. 2009a). Concentrations tended to increase as particle size ranges decreased. Concentrations in China were much higher than in other countries, and ranged from 87 mg/kg for the largest particle size range (250–900 μm) to 193 mg/kg for the smallest particle size range (<63 μm) (Zhao et al. 2009a). Concentrations were lowest in Australia (Herngren et al. 2006) (Table 3). Of the two studies conducted in the United States, residential concentrations were as much as 35 times lower in Florida than in Massachusetts (Liebens 2001; USGS 2005).

4.2.4 Copper

Sources of copper include brake linings, tires, motor vehicle alloys, and weathered pavement (Jang et al. 2009; Sadiq et al. 1989). Levels at which copper is detected also has a high degree of site-specific variability. Concentrations of copper among the selected studies were highest in China and Massachusetts in the lowest particle size range (<63 μm) and in Sweden (German and Svensson 2002; USGS 2005; Zhao et al. 2009a). Concentrations were much lower in Brisbane in all particle size ranges (Herngren et al. 2006).

4.2.5 Lead

Traditional sources of lead are leaded paint and gasoline (Gulson et al. 1995). Although lead has been banned from paint and gasoline in the United States since 1978, lead may still come from washoff of lead paint from older buildings and structures (Davis et al. 2001). Maximum lead concentrations detected were 1,240 mg/kg in Massachusetts, with whole sample concentrations slightly exceeding the exposure-based guideline value (USGS 2005) (Table 3). The second highest lead concentration (311 mg/kg) was recorded in China at (Zhao et al. 2009a). Concentrations of lead were measured between 0.01 and 0.96 mg/kg (multiple particle size fractions) in eastern Australia, and orders of magnitude higher in the United States, ranging as high as 1,240 mg/kg in Massachusetts, and 94 mg/kg in Florida (Herngren et al. 2006; Jang et al. 2009; Liebens 2001; USGS 2005). Lead concentrations were comparable in two separate studies in Florida (18.3 mg/kg and 19.98 mg/kg) (Jang et al. 2009; Liebens 2001). Concentrations in Sweden were 45 mg/kg for particle sizes <0.25 mm (German and Svensson 2002) (Table 3).

4.2.6 Nickel

Nickel is associated with gasoline, oil, asphalt, vehicle exhaust, and the weathering of asphalt and concrete (Lindgren 1996; Muschack 1990). Nickel concentrations were greatest in China, followed by Massachusetts in the lowest particle size range (<63 μm) (USGS 2005; Zhao et al. 2009a). Nickel concentrations in Florida were lowest in two separate studies (Jang et al. 2009; Liebens 2001). Sweden concentrations were in the middle range (~25 mg/kg in the <0.25 mm range) (German and Svensson 2002).

4.2.7 Zinc

Zinc is associated with vehicle exhaust, tires, vehicle body wear, and fluid leakage from vehicles, weathered steel structures, and weathering of pavement (Jang et al. 2009; Lindgren 1996). Zinc concentrations were highest in Massachusetts in the lowest particle size range (<63 μm) (USGS 2005). In China, concentrations were comparatively lower in the <63 μm range (Zhao et al. 2009a). The lowest concentrations were found in Brisbane, Australia and these ranged from 0.04 to 2.32 in all particle size ranges (Herngren et al. 2006). In two separate studies performed in Florida, concentrations in the middle range were reported (viz., 65.1 and 38.48 mg/kg) without particle size being noted (Jang et al. 2009; Liebens 2001). Concentrations in Sweden were relatively higher at 257 ± 40 in the <0.25 mm particle size range (German and Svensson 2002).

4.3 Organic Contaminants

Although metals are the most frequently studied contaminants in street dust, PAH concentrations have been frequently reported in this medium and in stormwater runoff (Jang et al. 2009; NWRI 2007; USGS 2005; Zhao et al. 2008; Zhao et al. 2009a; Table 4). PAHs in street dust originate from vehicle exhaust, motor, waste oil and greases, gasoline, tire and asphalt particles, and wood soot (Jang et al. 2009; Takada et al. 1990; USGS 2005). A forensic study in urban Beijing, China found that vehicle emissions contributed to 57 % of PAHs in road dust, followed by 42 % contribution from coal/oil combustion (Zhang et al. 2008). In the United States and other Western countries, where coal is not used for residential heating, the profile of PAH sources would clearly be expected to differ. For example, a study conducted in Paris indicated that traffic was the primary contributor to PAHs there (Gasperi et al. 2005). Tire and brake lining particles contain noteworthy concentrations of a number of PAHs (Rogge et al. 1993). It has also been noted that vehicular PAHs may adsorb to road salt particles, which would suggest that colder weather environments may have higher concentrations of PAHs in spring runoff (Harrison et al. 1996). Furthermore, although traffic is a predominant source, industrial activities are also an important contributor (Hoffman et al. 1984). Numerous studies conducted by USGS have documented increasing environmental concentrations of PAHs attributable to the use of coal-tar based pavement sealants, though this has not been directly assessed in street dust to date (Van Metre et al. 2009; Mahler et al. 2010).

Lau and Stenstrom (2005) found that heavier molecular weight PAHs, such as chrysene and benz[a]anthracene, increased as particle size decreased, with concentrations as much as 10 times more in the <43 μm range than the 250–841 μm range in commercial and residential areas. This is consistent with findings reported elsewhere (Krein and Schorer 2000; Yang et al. 1997; Zhao et al. 2009b). However, no such trend was found in lower molecular weight PAHs such as biphenyl and acenaphthene (Krein and Schorer 2000; Lau and Stenstrom 2005).

Florida street sweepings were tested for 74 volatile organic compounds (VOCs) and 116 semi-volatile organic compounds (SVOCs) (Jang et al. 2009). Five VOCs were detected including: n-butyl benzene, isopropyl benzene, isopropyl toluene, 1,3,5-trimethylebenezne, and o-xylene in some samples. PAHs were also detected in a small number of the 169 samples analyzed (Jang et al. 2009). Some of the samples contained two base–neutral phthalate compounds, bis(2-ethylhexyl) phthalate and di-n-butyl phthalate, which are phthalic acid esters (PAE). The source of phthalates in street dust is likely discarded plastic materials (Jang et al. 2009).

USGS (2005) detected 27 out of 30 PAH analytes in street dust, with concentrations increasing with decreasing particle size. Four PAH concentrations were measured above their exposure-based guidelines of 0.7 mg/kg (MDEP 1996; method 2, soil category S-1), including benzo[*a*]anthracene and indeno[1,2,3-*cd*] pyrene concentrations (<63 μm) (Table 4). Benzo[*a*]pyrene concentrations also exceeded these guidelines in the 63–125 μm size range. Benzo[*b*]fluoranthene concentrations exceeded exposure-based guidelines by 1.2, 1.8, and 2.7 times, in the <63 μm, 63–125 μm, and 125–250 μm particle size ranges respectively.

Pesticides have also been detected in street dust. Low concentrations of DDT (25.1–461 mg/kg) were detected in 18 % of street sweeping samples in Florida, though it has not been in use for almost 40 years. In the same study, endosulfan II

Table 4 A summary of organic contaminant levels detected in street dust samples

Analyte	Concentration (ppm)	Particle fraction	Geographic location	Street type	Citation
Acenaphthene					
	0.033	<63 μm	Xincheng	Various	Zhao et al. (2009b)
	0.033	<63 μm	Xincheng	Various	Zhao et al. (2008)
	0.03	63–125 μm	Xincheng	Various	Zhao et al. (2008)
	0.029	125–250 μm	Xincheng	Various	Zhao et al. (2008)
	0.017	250–900 μm	Xincheng	Various	Zhao et al. (2008)
	0.033	<63 μm	New Bedford	Residential	USGS (2005)
	0.052	63–125 μm	New Bedford	Residential	USGS (2005)
	0.031	125–250 μm	New Bedford	Residential	USGS (2005)
	0.025	250–2,000 μm	New Bedford	Residential	USGS (2005)
Acenaphthylene					
	0.086	<63 μm	Xincheng	Various	Zhao et al. (2009b)
	0.086	<63 μm	Xincheng	Various	Zhao et al. (2008)
	0.083	63–125 μm	Xincheng	Various	Zhao et al. (2008)
	0.072	125–250 μm	Xincheng	Various	Zhao et al. (2008)
	0.043	250–900 μm	Xincheng	Various	Zhao et al. (2008)
	0.19	<63 μm	New Bedford	Residential	USGS (2005)
	0.076	63–125 μm	New Bedford	Residential	USGS (2005)
	0.045	125–250 μm	New Bedford	Residential	USGS (2005)
	0.037	250–2,000 μm	New Bedford	Residential	USGS (2005)
Anthracene					
	ND–680	<500 μm	Bordeaux	Bridges and highway	Durand et al. (2003)
	0.168	<63 μm	Xincheng	Various	Zhao et al. (2009b)
	0.168	<63 μm	Xincheng	Various	Zhao et al. (2008)
	0.172	63–125 μm	Xincheng	Various	Zhao et al. (2008)
	0.161	125–250 μm	Xincheng	Various	Zhao et al. (2008)
	0.113	250–900 μm	Xincheng	Various	Zhao et al. (2008)
	0.31	<63 μm	New Bedford	Residential	USGS (2005)

0.2	63–125 µm	New Bedford	Residential	USGS (2005)
0.12	125–250 µm	New Bedford	Residential	USGS (2005)
0.084	250–2,000 µm	New Bedford	Residential	USGS (2005)
Benzo(a)anthracene				
ND–1,500	<500 µm	Bordeaux	Bridges and highway	Durand et al. (2003)
0.015	Raw sweepings (<4.75 mm)	Florida	Various municipal	Jang et al. (2009)
0.364	<63 µm	Xincheng	Various	Zhao et al. (2009b)
0.364	<63 µm	Xincheng	Various	Zhao et al. (2009b)
0.283	63–125 µm	Xincheng	Various	Zhao et al. (2009b)
0.218	125–250 µm	Xincheng	Various	Zhao et al. (2009b)
0.167	250–900 µm	Xincheng	Various	Zhao et al. (2009b)
1.02	<63 µm	New Bedford	Residential	USGS (2005)
0.69	63–125 µm	New Bedford	Residential	USGS (2005)
0.45	125–250 µm	New Bedford	Residential	USGS (2005)
0.22	250–2,000 µm	New Bedford	Residential	USGS (2005)
Benzo(a)pyrene				
0.009	Raw sweepings (<4.75 mm)	Florida	Various municipal	Jang et al. (2009)
0.537	<63 µm	Xincheng	Various	Zhao et al. (2009b)
0.537	<63 µm	Xincheng	Various	Zhao et al. (2009b)
0.37	63–125 µm	Xincheng	Various	Zhao et al. (2009b)
0.246	125–250 µm	Xincheng	Various	Zhao et al. (2009b)
0.157	250–900 µm	Xincheng	Various	Zhao et al. (2009b)
1.4	<63 µm	New Bedford	Residential	USGS (2005)
0.96	63–125 µm	New Bedford	Residential	USGS (2005)
0.58	125–250 µm	New Bedford	Residential	USGS (2005)
0.25	250–2,000 µm	New Bedford	Residential	USGS (2005)
Benzo(e)pyrene				
1.4	<63 µm	New Bedford	Residential	USGS (2005)
0.76	63–125 µm	New Bedford	Residential	USGS (2005)
0.49	125–250 µm	New Bedford	Residential	USGS (2005)
0.22	250–2,000 µm	New Bedford	Residential	USGS (2005)

(continued)

Table 4 (continued)

Analyte	Concentration (ppm)	Particle fraction	Geographic location	Street type	Citation
Benzo(b)fluoranthene					
	ND–360	<500 μm	Bordeaux	Bridges and highway	Durand et al. (2003)
	0.0132	Raw sweepings (<4.75 mm)	Florida	Various municipal	Jang et al. (2009)
	0.917	<63 μm	Xincheng	Various	Zhao et al. (2009b)
	0.917	<63 μm	Xincheng	Various	Zhao et al. (2008)
	0.736	63–125 μm	Xincheng	Various	Zhao et al. (2008)
	0.531	125–250 μm	Xincheng	Various	Zhao et al. (2008)
	0.224	250–900 μm	Xincheng	Various	Zhao et al. (2008)
	1.87	<63 μm	New Bedford	Residential	USGS (2005)
	0.25	63–125 μm	New Bedford	Residential	USGS (2005)
	0.84	125–250 μm	New Bedford	Residential	USGS (2005)
	0.33	250–2,000 μm	New Bedford	Residential	USGS (2005)
Benzo(g,h,i)perylene					
	0.0076	Raw sweepings (<4.75 mm)	Florida	Various municipal	Jang et al. (2009)
	0.491	<63 μm	Xincheng	Various	Zhao et al. (2009b)
	0.491	<63 μm	Xincheng	Various	Zhao et al. (2008)
	0.377	63–125 μm	Xincheng	Various	Zhao et al. (2008)
	0.288	125–250 μm	Xincheng	Various	Zhao et al. (2008)
	0.164	250–900 μm	Xincheng	Various	Zhao et al. (2008)
	1.23	<63 μm	New Bedford	Residential	USGS (2005)
	0.716	63–125 μm	New Bedford	Residential	USGS (2005)
	0.39	125–250 μm	New Bedford	Residential	USGS (2005)
	0.13	250–2,000 μm	New Bedford	Residential	USGS (2005)
Benzo(k)fluoranthene					
	0.315	<63 μm	Xincheng	Various	Zhao et al. (2009b)
	0.315	<63 μm	Xincheng	Various	Zhao et al. (2008)
	0.227	63–125 μm	Xincheng	Various	Zhao et al. (2008)
	0.124	125–250 μm	Xincheng	Various	Zhao et al. (2008)
	0.076	250–900 μm	Xincheng	Various	Zhao et al. (2008)
	1.7	<63 μm	New Bedford	Residential	USGS (2005)

1.08	63–125 μm	New Bedford	Residential	USGS (2005)
0.72	125–250 μm	New Bedford	Residential	USGS (2005)
0.26	250–2,000 μm	New Bedford	Residential	USGS (2005)
Chrysene				
ND–600	<500 μm	Bordeaux	Bridges and highway	Durand et al. (2003)
0.613	<63 μm	Xincheng	Various	Zhao et al. (2009b)
0.613	<63 μm	Xincheng	Various	Zhao et al. (2008)
0.467	63–125 μm	Xincheng	Various	Zhao et al. (2008)
0.366	125–250 μm	Xincheng	Various	Zhao et al. (2008)
0.195	250–900 μm	Xincheng	Various	Zhao et al. (2008)
1.91	<63 μm	New Bedford	Residential	USGS (2005)
1.25	63–125 μm	New Bedford	Residential	USGS (2005)
0.77	125–250 μm	New Bedford	Residential	USGS (2005)
0.36	250–2,000 μm	New Bedford	Residential	USGS (2005)
Dibenz(*a*,*h*)anthracene				
0.436	<63 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2009b)
0.436	<63 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
0.208	63–125 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
0.176	125–250 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
0.18	250–900 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
0.33	<63 μm	New Bedford, MA, USA	Residential	USGS (2005)
0.13	63–125 μm	New Bedford, MA, USA	Residential	USGS (2005)
0.12	125–250 μm	New Bedford, MA, USA	Residential	USGS (2005)
0.054	250–2,000 μm	New Bedford, MA, USA	Residential	USGS (2005)
Fluoranthene				
ND–1,400	<500 μm	Bordeaux, France	Bridges and highway	Durand et al. (2003)
2.3	<64 μm	Toronto, Ontario, Canada	Industrial	NWRI (2007)
0.8	64–2,000 μm	Toronto, Ontario, Canada	Industrial	NWRI (2007)
0.0054–0.0334	raw sweepings (<4.75 mm)	Florida, United States	Various municipal	Jang et al. (2009)
0.925	<63 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2009b)
0.925	<63 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
0.698	63–125 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)

(continued)

Table 4 (continued)

Analyte	Concentration (ppm)	Particle fraction	Geographic location	Street type	Citation
	0.54	125–250 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.353	250–900 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	2.96	<63 μm	New Bedford, MA, USA	Residential	USGS (2005)
	2.55	63–125 μm	New Bedford, MA, USA	Residential	USGS (2005)
	1.75	125–250 μm	New Bedford, MA, USA	Residential	USGS (2005)
	0.71	250–2,000 μm	New Bedford, MA, USA	Residential	USGS (2005)
Fluorene					
	0.158	<63 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2009b)
	0.158	<63 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.139	63–125 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.123	125–250 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.073	250–900 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
Indeno(1,2,3-cd)pyrene					
	0.229	<63 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2009b)
	0.229	<63 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.16	63–125 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.142	125–250 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.065	250–900 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	1.33	<63 μm	New Bedford, MA, USA	Residential	USGS (2005)
	0.44	63–125 μm	New Bedford, MA, USA	Residential	USGS (2005)
	0.48	125–250 μm	New Bedford, MA, USA	Residential	USGS (2005)
	0.18	250–2,000 μm	New Bedford, MA, USA	Residential	USGS (2005)
Naphthalene					
	ND–480	<500 μm	Bordeaux, France	Bridges and highway	Durand et al. (2003)
	0.322	<63 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2009b)
	0.322	<63 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.365	63–125 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.389	125–250 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.223	250–900 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
		<63 μm	New Bedford, MA, USA	Residential	USGS (2005)
	0.03	63–125 μm	New Bedford, MA, USA	Residential	USGS (2005)

	0.015	125–250 μm	New Bedford, MA, USA	Residential	USGS (2005)
	0.013	250–2,000 μm	New Bedford, MA, USA	Residential	USGS (2005)
Phenanthrene					
	ND–990	<500 μm	Bordeaux, France	Bridges and highway	Durand et al. (2003)
	1	<64 μm	Toronto, Ontario, Canada	Industrial	NWRI (2007)
	0.5	64–2,000 μm	Toronto, Ontario, Canada	Industrial	NWRI (2007)
	1.022	<63 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	1.022	<63 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	1.035	63–125 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.858	125–250 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.587	250–900 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	1,200	<63 μm	New Bedford, MA, USA	Residential	USGS (2005)
	785	63–125 μm	New Bedford, MA, USA	Residential	USGS (2005)
	412	125–250 μm	New Bedford, MA, USA	Residential	USGS (2005)
	267	250–2,000 μm	New Bedford, MA, USA	Residential	USGS (2005)
Pyrene					
	ND–2,600	<500 μm	Bordeaux, France	Bridges and highway	Durand et al. (2003)
	1.9	<64 μm	Toronto, Ontario, Canada	Industrial	NWRI (2007)
	0.7	64–2,000 μm	Toronto, Ontario, Canada	Industrial	NWRI (2007)
	0.645	<63 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.645	<63 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.483	63–125 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.395	125–250 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	0.271	250–900 μm	Xincheng, Zhejiang, China	Various	Zhao et al. (2008)
	2,300	<63 μm	New Bedford, MA, USA	Residential	USGS (2005)
	1,950	63–125 μm	New Bedford, MA, USA	Residential	USGS (2005)
	1,150	125–250 μm	New Bedford, MA, USA	Residential	USGS (2005)
	550	250–2,000 μm	New Bedford, MA, USA	Residential	USGS (2005)
Bis(2-ethylhexyl)phthalate					
	0.0054–0.0149	Raw sweepings (<4.75 mm)	Florida, United States	Various municipal	Jang et al. (2009)
Di-n-butyl phthalate					
	0.0055–0.0157	Raw sweepings (<4.75 mm)	Florida, United States	Various municipal	Jang et al. (2009)

(continued)

Table 4 (continued)

Analyte	Concentration (ppm)	Particle fraction	Geographic location	Street type	Citation
Di-n-octyl phthalate					
	0.0054–0.0149	Raw sweepings (<4.75 mm)	Florida, United States	Various municipal	Jang et al. (2009)
DDD					
	0.0287–0.111	Raw sweepings (<4.75 mm)	Florida, United States	Various municipal	Jang et al. (2009)
DDE					
	0.0289–0.0494	Raw sweepings (<4.75 mm)	Florida, United States	Various municipal	Jang et al. (2009)
DDT					
	0.0251–0.461	Raw sweepings (<4.75 mm)	Florida, United States	Various municipal	Jang et al. (2009)
Alpha-BHC					
	0.05	Raw sweepings (<4.75 mm)	Florida, United States	Various municipal	Jang et al. (2009)
Beta-BHC					
	0.0281–0.0326	Raw sweepings (<4.75 mm)	Florida, United States	Various municipal	Jang et al. (2009)
Alpha-chlordane					
	0.0426–0.127	Raw sweepings (<4.75 mm)	Florida, United States	Various municipal	Jang et al. (2009)
Gamma-chlordane					
	0.0264–0.0489	Raw sweepings (<4.75 mm)	Florida, United States	Various municipal	Jang et al. (2009)
Dieldrin					
	0.0338–0.235	Raw sweepings (<4.75 mm)	Florida, United States	Various municipal	Jang et al. (2009)
Endosulfan II					
	0.039–2.410	Raw sweepings (<4.75 mm)	Florida, United States	Various municipal	Jang et al. (2009)
Endrin					
	0.0732–0.0787	Raw sweepings (<4.75 mm)	Florida, United States	Various municipal	Jang et al. (2009)

was also detected in 18 % of samples at concentrations ranging from 39 to 2,410 mg/kg (Jang et al. 2009).

4.4 Nutrients

Nitrogen and phosphorus are also contaminants of particular importance in street dust (Table 5). Urban nonpoint sources of nutrients include fertilizers in runoff from lawns, pet wastes, failing septic systems, maintenance/traction, and atmospheric deposition from industry and automobile emissions (USEPA 2005). Fertilizers may be released either slowly or rapidly, depending on how they are formulated. Rapid

Table 5 A summary of nutrient levels detected in street dust samples

Nutrients	Concentration (ppm)	Geographic location	Sample	Citation
Total Kjeldahl Nitrogen	2,400	Toronto, ON, Canada	North Bound Unswept Street 2004	NWRI (2007)
	1,055	Toronto, ON, Canada	South Bound Unswept Street 2004	NWRI (2007)
	1,133	Toronto, ON, Canada	North Bound Unswept Street 2005	NWRI (2007)
	937	Toronto, ON, Canada	South Bound Unswept Street 2005	NWRI (2007)
Total Nitrogen	1,999	Florida, USA	Highway–Commercial	Berretta et al. (2011)
	3587.7	Florida, USA	Highway–Residential	Berretta et al. (2011)
	2342.4	Florida, USA	Highway–Highway	Berretta et al. (2011)
Total Phosphorus	346–1,375	Bordeaux, France	Bridges and highway	Durand et al. (2003)
	1,333	Toronto, ON, Canada	North Bound Unswept Street 2004	NWRI (2007)
	1,185	Toronto, ON, Canada	South Bound Unswept Street 2004	NWRI (2007)
	1,313	Toronto, ON, Canada	North Bound Unswept Street 2005	NWRI (2007)
	1,335	Toronto, ON, Canada	South Bound Unswept Street 2005	NWRI (2007)
	474.6	Florida, USA	Highway–Commercial	Berretta et al. (2011)
	702.8	Florida, USA	Highway–Residential	Berretta et al. (2011)
	759.4	Florida, USA	Highway—Highway	Berretta et al. (2011)

Total Kjeldahl Nitrogen is the sum of organic nitrogen, ammoia (NH_3, and ammonium (NH_4^+)
Total Nitrogen is the sum of nitrate−N and nitrite−N and TKN

release fertilizers are of greater concern, because they are readily soluble and are easily transported into storm sewers (Brinkmann and Tobin 2001). The National Research Institute in Canada conducted a street cleaning study and found that nutrients were preferentially associated with finer street dust particles by nearly twofold on average; this observation indicates that such particles would much more likely be transported by even small amounts of stormwater runoff (NWRI 2007).

During a rainfall event, nutrients from these sources can make their way to streets in surface runoff, which in turn flows to storm sewers, and then enters aquatic receiving system where it may impair surface water quality (USEPA 2005c). Moderately high concentrations of nutrients, for example, may produce eutrophication of sensitive receiving waters, which include lakes where phosphorus is a limiting nutrient, or coastal or estuarine areas where nitrogen is limiting. A study conducted by the USEPA noted that lawns are a large source of dissolved phosphorus in some regions (USGS 2003). Fish kills can result from hypoxia and anoxia due to extreme eutrophication (USEPA 2005c). In the Gulf of Mexico, areas of chronic hypoxia have apparently resulted from increased nitrogen loads from the Mississippi River system, beginning in the 1950s (Rabalais et al. 2007). Monitoring data suggest that urban sources of nitrate are not high enough to pose a direct risk to humans, but excessive nutrient levels in receiving waters can exceed the drinking water criterion (10 mg/L for nitrate-nitrogen) (USEPA 2005c).

In a study to determine the magnitude of nutrient runoff from near shore residential lawns surrounding Lauderdale Lakes in Wisconsin, fertilizer use did not affect nitrogen concentrations in runoff (USGS 2002). However, total phosphorus concentrations in lawn runoff was directly related to phosphorus concentration of lawn soils, and test sites that used fertilizer regularly had dissolved phosphorus concentrations that were twice that from test sites that used non-phosphorus fertilizer or that did not use fertilizer (USGS 2002). This result is consistent with previous studies conducted by USGS (USGS 2003).

A study in Melbourne, Australia showed that as much as 50 % of the nutrients in street solids are associated with street dust particles smaller than 300 μm, suggesting that treatment facilities, (e.g., ponds, wetlands, and sediment basins) would remove the finer particles (down to 50 μm for total phosphorus and down to 10 μm for total nitrogen), and not just the total sediment or suspended solid load (Vaze and Chiew 2002).

5 Relevance of Street Cleaning Technologies to Ecological and Human Health Risk

5.1 Ecological Risk

More than 150 years of technological development has been invested in street cleaning as a Best Management Practices (BMP) for improving water and air quality. Few quantitative studies relative to street cleaning exist that have compared relative risks to human health or ecological risk. These gaps were highlighted in a review of 44 reports on the biological effects of highway runoff on local ecosystems (Buckler and Granato 1999). The authors cited a lack of consistency of methods and sufficient documentation for studies performed on this topic. Most studies that modeled contaminant concentrations in highway runoff predicted low acute toxicity. However, other investigations have indicated that highway runoff can impart contaminant loads to soils and sediments that affect ecosystems near discharge points (Lau et al. 2009; Lee et al. 2011; Meland et al. 2010). For example, analysis of aquatic biota revealed bioaccumulation of metals from highway runoff (Buckler and Granato 1999). One study, in which a regenerative air sweeper, a mechanical sweeper and a high efficiency regenerative air sweeper were compared, examined whether artificially generated runoff (simulated rain on a street) resulted in differential aquatic toxicity to rainbow trout and *Daphnia magna*. After exposure to simulated runoff, *D. magna* suffered less than a 50 % mortality (i.e., LC_{50}). Sweeping with the high efficiency regenerative air sweeper prior to simulating runoff resulted in reduced toxicity, but similar reductions were not observed after using the mechanical and older regenerative air sweepers (NWRI 2007).

Zhao et al. (2009a, b) conducted a risk assessment of PAHs in street dust that contributed to water quality degradation in China through surface runoff, and reported several measurements above the effects range low (ERL) and effects range median (ERM) values. Such levels respectively pose a moderate and severe impact on biota. The highest concentrations of PAHs were observed in the smallest size classes (<63 μm and 63–125 μm), and thus it is not surprising that total PAH concentrations rise as much as 43–62 % during significant rainfall events from mobilization of these smaller particles (Long et al. 1995; Zhao et al. 2009a, b).

In a study of stormwater runoff from a parking lot that received coal tar sealant nine months earlier, total PAH concentrations exceeded the National Oceanic Atmospheric Administration's (NOAA) ERM of 44.7 mg/kg, by almost twofold, compared to <5 mg/kg near non-sealed surfaces. Concentrations remained elevated three years after the initial application. PAH concentrations in dust samples on coal-tar sealed surfaces were as high as 1,192 mg/kg, compared to <2 mg/kg on non sealed surfaces (Watts et al. 2010a, b).

A risk assessment of runoff-related input of five heavy metals in several tributaries of the Yangtze River delta was also conducted and was published in a separate paper (Zhao et al. 2009a). Each of the metals (viz., chromium, copper, nickel, lead, zinc) were detected at concentrations above "severe effect screening levels" (SEL) within multiple size range categories in street dust and suspended solids in runoff during two rain events (NYSDEC 1999; Zhao et al. 2009a).

5.2 Human Health Risk

Re-entrainment of street dust is a major source of urban $PM_{2.5}$ and PM_{10}, which have significant impacts on human health (Amato et al. 2010a, b). An association between ambient levels of PM and mortality has been observed in numerous studies (Brunekreef and Forsberg 2005; Ruckerl et al. 2011). Recently, street sweeping has been explored as a potential method for reducing ambient PM levels, with researchers reporting mixed evidence on effectiveness (Amato et al. 2010b; Gertler et al. 2006; Keuken et al. 2010). A study conducted in Nevada showed increased aerial re-entrainment of street dust when "brush and water wash street sweepers" were used (Gertler et al. 2006). Another study conducted in the Netherlands using similar technology indicated that sweeping did not reduce non-exhaust PM emissions (Keuken et al. 2010). However, a trial conducted using a vacuum-assisted mechanical sweeper did show a small but significant reduction in ambient PM (Amato et al. 2010b). Using water for PM suppression in each of these trials may reduce one risk (human health through improved air quality) and potentially increase another (environmental through decreased water quality). The comprehensive comparison of the available technologies on reduction of PM was conducted under the City of Toronto's Clean Roads to Clean Air initiative. The results of several studies indicated that regenerative air sweepers were most effective at reducing re-entrainment of PM (Morgan and Stevanovic-Briatico 2007).

In addition to the potential effects imposed by PM, street dust presents other hazards to human health. For example, in East China, PAHs from stormwater runoff have contaminated a potential drinking water supply (Chen et al. 2007). One hazard analysis indicated that oral ingestion of more than 100 mg/day of street dust that retained PAH concentrations could pose an unacceptable risk to human health, although ingestion of this much street dust seems unlikely (Lorenzi et al. 2011).

6 Research Needs and Conclusions

There are several variables that affect street cleaning efficiency that are essential if valid comparisons are to be made among studies. In this regard, the currently available database makes robust comparisons difficult, because the reporting of variables or test conditions in street-cleaning technology studies has been inadequate. In addition to a dearth of studies and data on the entire subject, shortfalls in addressing the following variables also exists: regional climate and soil types, street cleaning frequency, road surface type and conditions, nearby land use, and variations in technology types amongst street sweeper manufacturers. Several authors have commented on the lack of available comparative data on the effectiveness of street cleaning (Amato et al. 2010a; Kang et al. 2009; USGS 2005, 2007; Sutherland 2011). A primary objective of this paper was to provide a novel, and critical review of the efficacy of various street cleaning technologies and practices for managing environmental risks associated with stormwater and air quality. Forty-nine articles that addressed street cleaning have been examined (Table 1). Only nine recent studies reviewed herein incorporated a comparison of different types of technologies. Of these nine papers, six are empirical studies, and three are reviews that were based on computer modeling outputs. In addition, none of these studies were peer-reviewed for journal publication, and seven are government reports.

Our overall conclusions are:

1. Street dust contains significant concentrations of organic and inorganic contaminants that have the potential to negatively impact human and ecological health.

   We also reviewed the literature to quantify various constituents on street surfaces including metals, organic contaminants, and nutrients. Street cleaning in relation to environmental risk or human health has been evaluated in only a few studies (NWRI 2007; Zhao et al. 2008, 2009a, b). In several studies, concentrations of PAHs and metals in street dust, suspended solids in runoff, and bulk sediment were observed to exceed toxicity values, indicating a potential for risk to human health and the environment (Zhao et al. 2008, 2009a, b). In contrast, one set of direct tests of street dust on *Daphnia* and in an *in vitro* assay system indicated low or no toxicity (NWRI 2007). Clearly, this area deserved additional attention given the goals for stormwater management. In the context of human health, several studies noted reductions of ambient particulate matter following street cleaning, although these reductions may have been short-lived (Amato et al. 2009, 2010a, b; Chou et al. 2007; DeLuca et al. 2012; Gertler et al. 2006). In two cases, potential risks to human health were linked to soil cleanup levels (Jang et al. 2009) or estimates of high ingestion (Lorenzi et al. 2011). However, none of the available studies characterized margins of safety and/or the relative risk to human health and the environment among the available technologies and strategies for street cleaning.
2. Several types of street sweeper are available to manage street dust, including mechanical, vacuum, and regenerative air. Based on the available literature, regenerative air sweepers appear to be most effective at collecting the smallest particles and preventing re-entrainment of particulate matter.

   In this review, we examined the available literature and compared the efficacy of various street cleaning technologies. The available literature suggests that vacuum and regenerative air sweepers are more efficient at picking up smaller particles and may be better at controlling ambient PM than mechanical sweepers (NWRI 2007; USGS 2005, 2007). Generally, studies, in which sweeper technologies were compared appeared to point to regenerative air as being the superior sweeper technology; however, the variability within tests renders this initial assessment inconclusive (Sutherland 2011; TYMCO 2012b; Weston Solutions, Inc. 2010).
3. Too few data are available to make robust conclusions about what constitutes the optimal technology or practices for street cleaning as best management practice for stormwater runoff or prevention of re-entrainment of particulate matter.

   The available studies in which street sweeping technologies were compared did not follow uniform protocols, and at times were ambiguous about the nature of the equipment being tested. Customization of some of the sweepers (e.g., adjusting the proximity of the gutter brooms to the pickup head on a regenerative air unit) can affect sweeping effectiveness; unfortunately, the details of these modifications were rarely specified nor their impacts quantitatively investigated. Furthermore, most studies focused on either re-entrainment of PM or efficiency of collection from the surface, but seldom both. At present, the most comprehensive study appears to have been conducted by the City of Toronto, under their 2003 initiative "Clean Roads to Clean Air" (ETV 2011, 2012a, b, c). However, even this comprehensive testing program had its shortcomings; it was conducted in a closed environment using simulated street dust. The inherent problem with studies using a simulated test material in a controlled environment is that they usually cannot emulate real world conditions (viz., anthropogenic trash and organic debris, potholes and cracks in streets, uneven distribution across street surfaces, wet vs. dry weather conditions, flat vs. crowned streets, traffic conditions, and impervious vs. pervious pavement). Conversely, "real-world" studies must contend with the problem of numerous variables (e.g., amount of material available to pick up, wind, geographic location, weather, climate, and traffic), which serve as confounders and render defensible conclusions impossible.

Operator error, testing different sweepers at different speeds, times of the year, or places may also affect street cleaning test results (NWRI 2007). Some studies have noted improvements in stormwater quality from changes in street sweeper technology and management practices, but did not evaluate changes in street sweeper technology and management practices separately (DeLuca et al. 2012; Talend 2012). Other researchers have attempted to combine results from disparate studies in an effort to compare technology efficacy, but the many variables listed above give ample opportunities for confounding results (Sutherland and Jelen 1997; Zarriello et al. 2002). At present, the authors believe that the City of Toronto evaluation of street sweeping technologies should serve as a reasonable model for future research.

4. No standardized protocol for assessing the effectiveness of street cleaning presently exists.

   It is not feasible for a single study to assess the importance of every parameter that may impact the efficiency of street dust management. The wide variation in experimental test protocols used to date prevented any rigorous assessment of comparative efficiency of the available street sweepers. Thus, we recommend establishing a standard methodology for assessing the comparative efficiency and efficacy of street cleaning technologies based on proven test protocols, establishing national standards for air and water quality though street cleaning mitigation, and establishing margins of safety for stormwater hazards and human health under multiple street cleaning strategies and technologies.

We recommend the following experimental parameters and goals for establishing a framework for evaluating street cleaning technology (Fig. 4):

1. Study environment
   (a) Ambient air quality in an enclosed area similar to the study conducted by the City of Toronto.

  (b) Various street surface conditions
      1. Smooth and rough pavement
      2. Damaged and undamaged pavement
      3. Curbed and non-curbed pavement
      4. Crowned and non-crowned surface
      5. Porous and non-porous pavement
  (c) Evaluate street cleaning technologies under various weather conditions
      1. Seasonality, particularly in drought susceptible regions and those experiencing extended winters
      2. Before and after precipitation events
      3. Cold, warm, and hot climates

2. Street dust material for testing
   (a) Simulant material such as that used in the City of Toronto study
   (b) Pure sand, silt, clay, and gravel at various moisture levels and comprising a range of particle size distributions
   (c) Collected street sweeping materials from various regions, including dirt, leaves, sticks, garbage, grass clippings, anthropogenic trash, and bulky material.
3. Street sweeping technologies, customization, and operational parameters
   (a) The effectiveness of water for dust suppression vs. flushing: efficacy and required output
   (b) Indirect environmental impacts: fuel usage and exhaust emissions per ton of material removed
   (c) Operational parameters: speed and frequency of cleaning, single vs. multiple passes, maintenance requirements, fan and broom speed and adjustment
   (d) Tandem operations

7 Summary

Street dust represents a source of dual potential risk to stormwater and air quality. It has been well documented that street dust washes into local watersheds and can degrade water quality. Research has also demonstrated that ambient particulate matter (PM_{10}), which is associated with adverse health outcomes, can arise from resuspension of accumulated street dust. Furthermore, many contaminants, including metals, are present at higher concentrations in the smallest available particles, which are more likely to be resuspended in air and stormwater runoff. Although street cleaning is listed as a best management practice for stormwater quality by the EPA, data are limited on the critical parameters (technology, environment, usage), which determine the effectiveness of any street cleaning program, particularly in the peer-reviewed literature. The purpose of the present study was to develop a comprehensive understanding of the efficacy of various street cleaning technologies and practices to protect both water quality and public health. Few studies have compared the effectiveness of street sweeping technologies to remove street dust. Unfortunately, the dearth of comprehensive data on exposure, contaminant concentrations, and efficacy of various sweeping technologies and strategies precludes developing quantitative estimates for potential risk to humans and the environment. Based on the few studies available, regenerative air street sweepers appear to provide the most benefit with regard to collection of small particles and prevention of re-entrainment. It is also clear from the available data that local conditions, climate, and specific

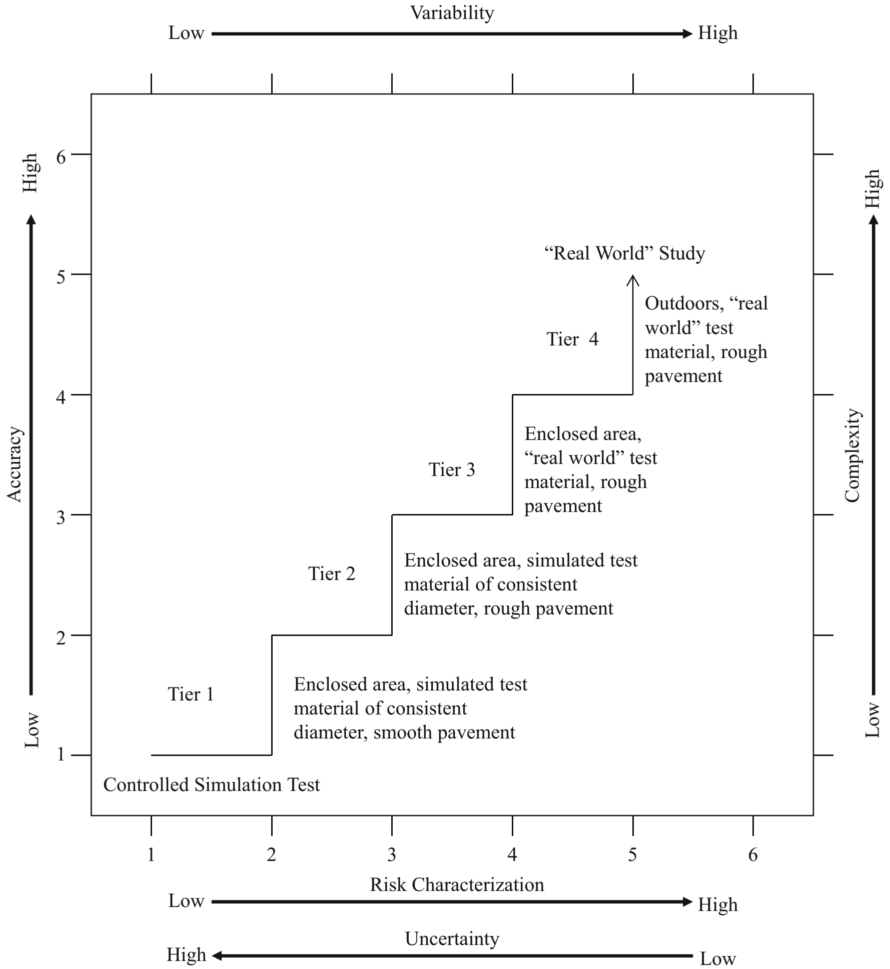


Fig. 4 A tiered risk assessment approach for evaluating efficacy of street sweeping

needs are critical determinants of the ideal street sweeping strategy (technology, frequency, speed, targeted areas, etc.). Given the critical need for protection of water and air quality in rapidly expanding urban regions (e.g., megacities), further research is necessary to develop best practices for street dust management. Herein, we provide a framework for future experimental studies to support risk-based assessments of street cleaning technologies (Fig. 4).

Acknowledgments This research was supported by an unrestricted grant from Tymco Inc to BWB, and the Department of Environmental Science at Baylor University. We thank Dr. Richard Brain for earlier discussions related to the design of Fig. 4.

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