Street sweeping: an effective non-structural Best Management Practice (BMP) for improving stormwater quality in Nelson?

Prepared for Nelson City Council

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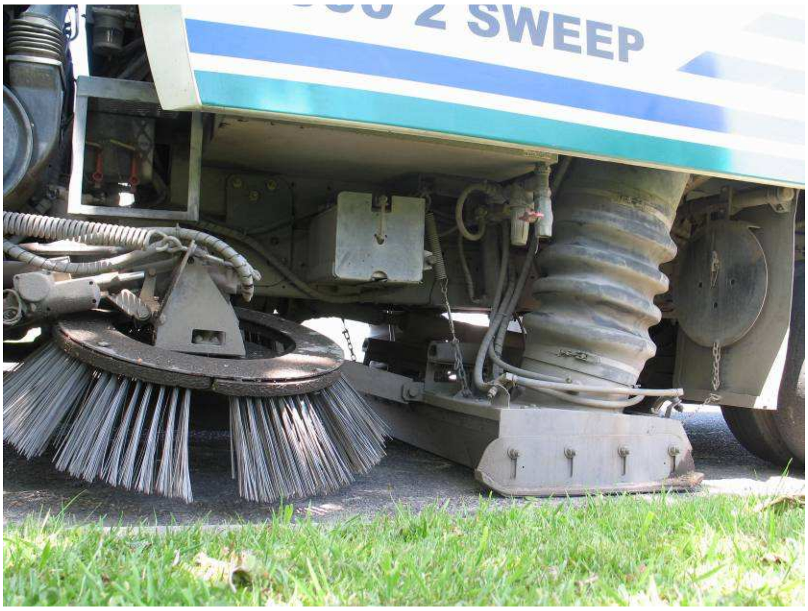

Version

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Photo credit from cover: regenerative air sweeper [C. Depree, NIWA]

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1. Executive summary

Nelson City Council (NCC) undertakes a wide range of environmental monitoring of surrounding surface water bodies. This monitoring has identified that stormwater discharges to some of these water bodies, including the Maitai River, are having detrimental effects on water and sediment quality. As part of ongoing efforts to mitigate the effects of stormwater on receiving environments, NCC is faced with the difficult challenge of reducing suspended sediment, and associated contaminants, in urban runoff from established catchments that offer limited scope for retrofitting conventional structural best management practices (BMPs).

This is a common problem around the world, especially in the U.S. where the Environmental Protection Agency's (EPA) Phase II requirements mean many cities are faced with the challenge of reducing stormwater contaminant loads by 40%. To achieve this, street sweeping is increasingly viewed as the most cost-effective management option. When street sweeping operations focus on maximising removal of particulate contaminants (i.e., a non-structural BMP), the term 'environmental sweeping' is used to differentiate from conventional cosmetic, or aesthetic, sweeping.

Street or road runoff is generally regarded as an important source of pollutants in catchment runoff, including reticulated stormwater. Typical mass loadings of street particulate material range between 100 and 250 kg per kilometre of curb (curb-km). Three major factors influencing the quantity of street particulates are: 1) local meteorology (i.e., frequency and intensity of storms and wind conditions); 2) use of streets and adjacent areas (e.g., land use, traffic type and volume); and 3) street surface condition (type and age of pavement, gutters and curbs).

Despite claimed pick up efficiencies of >90% by manufacturers (carried out under optimised, non-real world conditions), the reported efficiency of sweepers is typically in the 20-30% range under real world conditions. Under favourable conditions (explained below), it seems realistic to expect a 10-30% reduction in runoff contaminant loads. This may still represent an environmental benefit, given that on a catchment scale the contaminant reductions from street sweeping would combine with other management actions, such as source control and structural stormwater BMPs (e.g., retention ponds, filtration and infiltration devices). That is, street sweeping should be part of an integrated catchment approach in mitigating the potential impacts of stormwater on aquatic receiving environments.

The most important parameter determining the effectiveness of sweeping to reduce stormwater contaminant loads is the time interval between sweeping, relative to the time interval between storms. This is because street pollutant loads accumulate with time until the street is cleaned via sweeping or rainfall wash-off – hence substantial rainfall events between sweeping will result in the majority of the street pollutant mass being entrained in stormwater, as opposed to being removed via sweeping operations. Accordingly, the recommended sweeping interval should be a maximum of two-times the interval between storms, which means street sweeping has greater potential as a BMP in areas where the climate consists of long pronounced dry spells (i.e., long average inter-storm periods).

The total pollutant mass on street surfaces relative to the total mass on other catchment surfaces that are not removable via sweeping (e.g., roof tops, car parks, driveways, and commercial/industrial yards) is another important factor influencing sweeping effectiveness.

Greatest benefits from street sweeping will be for catchments where the street pollutant load makes a large contribution to total catchment runoff load (e.g., for arterial roads and motorways). If streets loads are a minor contributor, then other source controls (e.g., contaminants from various industrial/commercial operations) or conventional structural BMP options should be explored.

In summary, street sweeping as a non-structural BMP may provide measurable improvements (i.e., up to 30%) in stormwater quality. In catchments with limited space for retrofitting conventional structural BMPs, modifying existing 'aesthetic' sweeping programmes to focus on contaminant removal (i.e., environmental sweeping) is considered the most cost-effective option for meeting stormwater improvement targets. Accordingly, it is recommended that NCC implement further studies to explore the potential of environmental sweeping as an effective non-structural stormwater BMP. As a starting point, any such studies should incorporate the following key recommendations:

1. implementing a best practice approach to current structural treatment systems by ensuring regular cleaning of sump traps (6 monthly or annually depending on catchment)
2. identifying catchments with highest potential for sweeping to contribute to contaminant loads
3. determine the required sweeping frequency based on an analysis of Nelson's rainfall pattern, with a focus on having the biggest reduction in contaminants during the summer (dryer) months where sweeping effectiveness is less influenced by street dirt washoff
4. implement an appropriate level of monitoring of the quantity and contaminant characteristics of the street sweeping material collected.

2. Introduction

2.1 Background

Stormwater, and the associated contaminants (including faecal microorganisms, nutrients and suspended solids), have been shown to have detrimental effects to aquatic receiving environments in the Nelson region. State of the Environment reports (Wilkinson, 2007 and earlier reports referenced therein) have shown many of the streams draining the catchments in and around Nelson City to have degraded water quality. Sediment monitoring has indicated elevated concentrations (relative to ANZECC guidelines) of heavy metals in the Jenkins (zinc and lead) and York (lead) streams, and both polycyclic aromatic hydrocarbons (PAHs) and heavy metals (copper and lead) in the lower reaches of the Maitai River (Bailey and Conwell, 2010 and earlier reports referenced therein).

Because of its high recreational/social value, there is concern about the impacts of stormwater discharges on the Maitai River. Sediment contaminant concentrations in the lower reach of the Maitai River are reportedly high enough to cause adverse ecological effects (Crowe et al. 2004). As part of continuing efforts to mitigate the potential impacts of stormwater on aquatic receiving environments, P. Sheldon and P. Ruffell from Nelson City Council (NCC) approached NIWA to look at feasible options to improve stormwater quality in the largely commercial subcatchments discharging into the Maitai River. Because of the limitations of retrofitting additional stormwater treatment devices (SWTDs) in commercial subcatchments (i.e., lack of space), the focus of this report was on the effectiveness of street sweeping as a best management practice (BMP) for improving the quality of stormwater discharged to the Maitai River. Improved sweeper technology allowing efficient collection of fine particulates, combined with need for cost effective BMPs (driven by new EPA regulations in the U.S. that require significant reductions in stormwater contaminants) in developed catchments has seen renewed interest in sweeping as means to reduce contaminant loads in urban runoff (Selbig and Bannerman, 2007; DiBlasi, 2008; Horwatich and Bannerman, 2009).

One of the benefits of street sweeping is that all municipalities undertake some type of street sweeping maintenance. With the exception of leaf removal in autumn to prevent drain blockage, sweeping is largely for aesthetic reasons with any benefits from the removal of particulates and associated contaminants being secondary. When street sweeping operations focus on maximising removal of fine particulate contaminants (i.e., a non-structural BMP), the term ‘environmental sweeping’ is used to differentiate this from conventional cosmetic/aesthetic sweeping. Unfortunately at the time of writing this report, no information was available about NCC sweeping operations in the catchments of interest. Accordingly, it was not possible to compare current practice with recommended practice, and estimate what reductions in catchment loads might be expected from an optimised environmental sweeping programme.

2.2 Purpose of the report

The purpose of this report is to provide a literature review of studies relating to sweeper efficiency and the potential for this technology to yield improvements in stormwater quality (i.e., reduced contaminant loads). Then, based on the relative merits/potential of sweeping as a non-structural stormwater BMP, provide recommendations that will advance NCC’s evaluation and potential implementation of an environmental sweeping programme in selected sub-catchments.

Although stormwater contaminants include faecal microorganisms and particle-associated nutrients, this report is limited to suspended sediments and associated chemical contaminants (i.e., heavy metals and hydrocarbons) and their potential removal by sweeping technologies. It is acknowledged that there are other types of structural BMPs that are relevant to well developed urban catchments where space is limited; however these were beyond the scope of this report.

This report does not provide a comprehensive review of stormwater characterisation, stormwater treatment and/or street sweeping technologies, or the effectiveness of sweeping to mitigate contaminant loads in stormwater discharges. This would require inclusion of site-specific data related to the detailed characteristics of the Nelson catchments.

Contaminant concentrations vs loads

Although not critical to this report, which uses the terms ‘loads’ and ‘concentrations’ interchangeably, it is emphasized that for understanding stormwater management issues, it is important to distinguish between concentrations and loads of potentially toxic contaminants in stormwater. This is because contaminant concentrations are relevant to meeting water quality guidelines (concentration-based), while the total loads of contaminants are relevant for meeting sediment quality criteria (load-based).

Thus the stormwater management may include requirements for both meeting water quality guidelines (concentration-based) and sediment quality guidelines (load-based).

3. Street sweepers

3.1 History

Street sweeping, either manual or mechanical, has been carried out hundreds of years. Historically, street sweeping has been used for aesthetic (litter removal) cleaning of streets, as well as for safety reasons, like removing broken glass and other potentially harmful materials from the street. The first motorised sweeper was developed in the late 20^{th} century and today (at least in the U.S.) the mechanical sweeper remains the most commonly used piece of equipment for removing gross pollutants. Gross pollutants are defined as debris greater than 5 mm in size, which includes litter (e.g., cans, glass, plastic), car parts and plant material.

3.2 The evolving role of the sweeper

With growing environmental awareness about the ecotoxic nature and concentration of contaminants in urban stormwaters, together with the potential for adverse effects of aquatic receiving environments, there have been developments of sweeping technologies as a source control measure to improve stormwater quality. While traditional mechanical sweepers efficiently remove gross pollutants, they are relatively ineffective at removing the contaminated fine sand and silt-sized particulates (i.e., <250 *µ*m). However, new sweepers based on regenerative air, or high-efficiency vacuum-assisted systems, provide overall pickup efficiencies as high as 98% (Bannerman, 2000), and very high efficiencies for fine particulates (including <63 *µ*m fraction; Giles, 2009). With improved performance, a growing number of field and modelled studies (Schilling, 2005a; Sutherland and Jelen, 1997; DiBlasi, 2008; Selbig and Bannerman, 2007) are challenging the findings of the comprehensive U.S. nationwide urban runoff programme (NURP, U.S. EPA, 1983), undertaken in the 1980's with older generation mechanical sweepers, which found street sweeping to be an ineffective technique for improving stormwater quality.

Basically, with the ability to efficiently remove the fine contaminated material from streets before it is carried into the stormwater system, street sweeping has the potential to make significant reductions in stormwater contaminant loads, and thus be used as a non-structural BMP to mitigate the effects of stormwater on receiving environments. This is discussed further in Section 4.

3.2.1 Driving force for 'environmental sweeping' in the U.S.

In the U.S. the major driving force behind the interest in street sweeping as a BMP for stormwater management has been the introduction of U.S. Environmental Protection Agency's (EPA) National Pollution Discharge Elimination System (NPDES) Phase II permits. In short, this requires municipalities to file for stormwater permits and implement stormwater management controls that respond to six critical BMP's. Street sweeping (or vacuuming) technologies reportedly offer cost effective ways for municipalities (and hence communities) to meet their Phase II obligations. In the State of Wisconsin, to meet Phase II permit obligations, approximately 200 cities will need to meet new performance standards for established urban areas, which include reducing the annual total suspended solids (TSS) load by 40% (Selbig and Bannerman, 2007).

Although several structural BMPs have been designed to reduce TSS (and associated contaminants), such as wetlands, ponds, infiltration and filtration devices, the implementation of one or more of these structural BMPs in established urban catchments is often limited by available space, and cost of infrastructure installation and maintenance. Sweeping provides an alternative and non-structural BMP to improve the quality of street runoff as it permits the removal of particulates before becoming entrained in runoff. In addition, a distinct benefit of sweeping as a stormwater BMP is that it is already undertaken by all municipalities; hence implementation largely involves modifying an existing sweeping program to optimise stormwater improvement goals. That is, shifting from largely aesthetic-driven sweeping to an environmental sweeping regime where the focus is on reducing contaminant loads in stormwater.

3.3 Sweeper types

The major sweeper manufacturers are Elgin, Tymco, Johnston (United Kingdom) and Schwarze, and to a lesser extent, Tennant and Sweeprite, all of whom produce mechanical broom, regenerative air and vacuum models. Schilling (2005a) has reviewed the various sweeper models available in the U.S. from the above manufactures.

3.3.1 Mechanical broom sweepers

Although probably not that common in New Zealand (author personal observation), mechanical brooms are the most popular type of sweeper used in the U.S (probably related to cost). They generally consist of gutter brooms which sweep the debris rear-ward into the path of a pick-up broom (Figure 1, left). The pick-up broom sweeps the material moving upwards via a conveyor system into the hopper (Figure 1, right). Advantages include low cost, and highly efficient pick-up of gross pollutants. The main disadvantage is their lower efficiencies for picking up fine particulates, which limits effectiveness for reducing contaminant loads in storm water.

Figure 1: Left image, example of mechanical street sweeper (from Wayne Sweepers, LLC website, www.waynesweepers.com); right, a schematic showing conveyer belt system for transferring the pavement sweepings into the hopper (from Elgin website www.elginsweeper.com).

3.3.2 Regenerative air sweepers

The regenerative-air process blows air into one end of a horizontal pick-up head which typically runs approximately width of truck (Figure 2). This is directed onto the pavement, dislodging particulate materials and carrying them to the end of the pick-up head (curb-side). A vacuum hose attached to the pick-up head vacuums up the material into a hopper. For gutter cleaning, they are equipped with a rotating gutter brush that directs debris into the vacuum end of the pick-up head. The main advantage of regenerative air is that it efficiently removes fine particulates from flat surfaces, and they are reportedly the sweeper of choice for flat surfaces with minimal debris, such as airports and car parks (Elgin, 2008).

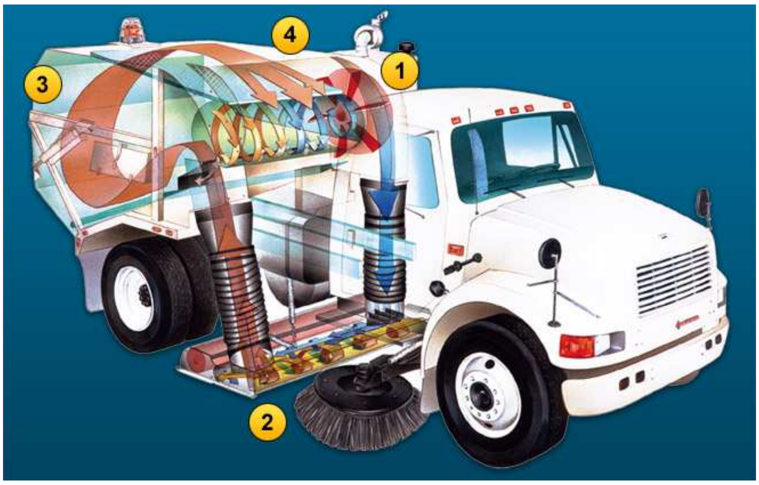

Figure 2: Schematic showing operating principles of regenerative air sweeper (from Tymco website www.tymco.com**).**

The main disadvantages of regenerative air are the relatively high cost, and that they use a gutter broom to clean the curb, and hence they are no more effective than a mechanical sweeper at picking up curb-side fines. Sartor and Boyd (1972) estimated that 70-80% of street debris lies within 150 mm of the curb-side and 90% within 300 mm. Although despite this, the latest regenerative air sweeper from Elgin, the Crosswind (NX), was the best performing sweeper (within Elgin's model range) removing 97.5% of particulate material under the test conditions (Giles, 2009).

3.3.3 Vacuum (high efficiency) sweepers

Pure vacuum sweepers use an impeller (or fan) to create suction and airflow that draws road-deposited sediment (RDS) into a nozzle, which is located just above the pavement surface. The vacuum nozzle sits directly behind the gutter brush and sucks up any particulate material removed by the rotating brush head. Vacuum sweepers are generally regarded as the most efficient way to remove particulate fines off the street surface before they can be conveyed to the stormwater system. In addition they are able to operate in dry mode without producing fine dust emissions, which is important with modern sweepers having to be 'PM10' (particles <10 μm) certified. Disadvantages include high cost, relatively ineffective at removing wet vegetation or large debris, and that the sweeping action of the gutter broom may expose fine silts for easy wash-off into the stormwater system (although this limitation is more pronounced for mechanical and regenerative air sweepers).

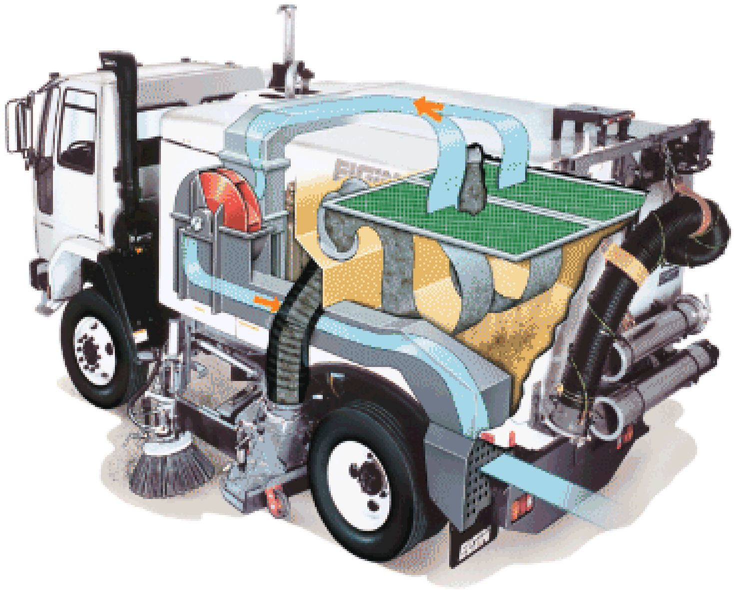

Figure 3: Schematic showing operating principles of vacuum sweeper (from Elgin website www.elginsweeper.com).

3.3.4 Indicative capital and running costs

Sweepers typically cost in the range of ca. $100,000 for mechanical sweepers through to $250,000 (USD) for high-efficiency vacuum and regenerative air sweepers (Schilling, 2005a?). The higher costs of the latter are, however, offset by lower running costs, with the cost per pound of street dirt removal being approximately US$5-10 for mechanical sweepers compared to US$2-5 for regenerative air and vacuum sweepers (Sutherland and Kidwell-Ross, 2010). Furthermore, regenerative air and vacuum sweepers typically have a life of 8 years compared to only 5 for mechanical sweepers (Schilling, 2005b). Schilling (2005b) indicated operation and maintenance costs (2005 USD values) for mechanical and vacuum sweepers of US$40 and $20 per curb mile, respectively.

3.4 Efficiency of street sweepers

3.4.1 Controlled testing conditions

As mentioned above, modern high-efficiency street sweepers are capable of removing up to 98% of particulate material under controlled conditions. The most detailed report of pick-up efficiency of different sweepers was a study undertaken by Pacific Water Resources (PWR) for the sweeper manufacturer, Elgin (Giles, 2009). Although an industry-funded study, PWR are reportedly one of the most recognised independent experts on stormwater control in the U.S. Although it was limited to Elgin sweepers, the usefulness of the study was that it compared five sweepers (2 regenerative air, 2 mechanical and 1 vacuum) under standardised, reproducible conditions. Briefly, the testing involved a 50 ft section of curbed test track (under a tent) that was set up on a car park surface. Dirt used for the pick-up trial had a similar particle size distribution (PSD) similar to the average PSD observed from hundreds of samples as part of the National Urban Runoff Project (NURP), and was applied to the test track at a rate of 225 g/meter (225 kg/km or 792 lb/mile) across a track width of ca. 60 cm. At a maximum test speed of ca. 5 mph, the sweeper performed a single pass over the test track, after which an industrial vacuum cleaner was used to collect any remaining particulate material. This material was weighed and sieved into 8 size fractions (in mm, these were <0.063, 0.063-0.125, 0.125-0.25, 0.250-0.6, 0.6-1, 1-2, 2-6.4) to determine overall efficiency, and the sweeper's removal efficiency for specific size fractions of particulates. Results of that study (Giles, 2005) are summarised in Table 1.

Table 1: Removal efficiencies of different types of sweeper manufactured by Elgin Sweeper (adapted from Giles 2005).

Sweeper model	Type	Overall removal efficiency (%)	Removal efficiency of silt (<63 μm) (%)
Crosswind (NX)	regenerative	97.5	90.8
Crosswind	regenerative	96.4	89.4
Waterless Eagle (FW)	mechanical	91.5	78.1
Waterless Eagle (FW) with water	mechanical	81.0	68.2
Whirlwind (MV)	vacuum	93.5	93.5

While the results indicate relatively high total and silt removal efficiencies, even for the mechanical sweepers, a number of factors contributed to these results probably over estimating the real world efficiency of the sweepers. These included the following: smooth and uniform 'road' sweeping surface (i.e., concrete car park surface); absence of gutter channel making sweeping easier; loose material applied to surface behaves differently to real street dirt, which can form sediment 'cakes' from wetting and drying cycles (i.e., more difficult for sweeper to pick up); uniform application of test material over the length and width of the test section (in reality, the distribution of street dirt is much more heterogeneous); the test material did not contain gross debris like litter and vegetation, which can be problematic for some sweeper types (i.e., vacuum); favourable weather conditions (e.g., no rain prior to or during sweeping trials); and finally, real street sweeping performance is hindered by vehicles parked on the street, with every car preventing the sweeping of approximately three car lengths of curb channel. Accordingly, the applicability of these optimised sweeping efficiencies to real world conditions are limited.

Breault and workers (2005) undertook sweeping efficiency tests (vacuum vs. mechanical) using a test dirt mix, but applied this to a real street in New Bedford, Massachusetts. The overall total pick up efficiencies ranged between 60-92% and 20-31% for the vacuum and mechanical sweepers, respectively. For the very fine sand fraction (63-125 μm), the respective pick up efficiencies ranged between 9-10% and 31-93% for mechanical and vacuum sweeper trucks, respectively. The lower efficiency values for the vacuum sweeper were attributable to windy conditions during the test. The performance of the mechanical sweeper under these test conditions was considerably lower than the 80-90% range in Table 1.

3.4.2 'Real world' testing conditions

Overall pick up efficiency

In 'real world' field studies where the amount of particulate material is determined before and after street sweeping, the pick up efficiency of modern sweepers is considerably less than the values reported in Table 1. In residential catchments in Madison, Wisconsin, the reported mean pick up efficiency for regenerative air, high efficiency vacuum and mechanical sweepers was 25, 30% and 5%, respectively (Selbig and Bannerman, 2007). The authors indicated that obstruction by parked cars was not a significant issue in the residential study catchments; presumably due to abundant off-street parking. With respect to load reduction in a swept catchment compared to an un-swept control catchment, performance was more favourable with reported values of 76%, 63% and 20% for regenerative air, vacuum and mechanical sweepers, respectively. The authors proposed that the higher removal rates were the result of sweeper action generating (discussed below) or exposing fine particulates, which facilitated dirt removal via rain and/or wind action (Selbig and Bannerman, 2007).

In a study using a new generation Elgin Whirlwind sweeper (DiBlasi, 2008), removal efficiencies based on the mean amount of material present before and after sweeping was ca. 20%. A potential limitation of the study, however, was the very short accumulation period (ca. 24 hours) for street particulate material prior to collection. In a recent study, Horwatich and Bannerman (2009) reported removal efficiencies of 25 to 77%, with a median of 32% using high-efficiency vacuum sweepers. Interestingly, the authors showed that the removal efficiency was positively correlated with street load and reached a maximum of 60-80% for loadings greater than about 140-210 kg/curb-km. For lower street loadings of between 40 and 100 kg/curb-km, the removal efficiency ranged between 20 and 40%. Hence frequent street cleaning, whether by rain or sweeping, means short accumulation times, low street dirt loads and therefore lower removal efficiencies by sweepers.

Pick up efficiency of fine material

Street pick up efficiencies of various sweeper types can be further differentiated by undertaking a particle size analysis. Numerous studies have concluded that mechanical-broom sweepers are largely ineffective at removing the fine fraction of street dirt, namely the fraction of particulates smaller than 250 μm (U.S. EPA, 1983, Bender and Terstriep, 1984; Pitt, 1985). In contrast, and as already discussed in section 3.4.1, modern high efficiency vacuum and regenerative air sweepers have claimed efficiencies for fine particulate material of ca. 90% under controlled, or more accurately, optimised sweeping conditions.

The ability of sweepers to effectively remove particulates under real world conditions is obviously an important parameter in determining the relative merits of sweeping as a stormwater BMP. For environmental sweeping, efficient pick up of fine material (e.g., <250 μm) would be advantageous since this material typically contains the highest concentrations of contaminants (particular heavy metals) and because it is the fine fraction that is most easily entrained in runoff to contribute to the TSS load. Pitt (1985) reported that much of the sediment washed-off street surfaces is <125 μm, with only ca. 10% of wash-off material being >500 μm.

Despite the promising pickup efficiencies shown in Table 1, Selbig and Bannerman (2007) found that the mechanical broom and regenerative air sweepers were unable to adequately pick up particles <250 μm and <125 μm, respectively. This data has been reproduced in Figure 4, which shows the mechanical broom and regenerative air sweeper efficiencies moving into the ‘red zone’ as the particulate material gets finer. The negative efficiency values in the ‘red zone’ represent net generation of particles by the sweeper (i.e., more fines present on the surface after sweeping than before). Vaze and Chiew (2002) and Horwatich and Bannerman (2009) similarly reported increased fines from sweeping activities. Of the three sweepers, only the vacuum sweeper maintained some ability to remove the fine particulate material from the street surface. However, the 10-20% efficiency for particulates <125 μm is almost an order of magnitude lower than the optimised values reported in Table 1.

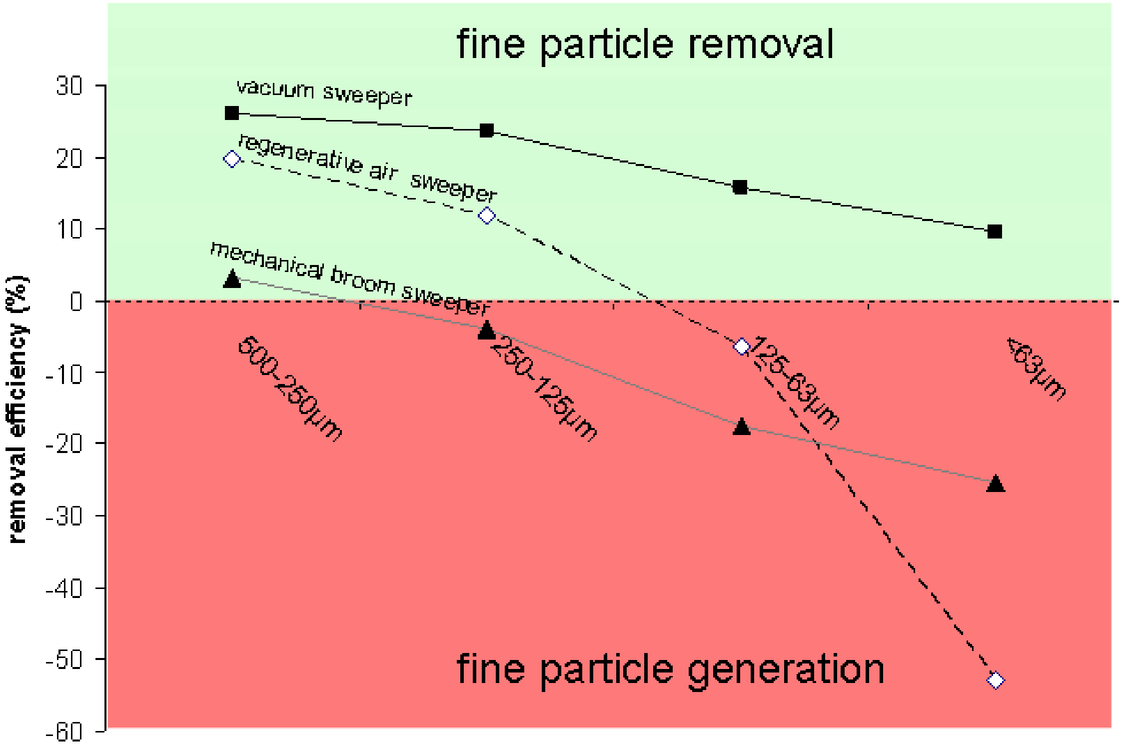

Figure 4: Average removal efficiencies of fine particulate material for three different types of sweepers operating in residential catchments in Madison, Wisconsin. Green and red regions denote net particulate removal, and net particulate generation, respectively, by the sweepers. *Figure adapted using data, with permission, from Selbig and Bannerman (2007).*

4. Sweepers as a non-structural BMP

Industry-based reports and commentaries indicate a number of potential benefits (or at least claims) of environmental sweeping as a BMP for stormwater quality (Pacific Water Resources, 2006). The following bullet points provide a summary of these industry claims, they are not necessarily supported by actual studies or field trials.

- **Cost effective:** street sweeping is the most cost-effective BMP based on cost per pound of pollutant removed from stormwater. Structural BMPs run at between US$10-60 (not including land purchase), compared to US$2-5 for vacuum/regenerative air sweepers.
- **Most effective:** based on the fact that 2/3 of all rain that falls on impervious surfaces in the urban landscape involves pavement, which can be swept, and hence potentially have the broadest impact on reducing stormwater pollutant concentrations.
- **Most immediate impact:** While it takes decades to retrofit catchments with structural BMPs, street sweeping on catchment-wide scales can be implemented immediately (or at least in relatively short time frames).
- **Most flexible:** Once a structural BMP is constructed it cannot be moved and is difficult to modify. In contrast, environmental sweeping programmes can be altered to reflect shifts in sweeping technology, budgets and changes in traffic patterns and landuse (and hence pollutant loadings).
- **Secondary benefits:** Air quality benefits from high efficiency sweeper reducing the amount of fine material on streets that can be resuspended in the air, and therefore potentially improving urban air quality via a reduction in PM10 particulate material.

4.1 Measuring the effectiveness of street sweeping

4.1.1 Mass of street particulate material collected

The success of an environmental sweeping programme depends on a number of factors, for example; sweeper pick up efficiency, sweeping frequency, catchment type (commercial vs residential vs industrial), amount and nature of the roads (i.e., surface condition, traffic volume, numbers of parked vehicles) in the catchment, and local weather conditions (frequency/intensity of rainfall events). One way to measure the benefits of sweeping is to determine the mass (tonnage) of material picked up by the sweeper, and therefore effectively 'removed' from stormwater system. Furthermore, by analysing the contaminant contents of the particulate material (e.g., heavy metals, petroleum hydrocarbons and nutrients), roading managers/municipalities/community groups can calculate the actual amount of specific contaminants that sweeping has prevented from potentially ending up in rivers, streams and estuaries (refer to Section 4.2).

To highlight this approach, without determining any percentage improvement in stormwater quality from sweeping, the city of New Bedford (Massachusetts) has reportedly removed 3.8 million kilograms (38,000 tonnes) of street dirt and associated heavy metals and PAHs via its street sweeping programme. These contaminants (including TSS) would otherwise end up in the city's catch pits, other structural BMPs, and the streams and rivers that ultimately receive urban runoff (Breault et al. 2005).

4.1.2 Measured or modelled decreases in stormwater loads

The impact of street sweeping on receiving water quality should be measured in terms of effectiveness in reducing end-of-pipe pollutant concentrations and loads in runoff, rather than being inferred from the mass of street particulates removed via sweeping operations (Sator and Gaboury, 1984). Although there are a number of studies reporting the ability of sweepers to remove large amounts of particulate material from a catchment, no studies have reported a statistically significant reduction in stormwater contaminant loads post sweeping treatment (Pitt, 1985; Selbig and Bannerman (2007); DiBlasi, 2008). A major problem is the high variability in stormwater loads. For example, Selbig and Bannerman (2007) reported coefficients of variation (COV) values for TSS in stormwater from residential catchments of between 1.0 and 2.9. Even with COV of 1.5, assuming a 95% confidence level and power of 0.5, approximately 200 paired samples would need to be collected to detect a 25% difference between the two data sets. Therefore, unless street sweeping has a large effect on stormwater contaminant loads; it is difficult to determine any statistically significant improvement in stormwater quality arising from sweeping BMPs using these simple sampling and statistical designs.

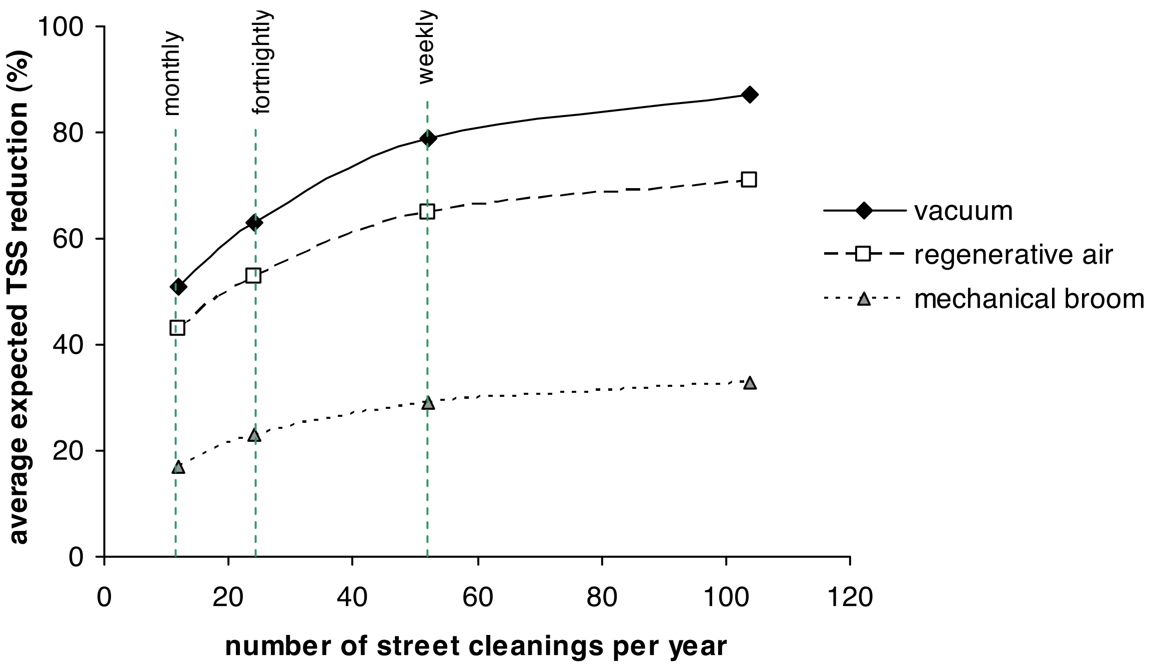

Figure 5: Average expected reductions in stormwater loads (TSS) for different sweeping scenarios for a 'single family residential' catchment using the SIMPTM model (Sutherland and Jelen, 1997). Figure generated using data provided in web published article (Minton and Sutherland, 1998) available at http://www.worldsweeper.com/Environmental/mintonvol4No4.html.

Most studies reporting stormwater load reductions are based on modelling (Sutherland and Jelen, 1997; Minton et al. 1998; Livonia, City of, 2001), including the basis of sediment accumulation, resuspension, removal (e.g., sweeping/catchpits) and washoff to predict contaminant concentrations in runoff. An example of one such model is the Simplified Particulate Transport Model (SIMPTM) developed by Sutherland and Jelen (1997). Sutherland and Jelen (1997) reported 'average expected reductions' (in loads) from twice-monthly sweeping of a 'single family residential' catchment of ca. 25%, 55% and 65% for mechanical, regenerative air and vacuum sweepers, respectively. When increased to weekly sweeping, the respective 'average expected reductions' increased to ca. 30%, 65% and 80% (Figure 5). Interestingly, when the model was applied to 'major arterials', weekly sweeping yielded 'average expected reductions' of ca. 5%, 25% and 75% for mechanical, regenerative air and vacuum sweepers, respectively. No explanation was provided for the lower predicted performance of regenerative air sweepers on major arterial versus residential catchments.

The other interesting 'take home' point shown by Figure 5 is that large gains can be made by carrying out more frequent (i.e., weekly over monthly) sweeping. Although potential reductions in stormwater loading continue to occur with increased sweeping frequency, it is a case of rapidly diminishing returns (i.e., flattening region of the curves) after weekly sweeping, suggesting a cost benefit analysis should be undertaken for each scenario.

The SIMPTM model was also used by the City of Livonia to evaluate the most effective use of street sweeping and catch pit sediment cleaning regimes to optimise contaminant loadings in runoff (Livonia, City of, 2001). The modelling results predicted TSS reductions of 76-81% with weekly sweeping and annual catch pit cleaning from residential areas (increased to 89% for commercial catchments). The current cleaning regime was predicted to be removing only 20-33%.

The SIMPTM model uses 'optimised' pick up efficiencies (similar to those in Table 1) to derive average expected reductions in stormwater loads. For example, the term that defines the 'base residual' amount of particulate material (material not picked up by sweeper) is defined as 0.0 lbs per paved acre for particulates <125 μm when using either a vacuum or regenerative air sweeper. This default value is not consistent with the data shown in Figure 4 (Selbig and Bannerman), and indicates that the model likely over estimates real world removal of accumulated street dirt, and in doing so, over estimates reductions in stormwater contaminant loads.

A 3 year study by Pitt (1985) included a regenerative air sweeper, along with a mechanical sweeper, which collected over 400 street dirt samples. Pitt concluded that intensive street sampling resulted in about a 25-50% reduction in street surface loadings and calculated that if a street surface contributes about half of the total runoff yield for a specific pollutant (e.g., zinc), then street sweeping may remove ca. 10 to 20% of the contaminant discharge (Pitt, 1985). The author indicated that if pick up efficiencies were low for runoff mobilised fine particulates, then this may result in sweeping having <6% improvement in runoff quality. The regenerative air sweeper used in the study by Pitt was about 1.3-times more effective than the mechanical sweeper for reducing runoff yields.

Sweeping removes street dirt that would otherwise, potentially, enter the stormwater system. The ability to reduce contaminant concentrations in urban runoff is dependent on the removal of fine particulates because these make the greatest contribution to stormwater contaminant loads. Currently, there is a disparity between street sweeper efficiency under optimised conditions compared to real world performance, with the latter being significantly lower. On the basis of field performance and the inability to detect sweeping-induced improvements in stormwater quality, it is reasonable to assume that realised benefits of environmental sweeping are markedly less than the 60-80% removals estimated by models such as SIMPTM. The Windows Source Load and Management Model (WinSLAMM) developed by Pitt and Voorhees (2002), which is used routinely by the U.S. Geological Survey in major sweeping projects, is therefore a more realistic tool for estimating reductions in stormwater pollutants via sweeping (Horwatich and Bannerman, 2009). Based on real world performance, it seems reasonable to assume that reductions in contaminant concentrations/loads are more likely to be in the vicinity of 10-30% (Pitt, 1983; Sartor and Gaboury, 1984).

4.1.3 Real world factors that influence the effectiveness of sweeping

End of pipe contaminant concentrations in catchment runoff (i.e., stormwater) are a function of three factors: 1) accumulation of contaminants on street surfaces, 2) rainfall/runoff washoff of contaminants, and (3) sweeper removal of contaminants (Sartor and Gaboury, 1984). In the absence of external disturbance factors, mass loads of street dirt would be expected to increase linearly with time. In reality, the rate of accumulation would decrease due to traffic and wind, resulting in the street dirt mass loading approaching a maximum value; however at any point along this accumulation curve, the mass of particulate material is reduced by cleaning events – which including rain wash-off and sweeping. The importance of rainfall as a ‘competing’ street cleaning mechanism, and how the relative ‘timing’ of sweeping vs. rainfall wash-off largely determines the effectiveness of street sweeping as a BMP for improving stormwater quality and is illustrated in Figure 6.

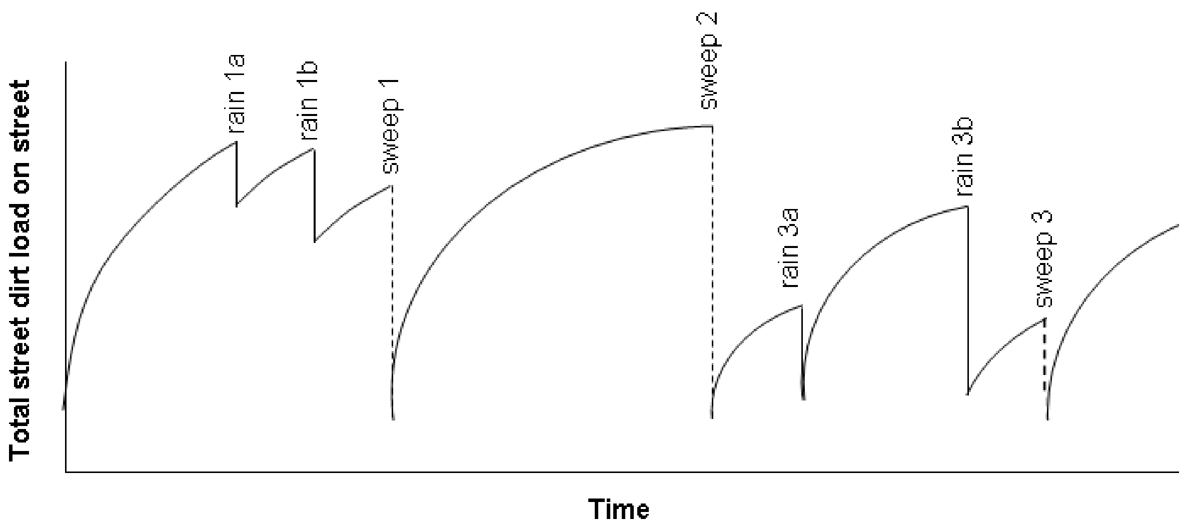

Figure 6: Schematic showing hypothetical street contaminant accumulation and removal by rain wash-off and street sweeping (adapted from Sartor and Gaboury, 1984. Solid vertical lines represent contaminant removal via wash-off, while dashed vertical lines represent removal by street sweeping. .

The hypothetical schematic in Figure 6 shows that for three sweeping intervals of the same duration, the amount of contaminants (or street dirt) removed by sweeping is dependent on the frequency, intensity and timing (relative to sweeping event) of rainfall events. In simple terms, the relative success of sweeping at removing street contaminants is the ratio of vertical black lines to vertical dashed lines. Hence, in sweeping interval 2 (middle), with no rainfall event, all accumulated material on the street is removed via sweeping (down to a 'threshold' loading value), and, in this instance, the street sweeping efficiency (i.e., measure of material remaining before and after sweeping) would be relatively high. In contrast, sweeping interval 3 (right) shows two rain events (3b larger than 3a), resulting in a low street dirt loading at the time of sweeping. Consequently, the measured street sweeper efficiency for "sweep 3" would be relatively low assuming a constant threshold value for the street surface. This is consistent with sweeper efficiencies being in the range 20-30% for low loadings and increasing to 70-80% when the initial loading was high (Horwatich and Bannerman, 2009).

The importance of establishing a sweeping frequency based around the average interval between rainfall events is discussed in Section 4.3.1.

From Figure 6, it is apparent why Sartor and Gaboury (1984) concluded that the dominant influence on the effectiveness of sweeping is time interval; that is, the period between street sweeping compared to the average interval between storms. Basically, to be effective (i.e., 30% modelled removal), the street sweeping interval can be no more than 2-times the average interval between storm events. Other secondary influences include: 1) total mass on street surface compared to mass load on other catchment surfaces not swept; 2) comparative removal efficiency of sweepers vs storm wash-off for the material (i.e., contaminant, particle size) of interest; 3) rate of pollutant accumulation on street surfaces; and 4) partition of pollutants between street dirt particle sizes (Sartor and Gaboury, 1984)

4.2 Street sweeping particulates: sources, quantity and quality

4.2.1 Sources

Street sweeping, in theory, has the potential to remove street particulate material before it is entrained by runoff. While it is easy and informative to measure the total mass of street dirt collected, it is difficult to know the significance of this particulate removal with respect to the total runoff loads coming from the catchment. To be able to do this, the contribution that street dirt makes to total runoff suspended sediment loads (and other contaminants) needs to be determined. Catchment surfaces consist of a variety of different pervious (e.g., lawns, reserves, construction sites) and impervious surfaces (e.g., roads, car parks, driveways, footpaths and roofs), all of which are sources of particulate material that, depending on the catchment, contribute to varying extents to the sediment/contaminant loads in runoff. As such, reducing street particulate material load through sweeping is only reducing one of multiple sources of stormwater sediment (and associated contaminants) within the catchment. A conceptual picture of the various sources and processes contributing to runoff pollutant loads is shown in Figure 7, which is discussed in more detail in Section 4.2.2.

Bannerman et al. (1993) found that streets were the most important source area for pollutants in urban runoff when compared to lawns, driveways, rooftops and car parks. Streets were found to be the main contributor of suspended solids, faecal micro-organisms and heavy metals, with these inputs, in many cases, being 4-8 times higher than the other catchment surfaces (pervious and impervious). This was supported by Waschbusch et al. (1999), who reported that streets contributed 70-80% of the total amount of suspended solids in urban runoff.

The actual contribution street particulates make to stormwater pollutant loads (i.e., TSS and associated contaminants) are catchment dependent. That is, street particulates would be expected to contribute more to total runoff in a commercial (i.e., CBD) catchment with high traffic volume roads making up ca. 30% of area, than a low-density residential catchment with low traffic volume roads making up <10% of the area. This is supported by Pitt (1985) who, for residential catchments, attributed 9% of the total TSS load to street surfaces and 6% to driveways. By comparison, TSS contributions from front and back yards were 44% and 39%, respectively.

Erosion of local soils via wind and/or rain is typically one of the largest sources of street particulates (Sartor and Boyd, 1972, Pitt 1979). Soil inputs contribute to TSS and nutrient loadings, but are only minor contributors to chemical contaminant loads. For example, Pitt (1985) reported that residential yards (back and front) contribute >80% of TSS load but only 4% and <1% of the total zinc and lead loads in runoff. In contrast, street particulate matter originating directly from vehicles (brake/tyre/road surface abrasion, and exhaust emissions) contributes only a small percentage of the total mass, but because of the high contaminant concentrations, this material contributes a much greater fraction of the total contaminant load (of particular heavy metals). For example, in the residential catchment mentioned above (Pitt 1985), street runoff contributed 9% of the total TSS, but 60% and 44% of the total runoff loads of lead and zinc, respectively. Street sweeping, therefore, has the greatest potential to reduce stormwater concentrations of contaminants for which streets are a major source (DiBlasi, 2008), such as heavy metals and, depending on the catchment, suspended solids (TSS).

4.2.2 Conceptual picture

Figure 7 summarises the many different sources of urban runoff pollutants (represented as particulate material) in a catchment, and the major sources of street sediment, which include: run-on from adjacent land areas (both pervious and impervious surfaces); vehicle emissions; abrasion of street surface; atmospheric deposition and grit/sand application (in cold climates). The white arrows indicate sources of particulates that could potentially be removed by sweeping. These include atmospheric deposition of particulates on the street, vehicle-derived particulates, and particulate material via run-on from adjacent land surfaces. The gray-shaded arrows indicate sources of urban runoff particulates that would not (at least directly) be reduced by sweeping, which include, atmospheric deposition outside street corridor, roof runoff and runoff from adjacent land areas (including contaminated industrial/commercial sites). Run-on is shown as both white and grey arrow. This is because dry deposition, and material deposited on the street via run-on (i.e., not conveyed to the stormwater system) can be removed via sweeping, whereas pollutants that are washed onto streets (run-on) and conveyed to drain inlets (i.e., not deposited on the street) contribute to total runoff loads (crossed-hatched arrows) but are not removable via street sweeping.

Another potential source contributing to total load is resuspension of sediment already in the stormwater system, namely particulate material in catch pits (sumps) and pipe bed load (black arrows, Figure 7). The contribution of this source to total load is dependent on the size of the runoff event and state of sedimentation within the stormwater system. That is, a large storm event, combined with full catch pits will potentially mobilise a significant amount of sediment, which is independent of any street sweeping activities. For a residential catchment in Bellevue, Washington, it was found that nearly a full year was required for sediment to reach a stable volume in catch pits, which equated to about 60% of the physical sump volume. At higher storage levels (>60%) rain effectively removed the excess sediment via resuspension. The author concluded that cleaning inlets and catch pits about twice a year would reduce TSS concentrations in runoff by 10 to 25% (Pitt, 1985).

Non-street catch pits, and the surfaces they drain (e.g., driveways, car parks and various industrial and commercial yards) are sources of stormwater pollutants (particularly sediment containing high concentrations of heavy metals and/or hydrocarbons) that are largely unaffected by street sweeping. Both suspended sediment entrained in runoff water from these surfaces, and resuspension of sediment from poorly maintained sumps/pipes can contribute to the total pollutant load in catchment runoff.

In addition to street sweeper pickup efficiencies and sweeping frequency, the ability of an environmental sweeping programme to result in significant stormwater quality improvement is dependent on the relative contribution of street runoff to the total pollutant load in the catchment runoff. As such, sweeping has the highest potential to reduce stormwater concentrations of contaminants for which streets are the major source; for example, copper and zinc from vehicle emissions (brake and tyre abrasion). However, based on the numerous sources indicated in Figure 7, to maximise benefits of environmental sweeping, a holistic approach to catchment ‘source control’ should also be taken in order to mitigate contaminants from other sources, in addition to street dirt removal via sweeping.

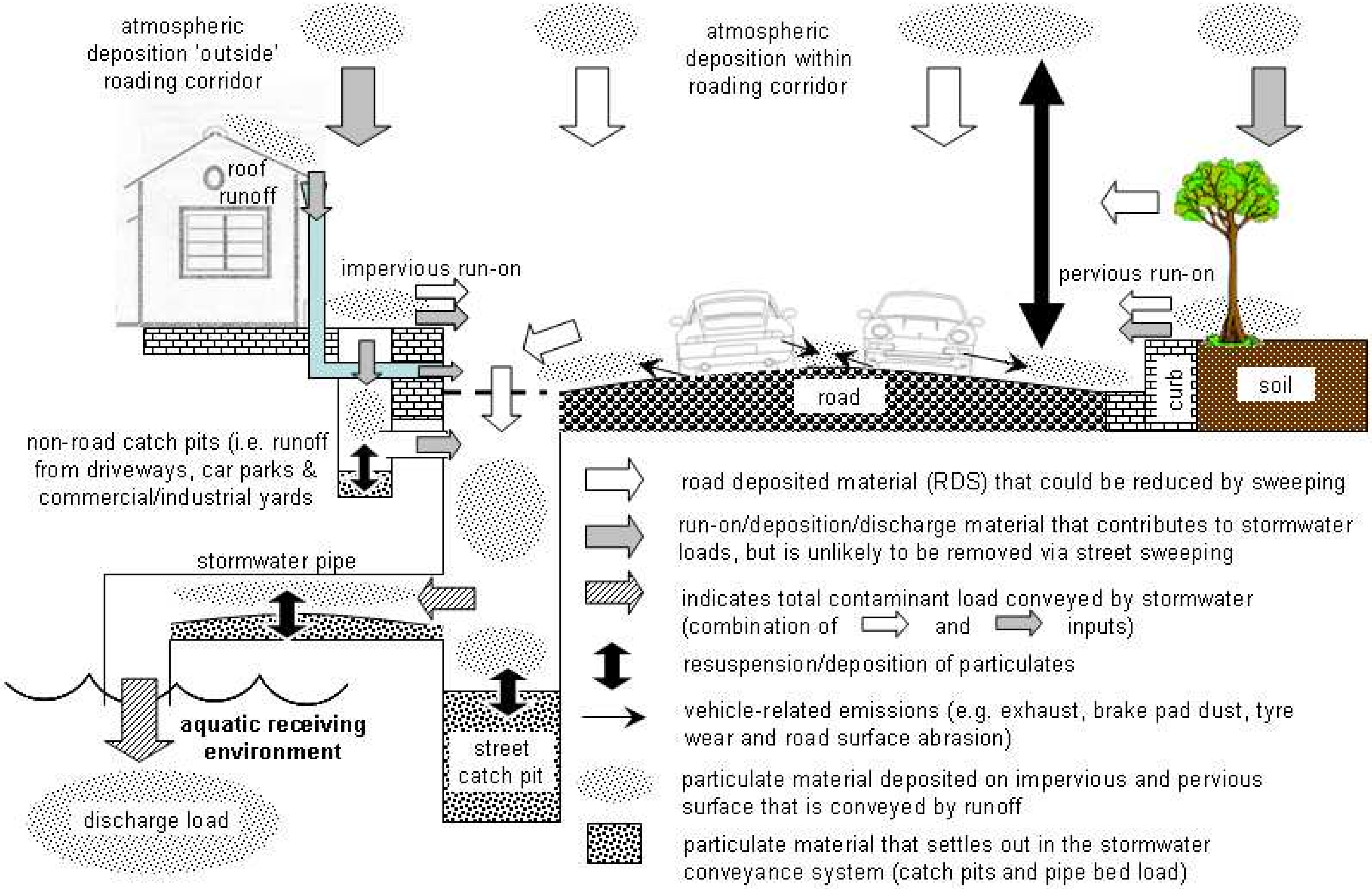

Figure 7: Schematic showing the various sources of particulate materials that contribute to total contaminant loads (i.e., TSS) in stormwater runoff.

4.2.3 Quantity

In general, the quantity of material on a street surface depends primarily on the length of time since last cleaning, either by sweeping or rainfall, with numerous other factors also having an influence. The main factors controlling street particulate accumulation fall into the following three major groups (Sartor and Boyd, 1984):

- local weather consisting of rainfall frequency, as well as secondary factors such as storm intensity and wind conditions
- use of streets and adjacent areas including land use, traffic types and quantity, and parking conditions
- street surface conditions, such as type and age, of pavement, gutters and curbs.

In the U.S. the mean amount of material removed during sweeping is typically between 400-800 pounds (lbs) per curb mile, which corresponds to 112-225 kg/curb-km. The nationwide average for the U.S. in a 1971 publication (Sartor and Boyd, 1971) was 391 pounds per curb mile or ca. 110 kg/curb-km. At the higher end, Sartor and Gaboury (1984) indicated typical street particulate material loadings of 250-300 kg/curb-km (890-1060 lbs/curb-mile).

At the time of writing this report, NCC was not able to provide any information regarding tonnages from Nelson's existing sweeping maintenance programme. Figure 8 shows street sweeping removal data for Auckland City (1146 km of swept road), where the average street-dirt yield was 116 kg/curb-km/month (or 410 pounds per curb mile/month). Assuming sweeping was monthly; the Auckland values are comparable to typical U.S. street dirt yields (which do not specify a time period).

Pitt (1985) reported street dirt accumulation rates of between 1 and 6 kg/curb-km/day, with an average value of about 3 kg/curb-km/day in residential areas in Bellevue, Washington. Horwatich and Bannerman (2009) reported a median street dirt accumulation rate on highways (Madison, Wisconsin) of 2.5 kg/curb-km/day. These are comparable to the Auckland accumulation rates (based on monthly collected tonnages) which ranged from 2.8 to 5.5 kg/curb-km/day, with an average of 3.8 kg/curb-km/day.

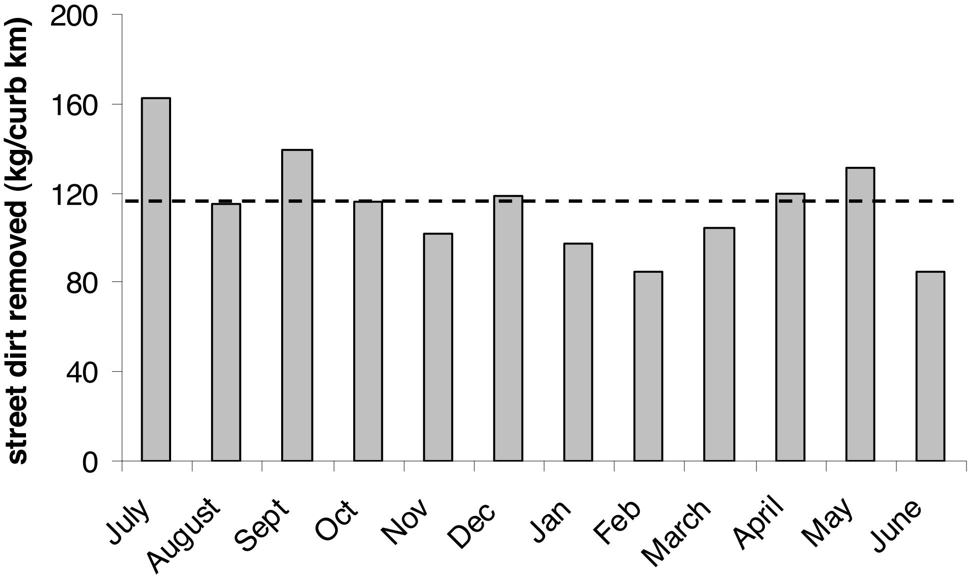

Figure 8: Street sweepings removed per month from Auckland City (2292 curb km), dashed line indicated mean value of 116 kg/km of curb swept. Data (2004-2005) provided by Auckland City Council.

4.2.4 Quality (typical contaminant concentrations)

A NZ Transport Agency report that included 33 street particulate samples (15 street sweepings and 18 catch pit sediments) from Auckland, Hamilton and Christchurch provides an indication of the typical contaminant concentrations that can be expected in street particulate material (Depree, 2008). The median concentrations for total petroleum hydrocarbons and PAHs were 1220 and 6.3 mg/kg, respectively. For heavy metals, the respective median concentrations (and lower and upper quartile values) of lead, copper and zinc were 122 (57-170) mg/kg, 67 (41-119) mg/kg and 422 (302-555) mg/kg. Leaching studies showed the street particulate material to be potentially toxic to aquatic life because of relatively high concentrations of copper and/or zinc (Figure 9). Leachate toxicity was subsequently confirmed using a fresh water algal assay, with the most toxic inhibiting 50% of algal growth at 2% of the original leachate concentration (i.e., 50-fold dilution) (Depree, 2008).

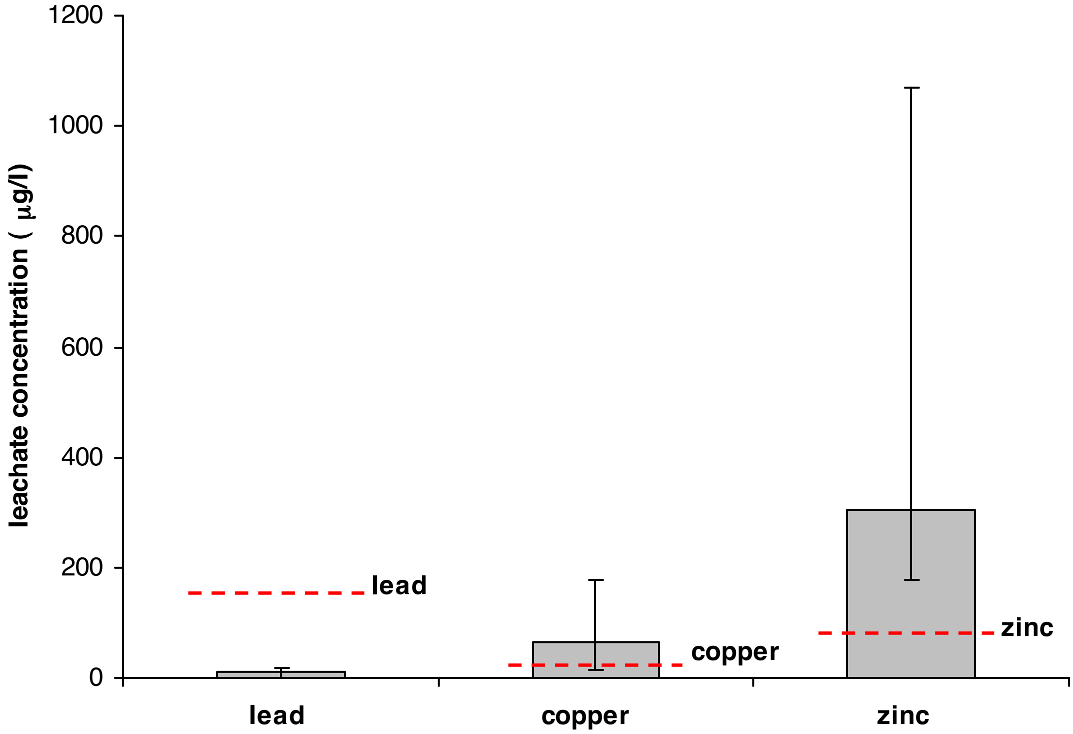

Figure 9: Freshwater leachate concentrations from street particulate material from Auckland, Christchurch and Hamilton (n=8) compared to aquatic hazardous concentration values at the 50% species effects level (HC_{50}, Verbruggen et al. 2001). Note: the HC_{50} values have been used here to provide an indication of the potential toxicity of leachates associated with street dirt - after reasonable mixing in the receiving environment, U.S. EPA acute water quideline values would be more relevant. Figure adapted from Depree (2008).

4.2.5 Potential mass of contaminants removed by sweeping: zinc

Based on Auckland City's average annual street dirt removal of ca. 1400 kg/curb-km, the estimated amount of zinc removed per km by sweeping in Nelson is between 0.4 and 0.8 kg. This amount can then be multiplied by the total amount of curb-km swept to generate a total quantity of zinc (or any other contaminant of interest) removed via sweeping. Although not all of the mass removed by sweeping would end up in the receiving environment, the material (and associated contaminants) removed can no-longer contribute to catchment runoff loads or burden existing stormwater infrastructure (e.g., catch pits and other structural BMPs).

However, street catch pit sediments in industrial areas, particularly those with automotive (e.g., car wreckers, repair workshops, battery manufacture) and metal processing industries, can contain thousands to tens or thousands of mg/kg of zinc (e.g., sediment from a street catch pit in Auckland contained ca. 60,000 mg/kg of zinc in the <1mm fraction). Accordingly, targeted street sweeping (and catch pit cleaning) in industrial areas has the potential to remove a major source of catchment contaminants. That is, catchments may yield similar amounts of street dirt, but in certain catchments the street dirt may be markedly more contaminated, and hence make a much great contribution to the total runoff contaminant load.

4.3 Industry recommended sweeping practice

4.3.1 Frequency

There are numerous industry-based articles on how to implement a cost effective, environmental sweeping programme (Sutherland and Kidwell-Ross, 2010, Pacific Water Resources, 2006). With respect to sweeping frequency the general guidelines seem to apply:

1) arterial streets with high traffic volumes: weekly (minimum fortnightly)
2) commercial streets with moderate traffic volumes: optimum fortnightly (minimum monthly)
3) residential streets with low traffic volumes: ideally monthly (minimum quarterly).

Schilling (2005b) defined a set of minimum and maximum sweeping frequencies for various catchment types which recommended fortnightly (maximum) to monthly (minimum) sweeping frequencies for arterials, commercial and industrial areas. Minimum and maximum recommended sweeping frequencies for residential areas were between 6 (bimonthly) and 14 times (> monthly) per year. Twice weekly sweeping of the CBD was recommended, although presumably this is driven by aesthetic reasons, as opposed to improving environmental outcomes. These recommendations were based on modelled TSS removal rates of 30%, 50% and 68% for respective sweeping frequencies of bimonthly, monthly and biweekly (refer to Section 4.1.2 for discussion on SIMPTM model).

Importance of considering the average interval between storms

Since the amount of street dirt on surfaces depends largely on the length of time between cleaning (whether by sweeping or rain), when the average time between rainfall events is much less than the sweeping interval most of the street particulate material that accumulates will be washed away by the rain – hence street sweeping would be relatively ineffective. As such, Sartor and Gaboury (1984) concluded that rainfall statistics are central to the effectiveness of sweeping programmes. Based on modelled results, to be effective (i.e., 30% removal under model assumptions) the street sweeping interval must be, at the most, two times the average interval between storms. Increasing the sweeping frequency to one or two times during the average interval between storms has the potential to remove 50% of street particulate matter. For four U.S. cities, the average time between storms range from 2.8 days for Boston, Massachusetts, to 21 days for San Francisco, California (Sartor and Gaboury,1984). Hence to achieve 50% modelled removal of street particulates would require a sweeping frequency of every 2-3 days in Boston, and yet only 10-20 days in San Francisco, respectively. Environmental sweeping to achieve 50% removal is therefore going to be far more cost effective in locations like San Francisco with 'semi-arid' climates resulting in long pronounced dry spells that limit street dirt removal by wash-off (Sartor and Gaboury, 1984).

Even if it were economically feasible to sweep 2-3 times per week (as calculated for Boston), Horwatich and Bannerman (2009) indicated the sweeper efficiency is related to street dirt loads, therefore, very high frequency sweeping means low street dirt loads and correspondingly, low sweeper removal efficiencies. When considering the relationship between dirt accumulation, wash-off interval and sweeper efficiencies, it becomes apparent how the effectiveness of sweeping as a BMP is dependent on climatic conditions.

Given the low rainfall in Nelson, this approach of optimising sweeping frequency based on the average dry period between storms to maximise pollutant removal, particularly over the summer period when receiving waters are most sensitive to contaminant loads, would have to be an essential component of any optimised environmental sweeping programme.

Regular maintenance of the currently installed catch pits will assist in the catchment-wide management of contaminants. The recommended clean out frequency for catch pits (sumps) is between once and twice yearly, depending on the catchment (Pitt, 1985).

4.3.2 Sweeping industry 'top tips'

The following is a summary of the U.S. sweeping industry's 'top tips' for ensuring a more environmentally-focussed and cost-effective street sweeping programme (Sutherland and Kidwell-Ross, 2010). Some additional points have been added by the author.

1) Make sure sweepers are well maintained and the brooms are changed regularly based on manufacturers recommendations.
2) Utilise modern, high efficiency sweepers, which are thought to remove 30-50% more street particulates than mechanical broom sweepers (Note: vacuum and regenerative air sweepers appear common-place in NZ, hence capital investment in new sweepers is probably not required).
3) Only sweep curbed streets (or streets with barriers) and focus on high traffic volume streets. Shaheen (1975) found that street loadings increase with curb height.
4) Street particulate material is not uniformly distributed over the road. Sartor and Boyd indicated that 90% of street dirt lies within 300 mm of the curb. Pitt (1979) and Selbig and Bannerman (2007) reported that up to 80% of street dirt resides within the curb lane. Accordingly, there is no requirement to sweep areas other than the curb lane of streets.
5) Commit to sweeping in the speed range of 5 to 7 km/h, depending upon specific conditions.
6) Implement and enforce parking restrictions where parked cars are making it difficult to reach the curb (one car = 3 car lengths of unswept curb).
7) Implement GPS monitoring on all sweepers to keep track of the day-to-day operations of each sweeper (including linking GPS to actual engagement of sweeping mechanism to enable determination of actual sweeping operations).
8) Divide municipality into sensible sweeping sectors; for example, by drainage water shed, by general roadway usage type (industrial, residential, commercial) and/or by road traffic volume.
9) Implement (or contract out) monitoring of street dirt accumulation (i.e., keep track of the amount of street particulates removed from all sweeping sectors).
10) Implement (or contract out) analysis of street dirt for relevant contaminants to determine what sweeping sectors are yielding the highest contaminant loads, and hence may benefit from increased/optimised sweeping regimes.

11) Implement (or contract out) testing to evaluate pickup performance of existing and/or new sweeper models (this should involve real world testing conditions).

5. Recommendations for moving ahead

At the time of writing this report, there was no information provided about the current NCC sweeping programme (e.g., tonnages, curb-km swept, type of sweepers, frequency of sweeping). Therefore it is not possible to make recommendations on how to optimise the existing sweeping programme for contaminant removal in order to evaluate sweeping as a non-structural BMP for stormwater in selected Nelson catchments. The following broad recommendations are suggestions for areas that could be further developed and implemented as part of an ongoing effort to determine the contribution sweeping can make towards improved stormwater quality, which, in-turn, will have positive implications for aquatic receiving environments, namely the Maitai River and downstream estuary.

Phase 1: Catchment identification and street dirt characterisation

a) Review existing sweeping programme in Nelson and determine information (where available) such as: sweeping sectors, curb-km swept, sweeping frequency, tonnage, contractors vs NCC sweeping, sweeper-types, annual budget and sweeper operation (i.e., speed).

b) Review of relevant climatic conditions, namely frequency and intensity of rainfall events. This particularly applies to the summer season, when receiving water benefits from improved stormwater quality would be greatest.

c) Identify potential catchments (sub-catchments) of concern. This may be largely a desktop exercise based on catchment type (industrial/commercial), road vehicle traffic (high), aquatic receiving environment (Maitai River) and/or where historic data indicates high contaminant loads are associated with a particular catchment.

d) Collect a range of street sweepings and catch pit sediments (possibly pipe bed load) from catchments identified in c) and analyse for particle size distribution (PSD) and a suite of relevant urban contaminants – including the heavy metals copper, zinc and lead, PAHs. Additionally, some marker compounds/elements could be included to enable some source identification (e.g., hopanes for PAHs, and aluminium and/or lithium for normalising anthropogenic heavy metal concentrations).

e) Analyse receiving environment sediment from the Maitai River (and downstream estuary) along gradients in the vicinity of stormwater outlets from the selected catchments. Analyse for PSD, heavy metals, PAHs and marker compounds/elements to enable comparisons with street particulates – this should enable a preliminary estimate of the contribution of contaminants attributable to street particulate material that is removed by sweeping.

f) Investigate sources of contaminants, other than street dirt, that may be significant contributors to catchment stormwater loads. For example, sediments sampled from catch pits/sumps located on industrial sites that drain into the stormwater system. If found that industry are contributing significant amounts of contaminants to stormwater, then improved BMP for managing stormwater is necessary. Such industrial sites may also be responsible for high concentrations of contaminants in street dirt via wind transport and/or vehicle tracking. This would be part of an integrated approach to catchment source control – that is, non-structural BMPs that prevent or remove contaminants prior to being washed into the stormwater system and receiving environment.

g) Use a simple street particulate accumulation-wash-off model (for example Windows Source Load and Management Model (WinSLAMM) software) to determine estimated reductions of suspended sediments in runoff from Nelson catchment as a result of different sweeping scenarios.

Phase 2: Environmental sweeping field trials

This trial assumes access to a modern, well maintained high efficiency sweeper – based on literature; preference would be for waterless vacuum-based sweeper, although regenerative air would also be suitable.

h) From phase 1 data, select comparable paired catchment with relatively similar land use, size and hydrodynamic properties. One would be used as a control where the existing sweeper frequency is used – presumably at the low end for environmental sweeping = LOW. The other catchment would be used to test the benefits of increasing sweeping frequency (i.e., to a maximum of weekly) – i.e., HIGH. Ideally, the study would be long-term, with a 'baseline' period (i.e., one year) where low frequency sweeping was carried out in both catchments, after a year, the test catchment would switch to high frequency sweeping to determine potential beneficial outcomes. Prior to initiating the baseline period, and the test period, all catch pits in the study and control catchment would be cleaned (if any end-of-pipe stormwater sampling was to be done, then pipe bed load should also be cleaned out to remove all 'historic' sediment prior to baseline and test periods).

i) Because stormwater sampling of events is relatively expensive, especially given the number of samples required to observe a statistically significant improvement in stormwater contaminant concentrations, it is unlikely that this would be a feasible approach. Thus a cost-effective programme would focus on assessing sweeping tonnage of material removed (and hence accumulation/removal rates) and accumulation of sediment in catch pits. Periodically, samples of road sweepings would be analysed to determine the mass of contaminants removed.

j) First flush sampling to determine if the amount of particulate material washed of the road is reducing should also be determined. This would be done using simulated rainfall on a relatively small scale (Herngren et al. 2005). Wash-off during average rain events would be too variable and introduce considerable logistical issues regarding timing of sampling.

k) Determine sweeper pick up efficiency for range of particle sizes under real world operating conditions – including chip seal vs asphalt. This would involve vacuuming (with power hand held commercial vacuum) the street surface before and after sweeping, with sweeper efficiency measure as:

$$removal\_efficiency(\%) = \frac{mass(before) - mass(after)}{mass(before)} \times 100$$

6. References

Baily, M.; Conwell, C. (2010). Sediment contaminant levels in Nelson area catchments: 2010. Prepared for Nelson City Council. *Cawthron Report No. 1732,* 22 p plus appendices.

Bannerman, R.; Owens, R.D.; Dodds, R.; Hornewer, N. (1993). Sources of pollutants in Wisconsin stormwater. *Water Science and Technology 28*: 3–5, 241–259.

Bannerman, R.T. (2000). Best way to control stormwater runoff pollution may be the cheapest way to control – State agency doing study to confirm it. Online article from Public Works.com, January 20, 2000. [Available from: http://www.publicworks.com/article.mvc/Best-way-to-control-stormwater-runoff-polluti-0002]

Bender, G.M.; Terstriep, M.L. (1984). Effectiveness of street sweeping in urban runoff pollution control. *Science of the Total Environment 33*: 185–192.

Breault, R.F.; Smith, K.P.; Sorenson, J.R. (2005). Residential street-dirt accumulation rates and chemical composition, and removal efficiencies by mechanical- and vacuum-type sweepers, New Bedford, Massachusetts, 2003–04. U.S. *Geological Survey Scientific Investigations Report 2005-5184*, 27 p.

Crowe, A.; Hayes, J.; Stark, J.; Strickland, R.; Hewitt, T.; Kemp, C. (2004). The current state of the Maitai River: a review of existing information. Prepared for Nelson City Council. *Cawthron Report No. 857*, 166 p.

Depree, C. (2008). Contaminant characterisation and toxicity of road sweepings and catchpit sediments: Towards more sustainable reuse options. *Land Transport NZ Research Report 345*. 114 p.

DiBlasi, C.J. (2008). The effectiveness of street sweeping and bioretention in reducing pollutants in stormwater. Master of Science (MSc) Thesis in Civil Engineering. University of Maryland Baltimore County (UMBC).

Elgin (Elgin Sweeper Company). (2008). Stormwater, Street Sweeping, Vacuum Cleaning & Vacuum Excavation. Brochure produced by Elgin Sweeper Co. (Subsidiary of Federal Signal Corp.), USA. [Available from: http://www.elginsweeper.com/pdf/StormwaterBrochure.pdf]

Giles, B. (2009). Reducing Storm-water pollution through effective street sweeping: Street sweeper pickup performance test results for Elgin Sweeper. Elgin Sweeper, Elgin, Illinois, 16 p.

Herngren, L.; Goonetilleke, A.; Ayoko, G.A. (2005). Understanding heavy metal and suspended solids relationships in urban stormwater using simulated rainfall. *Journal of Environmental Management 76*: 149–158.

Horwatich, J.A.; Bannerman, R.T. (2009). Pollutant loading to stormwater runoff from highways: Impact of a highway sweeping program (Phase II, Madison, Wisconsin. Wisconsin Department of Transportation. *Final Report No. 0092-04-04,* 136 p.

Pacific Water Resources (2006). Pavement Cleaning. Information fact sheet, Pacific Water Resources, Inc., Beaverton, Oregon, May 2006. 4 p. [Available from http://www.pacificwr.com/Publications/PavementCleaning.pdf].

Pitt, R. (1979). Demonstration of nonpoint source pollution: abatement through improved street cleaning practices. *EPA-600/2-79-161*. U.S. Environmental Protection Agency. Cincinnati, Ohio.

Pitt, R. (1985). Characterizing and controlling urban runoff through street and sewerage cleaning – Project Summary. *United States Environmental Protection Agency Research and Development Report EPA/600/S2-85/038 June 1985*. Water Engineering Research Laboratory, Cincinnati, Ohio, 8 p.

Sartor, J.D.; Boyd, G.B. (1972). Water pollution aspects of street surface contaminant. *U.S. Environmental Protection Agency, EPA-R2-72-081.*

Sartor, J.D.; Gaboury, D.R. (1984). Street sweeping as a water pollution control measure: lessons learned over the past ten year. *The Science of the Total Environment 33*: 171–183.

Selbig, W.R.; Bannerman, R.T. (2007). Evaluation of street sweeping as a stormwater-quality-management tool in three residential basins in Madison, Wisconsin. *U.S. Geological Survey Scientific Investigations Report 2007-5156,* 103 p.

Schilling, J.G. (2005a). Street sweeping – Report No. 1, State of practice. Prepared for Ramsey-Washington Metro Watershed District. North St. Paul, Minnesota. June 2005, 40 p.

Schilling, J.G. (2005b). Street sweeping – Report No. 3, Policy development & future implementation options for water quality improvement. Prepared for Ramsey-Washington Metro Watershed District. North St. Paul, Minnesota. June 2005, 23 p.

Shaheen, D.G. (1975). Contribution of urban roadway usage to water pollution. U.S. Environmental Protection Agency, *EPA-600/2-75-004.*

Sutherland, R.C.; Jelen, S.L. (1997). Contrary to conventional wisdom, street sweeping can be an effective BMP. Chapter 9 in, *Advances in Modeling the Management of Stormwater Impacts* – Vol. 5 (ed. James, W.). Published by CHI, Guelph, Canada.

Sutherland, R.C.; Kidwell-Ross, R. (2010). 10 tips for ensuring a more environmental and cost-effective street sweeping program. On-line article at Worldsweeper.com, posted October 2010. [Available from: http://www.worldsweeper.com/Street/BestPractices/Sutherland10Tips10.10.html]

U.S. Environmental Protection Agency (1983). Nationwide Urban Runoff Program, Winston-Salem, N.C. – An evaluation of street sweeping as a runoff pollution control. Office of Water Programs, 229 p. [Available from National Technical Information Service, Springfield, VA 22161 (http://www.ntis.gov), item PB85–102507].

Vaze, J.; Chiew, F.H.S. (2002). Experimental study of pollutant accumulation on an urban road surface. *Urban Water 4*: 379–389.

Verbruggen, E.M.J.; Posthumus, R.; van Wezel, A.P. (2001). Ecotoxicological serious risk concentrations for soil, sediment and (ground)water: Updated proposals for the first series of compounds. RIVM report 711701 020. The Netherlands: Rijksinstituut Voor Volksgezondheid en Miliew (RIVM), National Institute of Public Health and the Environment. 263 p.

Walker, T.A.; Wong, T.H.F. (1999). Effectiveness of street sweeping for stormwater pollution control. *Technical Report 99/8* December 1999. Cooperative Research Centre for Catchment Hydrology, Canberra, Australia. 43 p.

Waschbusch, R.J.; Selbig, W.R.; Bannerman, R.T. (1999). Sources of phosphorus in stormwater and street dirt from two urban residential basins in Madison, Wisconsin, 1994-1995. *U.S. Geological Survey, Water Resources Investigations Report 99-4021.*

Wilkinson, J. (2007). Surface water quality in the Nelson region 2002 to 2007. Prepared for Nelson City Council. *Cawthron Report No. 1306*, 123 p.