EFFECTIVENESS OF STREET SWEEPING FOR STORMWATER POLLUTION CONTROL

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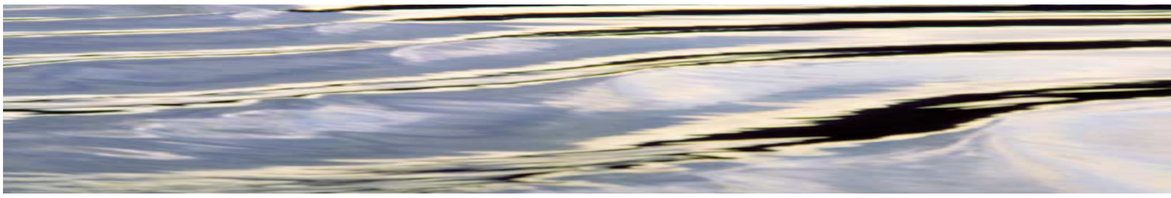

COOPERATIVE RESEARCH CENTRE FOR

CATCHMENT HYDROLOGY

Effectiveness of Street Sweeping for Stormwater Pollution Control

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Cooperative Research Centre for Catchment Hydrology

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Preface

This report investigates the effectiveness of street sweeping as a stormwater pollution source control measure. The Cooperative Research Centre for Catchment Hydrology (CRCCH) Project U1 (Gross pollutant management and urban pollution control ponds) focuses on ways to improve the quality of stormwater runoff. The project covered means to reduce gross pollutants both before and after they entered the piped stormwater drainage system. This report describes a scoping study to assess the efficiency of Australian street sweeping practices in the removal of pollutants from street surfaces. This study has provided information on the effectiveness of street sweeping, currently practiced, in the collection of pollutants across the range of particle sizes representative of a street surface load.

It is a pleasure to acknowledge the contribution of Tracey Walker and Tony Wong to the Urban Hydrology Program. This work has provided important insights into the limited role street sweeping plays in improving stormwater quality.

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Executive Summary

Street cleansing is a common (and expensive) practice undertaken by most urban municipalities with annual expenditure by a municipality often exceeding one million dollars. Street sweeping, essentially the operation of large trucks for cleaning street surfaces, is primarily performed for aesthetic purposes. It is, often perceived to lead to improvements in the environmental conditions of urban waterways by preventing pollutants deposited on street surfaces from reaching the stormwater system. There is, however, little available evidence to quantify the extent to which street sweeping can improve stormwater quality. This report investigates the effectiveness of street sweeping for stormwater quality improvement.

The effectiveness of street sweeping for stormwater pollution control is examined for two types of pollutants, gross pollutants (> 5 mm) and sediment (including associated pollutants). The research literature on street cleaning indicates a general dearth of studies that address the issues of gross pollutant management. Most studies predominantly examine the effectiveness of street sweeping for sediment and associated contaminant removal. This study looks at the effectiveness of street sweeping for gross pollutants using the results of Australian field studies, while sediment and other suspended solid removal is investigated with interpretation of results from overseas studies.

Experimental studies overseas found street sweeping to be highly effective in the removal of large solids greater than 2 millimetres under test conditions. However, field conditions are expected to significantly reduce the efficiency of solid removal because of limitations with sweeper access to source areas (mainly due to street design and car parking), sweeping mechanisms used and operator skills. Field studies undertaken by the Cooperative Research Centre for Catchment Hydrology (CRCCH) in Australia found significant stormwater gross pollutant loads generated from source areas in spite of a daily street sweeping regime.

An earlier CRCCH study, involving analysis of gross pollutant loads from a 50 hectare urban catchment of mixed residential, commercial and industrial land-use, found a clear relationship between the gross pollutant load in the stormwater system and the magnitude of the storm event. The shapes of the curves relating gross pollutant load to event rainfall and runoff were found to be monotonically increasing and representable by a logarithmic function. The shape of these curves suggests that the limiting mechanism affecting the amount of gross pollutants entering the stormwater system is rainfall dependent (ie. the available energy to re-mobilise and transport deposited gross pollutants on street surfaces) rather than being source limiting (ie. the amount of available gross pollutants deposited on street surfaces).

Overseas studies indicate that street sweeping is relatively ineffective at reducing the street surface load of fine particles (below 125 µm). The particle size distribution of suspended solids conveyed in stormwater in Australian conditions typically range from 1 µm to 400 µm with approximately 70% of the particles smaller than 125 µm. Therefore, street sweeping as it is currently practiced cannot be expected to be effective in the reduction of suspended solids and associated trace metals and nutrient concentrations in stormwater.

The study concludes that the performance of street sweeping for stormwater pollutant control is limited and must be accompanied by structural pollutant treatment measures to effectively reduce the discharge of gross and sediment associated pollutants in stormwater. The incremental benefits in increasing the frequency of street sweeping beyond what is required to meet street aesthetic criterion is expected to be small in relation to water quality improvements. As a result, there seems little benefit in conducting an in-depth field-based study into the effectiveness of street sweeping for stormwater pollution control.

Acknowledgements

The authors of this report would like to acknowledge the continued assistance and support provided by the Moreland City Council, particularly the cleansing manager, Les Horvath for sharing his knowledge of street cleaning operations. Many thanks to all those who were interviewed for Council information, especially Peter Barton from the City of Greater Dandenong who also arranged participation in an early morning street sweeping program.

In addition, Ranger Kidwell-Ross from American Street Sweeper magazine is thanked for his help and direction, and Roger Sutherland for forwarding current literature from America. The authors also wish to acknowledge in particular Dr Robin Allison for his advice and discerning suggestions, and Dr Francis Chiew for his comments and input.

1 Introduction

This report presents the findings of an investigation on the effectiveness of current Australian street sweeping practices in the collection of pollutants across the typical range of particle sizes found on street surfaces. The study was initiated to define and scope a further more-detailed field-based study to quantify the effectiveness of current street sweeping practices as an at-source stormwater pollution management measure. The term street sweeping is used here to describe essentially the operation of large trucks to remove deposited litter and debris from the kerb and channel of major roadways, streets, and carparks. The study examines the effectiveness of street sweeping practices to remove pollutants of two types:- (i) gross pollutant and litter removal and (ii) sediment and associated contaminant removal.

Over the past decade there has been an increase in the management of urban stormwater to protect urban waterways and receiving waters. These initiatives have, in part, resulted from community awareness of environmental impacts of urban stormwater pollution and their expectation that urban aquatic ecosystems should be protected from further environmental degradation.

Pollutants generated from urban land-use activities are transported by stormwater to urban receiving waters. Pollutants washed off street surfaces include gross pollutants, sediment and associated metals, nutrients, hydrocarbons and dissolved pollutants. Increased volumes of stormwater runoff and discharge rates resulting from increased impervious surface areas and hydraulically efficient drainage infrastructure throughout urban catchments have meant that the transport of urban pollutants to receiving waters is particularly efficient.

Most urban metropolitan councils perform cleansing of streets and similar impervious surfaces. This is commonly for the purpose of controlling gross pollutants, particularly litter, to maintain a level of street cleanliness and aesthetic quality. The focus on environmental issues is growing and local authorities are now considering street sweeping as a beneficial at-source method for reducing the amount of street borne pollutants entering the stormwater system. The actual contribution of street sweeping to the abatement of stormwater pollution is however not well understood. The objectives of street sweeping for street aesthetics and stormwater pollution control are very different, with the former placing particular emphasis on the visual impact of environmental pollution while the latter encompasses a much wider range of pollutant types and sizes. Despite street sweeping being widely considered an at-source stormwater pollution control method its effectiveness is unknown.

This report undertakes an interpretation of relevant street sweeping literature, research and survey results. The background to street sweeping operations, focusing on the effectiveness of sweeping for removal of street surface pollutants, is established in Section 2. The methodology undertaken for this investigation is discussed in Section 3. Results from a survey of 21 Melbourne Metropolitan councils on street sweeping practices are assessed in Section 4, to establish an understanding of current operations, target pollutants and sweeping frequencies. The different types of street sweeping mechanisms and their measured effectiveness are examined in Section 5. Pollutant types found on street surfaces are reviewed in Section 6, including an analysis of Australian sediment characteristics to assess the influence of street sweeping practices on fine particulates and associated contaminants.

Inter-event dry periods can influence street sweeping effectiveness and these are determined using Australian rainfall statistics in Section 7, and compared with current sweeping frequency and timing information. Section 8 examines field data to determine gross pollutant load generation and the influence of catchment land-use and associated sweeping frequency on pollutant load. The impact street sweeping has on gross pollutant loads entering the stormwater drainage system is discussed in Section 9, highlighting important issues affecting current sweeping efficiencies. Section 10 concludes with a summary of specific observations from each of the sections of the report from which the effectiveness of street sweeping as a stormwater pollution control method is assessed.

2 Background

2.1 Street Sweeping Pollutant Removal Monitoring

The role and usefulness of street sweepers to control street surface pollutants was first investigated in the late 1950's and early 1960's by the United States Environmental Protection Agency (US-EPA) and its associated researchers. Many of the US-EPA's National Urban Runoff Program (NURP) studies measured the efficiency of street sweeping as a stormwater pollution control method with particular emphasis placed on sediment and sediment-bound contaminants.

Since the late 70's studies have measured street sweeping effectiveness in terms of the reduction in end-of-pipe runoff pollution concentrations and loads rather than assessing the effectiveness of specific equipment. Sartor and Boyd (1972) found sweeping schedules based on a seven day cycle to be almost totally ineffective while daily sweeping was shown to potentially have a high level of pollutant removal for larger sized pollutants typical of street surface material (Sartor and Gaboury, 1984). Pitt and Shawley (1982) and Bannerrnan et al. (1983) concluded that only minor benefits to stormwater quality are provided by street sweeping practices. However, Terstrierp et al. (1982) and Pitt and Bissonette, (1984) demonstrated that street sweeping collects significant amounts of particles, for select particle size ranges, from street surfaces. The overall conclusion reached by the US-EPA, was that, as a water quality best management practice, street sweeping did not appear to be effective at reducing end-of-pipe urban runoff pollutant loads.

Subsequent investigations into the effectiveness of street sweeper mechanisms for water quality improvement report findings that vary to those presented in the conclusions of the earlier NURP studies. Alter (1995) and Sutherland and Jelen (1996b) assert that the NURP studies concluded that street sweeping is largely ineffective, because the sweepers used at the time of these studies were not able to effectively remove very fine accumulated sediments which are often highly contaminated. Sutherland and Jelen (1996a) suggest that street sweeping can significantly reduce pollutant washoff from urban streets due to the improved efficiencies of newer technologies now employed to conduct street sweeping in some American states. Their investigations showed that when street sweeping mechanisms and programs are designed to remove finer particles (ie. small-micron surface cleaners or tandem sweeping) it can benefit stormwater runoff quality.

2.2 Modelling Sweeper Pollutant Removal Efficiencies

Sweeping technologies with the ability to effectively remove accumulated sediments, including fine particles, may significantly increase the efficiency of sweeping for the removal of a variety of stormwater pollutants. Sutherland and Jelen (1993) described the use of a calibrated version of the Simplified Particle Transport Model (SIMPTM) as being able to accurately simulate the complicated interaction of accumulation, washoff, and street sweeper removal that occurs over a time period. For varying street sweeping operations Sutherland and Jelen (1997) employed the SIMPTM to predict the average annual expected reduction in total suspended solids (TSS) at two sites in Portland, Oregon. Sweepers used in their simulations included the NURP era broom sweeper, a mechanical broom sweeper, a tandem operation involving a mechanical broom followed by a vacuum sweeper and a newer technology, the small-micron sweeper. The predicted reductions in TSS showed that all of the newer street sweeping technologies are significantly more effective than the NURP era broom sweeper. It was further concluded that new street sweeping technologies designed for effective removal of fine particles, are capable of removing significant sediment loads and associated pollutants from urban street surfaces.

In a further study Sutherland and Jelen (1998) compared the new small-micron street sweeping technology to wet vaults, a widely used stormwater quality treatment method. The ability of the small-micron street sweeper to achieve significant reductions in urban pollutant washoff led Sutherland and Jelen to consider it an effective Best Management Practice (BMP) for stormwater pollution control.

2.3. Factors Influencing Street Sweeping Effectiveness

The pollutant reduction effectiveness of any street sweeping operation is dependent on the equipment used and the environmental and geographic conditions (eg. wind and presence of parked vehicles). Unless other influential factors (such as street parking) are addressed, the efficiency of individual sweeping mechanisms can be a relatively insignificant factor in the overall effectiveness of street sweeping operations. It is anticipated that the effectiveness of street sweeping programs depend more on factors such as land-use activities, the inter-event dry period, street sweeping frequency and timing, access to source areas and sweeper operation than the actual street sweeping mechanism. These factors all influence the deposition, accumulation and removal rates of pollutants on street surfaces. Physical features such as the degree of catchment imperviousness and the hydraulic characteristics of street surfaces can also influence the effectiveness of street sweeping. These factors require consideration before a thorough assessment of street sweeping efficiency for stormwater pollution control can be achieved.

3 Methodology

This study assesses the effectiveness of street sweeping for stormwater pollution control by:

- reviewing previous studies on sweeper performances and street pollutant characteristics,
- reviewing objectives for street sweeping operations (eg. aesthetic),
- considering rainfall distributions with street sweeping frequency and timing to investigate likely sweeper performance,
- examining field data from an earlier CRC study and others on gross pollutants,
- investigating the potential effects of changing street sweeping regimes on the gross pollutant loads in stormwater.

This study interprets available Australian and overseas field data on the measured efficiencies of street sweeping and street surface sediments. Various studies describing the particle size distribution of sediment loads were also collated to provide an insight into the particle size distribution pattern of suspended solids typical of street surface runoff. Some significant overseas studies on the partitioning of sediment sizes and the contaminant associations (eg. metals and nutrients) with each particle size partition were used to assess the pollutants likely to be discharged into the stormwater system from street surfaces. Information regarding street sweeping efficiencies and sediment contaminant associations from these studies are combined with data on Australian stormwater suspended solids characteristics to enable an assessment of street sweeping practices on removal of fine particulate associated pollutants.

A survey of street sweeping practices amongst municipalities in Melbourne was carried out to examine current sweeping objectives, procedures and mechanisms in these municipalities. This survey was also used to determine the perceived effectiveness of street sweeping in maintaining a certain standard of street aesthetics. Australian rainfall distributions were then examined and used to assess typical statistics of inter-event dry periods for Melbourne and other major capital cities in Australia. Melbourne inter-event periods were compared to the surveyed results of typical sweeping frequency and timing to investigate likely sweeper performance. This information facilitates a “hydrological basis” for selecting a street sweeping frequency that would optimise gross pollutant removal.

The study also examines data obtained from field studies previously undertaken by the CRC for Catchment Hydrology and others to investigate the effectiveness of street sweeping on litter and gross pollutant removal. Gross pollutant load data gathered at 192 side entry pit traps (SEPTs - baskets fitted into roadside stormwater entry pits) in the suburb of Coburg in Melbourne by Allison et al. (1998) were grouped according to the street sweeping frequencies in their respective streets. Similar data are available at two further study catchments in the suburbs of Carnegie and McKinnon in Melbourne (Hall and Phillips, 1997). The load data captured by the SEPTs during a typical street sweeping program are used to evaluate the amount of gross pollutants typically entering the stormwater system under normal Melbourne street sweeping frequencies and conditions. While it was not possible to compute a measure of pollutant removal efficiency owing to an inability to account for pollutants by-passing the SEPTs, the data nevertheless provided an insight on what might be the expected gross pollutant export load from streets that are swept at regular intervals.

4 Melbourne Street Sweeping Practices

4.1 Street Sweeping Operations

The responsibility of keeping urban streets clean, commonly by sweeping road surfaces with large vacuum trucks is an operation carried out by local government. A survey of 21 Melbourne metropolitan councils was performed to determine the motivation for the large expenditure on street cleaning. The results indicated that street sweeping is primarily undertaken for aesthetic purposes in response to community expectations. Table 4.1 summarises the street sweeping practices of 21 municipalities in Melbourne.

4.2 Target Pollutants

Street cleansing programs are generally designed to concentrate on collecting human derived litter to address the obvious visual impacts. However, during autumn, organic matter becomes a focus and the sweeping frequency is altered to reduce the safety hazard associated with decomposing leaf litter on street surfaces and to reduce drain blockages. Street surface sediment collection was not identified as a major issue when designing street sweeping programs.

Street cleansing programs involve what is often termed ‘building line to building line’ cleansing, incorporating footpath cleaning, and the standard kerb and channel street sweeping where it is apparent a large proportion of litter accumulates. This requires a combination of cleansing methods and equipment for the successful removal of such pollutants. Australian streets are cleaned customarily with large truck mechanical broom and vacuum systems. However, it is becoming common practice to operate smaller broom and vacuum sweepers designed for cleansing areas inaccessible to the traditional larger plants. The most commonly used sweepers are the regenerative air model, for both large truck and small plant systems.

4.3 Contracts and Sweeping Frequency

Under new competitive tendering legislation, the bidding process for street cleansing contracts establishes a requirement for operators to become very competitive. Contractor performance is measured against output based specifications set by the council. This means the council stipulates a set of cleanliness requirements they wish to achieve with a street cleansing program but not the frequency or operation methods used. Street sweeping practices therefore differ considerably between Melbourne metropolitan councils. Street sweeping frequencies can range from every two weeks to every six weeks in residential areas and from daily to every two weeks in commercial areas. Shopping centres and commercial areas are swept more frequently, typically ranging from once or twice a day in busy areas and once or twice a week in less popular areas. Street sweeping frequencies for residential areas range from once a week for highly populated areas to every six weeks in less populated areas.

Table 4.1 Street Sweeping Practices for Melbourne Municipalities

COUNCIL	PURPOSE	TARGET POLLUTANT	CONTRACT	FREQUENCY		SWEEPING MECHANISM	COUNCIL PERSPECTIVE
				Commercial	Residential		
Bayside:							
Hobsons Bay	Aesthetic	Litter / Leaves	Internal (3-5yrs)	1 day	4 weeks	Regenerative	Effective
Port Phillip	H&S / SW / CD	Litter / Leaves	Internal (3-5yrs)	1 day	2 weeks	Regenerative	Effective
Bayside	SW / aesthetics	Litter / Leaves	Internal (3-5yrs)	1 day	3 weeks	Regenerative	Effective
Kingston	SW / aesthetics	Litter / Leaves	External (3-5yrs)	1 day	5 weeks	Regenerative	Effective
Inner City:							
Banyule	Amenity / SW	Litter / Leaves	Internal (3-5yrs)	2 weeks	5 weeks	Regenerative	Effective
Boroondara	Aesthetics / H&S / SW	Litter / Leaves	Internal (3-5yrs)	3-7 days	4 weeks	Regenerative	Effective
Glen Eira	CD	Litter / Leaves	External (3-5yrs)	1-3 days	4 weeks	Regenerative	Not Effective
Manningham	Amenity / SW / CD	Litter / Leaves	Internal (3-5yrs)	1 day	6 weeks	Regenerative	Effective
Whitehorse	Aesthetics / SW	Litter / Leaves	Internal (3-5yrs)	1 day	3 weeks	Regenerative	Effective
Stonnington	Amenity / Aesthetics	Litter / Leaves	Internal (3-5yrs)	1 day	1-2 weeks	Regenerative	Effective
Moonee Valley	SW	Litter / Leaves	Internal (3-5yrs)	1 day	6 weeks	Regenerative	Effective
Melbourne City	CD / amenity	Litter / Leaves	External (3yrs)	1 day	2 weeks	Regenerative	Effective
Maryibynong	CD / aesthetics	Litter / Leaves	Internal (3-5yrs)	1 day	2 weeks	Regenerative	Effective
Monash	Aesthetic / CD / SW	Litter	Internal (3-5yrs)	1 day	6 weeks	Regenerative	Not Effective
Moreland	CD / aesthetics / SW	Litter / Leaves	Internal (3-5yrs)	1 day	2 weeks	Regenerative	Effective
Outer City:							
Brimbank	SW / CD	Litter / Leaves	Internal (3-5yrs)	1 day	5 weeks	Regenerative	Effective
Hume	Amenity / SW	Litter	Internal (3-5yrs)	1 day	4 weeks	Regenerative	Effective
Greater Dandenong	CD / amenity	Litter / Leaves	Internal (3yrs)	1 day	17 days	Regenerative	Effective
Knox City	SW / CD	Litter / Leaves	Internal (3-5yrs)	2 days	5 weeks	Regenerative	Effective
Moroondah	CD / amenity / SW	Litter	Internal (3-5yrs)	1 day	21 days	Regenerative	Effective
Nillumbik	Aesthetic / SW	Litter / Leaves	Internal (3yrs)	1-2 weeks	4 weeks	Regenerative	Effective

Note: Councils not listed were conducting tender negotiations for street sweeping practices during the time of the survey.
H & S = Health and Safety
SW = Stormwater Quality
CD = Community Demand

4.4 Council Perspective of Effectiveness

All but two councils indicated that street sweeping as it is currently practiced was an effective way of collecting litter. Numerous councils stated that street sweeping aided in the prevention of litter entering the stormwater system and therefore reduced the occurrence of stormwater pollution and drain blockage but had no data to validate these observations. Several councils regarded street sweeping as effective only when practiced in conjunction with other source pollution control methods such as bins, side entry pit traps and other gross pollutant traps.

Overall the survey indicated a general satisfaction with the effectiveness of street sweeping in collecting human derived litter and organic matter (gross pollutants) for aesthetic objectives. However, there is little quantitative information for councils to assess the effectiveness of street sweeping practices on stormwater pollution reduction. Throughout the literature there are many suggestions that street sweeping can have an effect on stormwater quality although the degree to which this practice is effective is unknown.

The assessment of the effectiveness of street sweeping in stormwater pollution control rather than just aesthetic requirements will need a detailed analysis of the following major influencing factors.

- street sweeping mechanism
- pollutant types (from sediment and associated contaminants to gross pollutants)
- sweeping frequency & timing
- pollutant load wash-off characteristics

Each one of these factors is examined in detail in the following sections of this report.

5 Street Sweeping Mechanisms

5.1 Types of Sweeping Mechanisms

Types of street sweeping mechanisms commonly utilised in Australian practice include:

1. Mechanical broom sweepers involving a number of rotating brushes sweeping litter into a collection chamber;
2. Mechanical broom and vacuum systems involving the combination of rotating brushes and a vacuum to remove street litter;
3. Regenerative air sweepers which are like mechanical vacuum sweepers but use recirculated air to blast the pavement, dislodging litter before it is swept by rotating brushes towards a vacuum for pick-up. This sweeper also uses water sprays for dust suppression,
4. Small-micron surface sweepers which combine rotating brooms enclosed in a powerful vacuum head in a single unit, performing a dry sweeping/vacuuming operation. A powerful fan pulls debris and air into a containment chamber before the air is finally passed through a series of filters to capture small micron material.

5.2 Sweeper Effectiveness

Pitt and Bissonnette (1984) found following a period of street sweeping trials that street sweeping equipment was unable to remove particles from the street surface unless the loadings were greater than a certain threshold amount. This value was found to be three times higher for a mechanical broom cleaner, most referred to in the US-EPA's NURP studies, compared to the regenerative air street sweeper trialed for a comparison in a study by Pitt and Bissonnette (1984). The study found the regenerative air vacuum sweeper to exhibit a substantially better performance than the regular mechanical street sweeper, especially for the smaller particle sizes. Such findings have progressively led to the mechanical broom method being replaced by the vacuum system method for street sweeping practices. The removal effectiveness data for the smallest particle sizes (less than 125 μm) between the two methods of street sweeping was however found to be inconclusive.

The regenerative air vacuum sweeper (Figure 5.1) is a common mechanism used for street sweeping in Australia. The recirculating air cycle tends to improve the effectiveness of sweepers for the removal of heavy debris but is less effective for removing fine sediment. The air blast is able to dislodge heavier

Figure 5.1 Australian streets are cleaned with large truck vacuum sweepers

materials and propel them into the vacuum airflow however finer materials often remain uncollected (Pitt and Bisonnette,1984). Fine particles may become airborne as a result of the air blast and take some time to settle back onto the road surface or may be left behind on the street surface.

The most recent technology to be employed for street sweeping is a highly effective, vacuum-assisted dry sweeper (the small-micron surface sweeper) originally developed and manufactured by Enviro Whirl Technologies Inc in the United States of America. The sweeper was originally developed for the containment of spilled coal dust along railway tracks. This system is reported to be extremely effective in removing fine street surface sediments and preventing their escape into the air by filtering air emissions down to sizes as small as 4 µm. Sutherland and Jelen (1997) described this system as having an advanced ability, when compared to other sweeping mechanisms, to remove a broad range of particles from road surfaces down to sub micron particulates. The small-micron surface cleaning technology has been shown by Sutherland and Jelen (1997) to have total removal efficiencies ranging from 70% for particles less than 63 µm up to 96% for street surface pollutants larger than 6370 µm.

Despite there being new street sweeping technologies reported to be more efficient, most municipalities and private street sweeping companies in Australia continue to use the mechanical broom and regenerative air vacuum street sweepers. This is because of the high capital costs of newer technologies and their limited availability on the Australian market.

Street Sweeping Mechanism:

- Mechanical and regenerative air street sweeping equipment requires a minimum threshold load of sediment on the street surface before they become effective.
- The threshold load can be three times higher for the mechanical sweeper compared to the regenerative air system.
- Overall the regenerative air sweeper exhibits a substantially better performance than the regular mechanical sweeper.
- Street sweeping technology is developing and improving to remove finer street surface particles for a variety of street surface loads,

6 Pollutant Types

The effectiveness of street sweeping to remove pollutants, across the typical range of particle sizes found on street surfaces, has not yet been successfully quantified for Australian conditions. The examination of street sweeping effectiveness in the present study focuses on two pollutant types:- (i) gross pollutants and litter and (ii) sediment and associated contaminants. Gross pollutants have been defined as any solids that are retained by a 5 mm mesh screen by Allison et al. (1998) and this definition is adopted here. Solids washed off street surfaces which are smaller than 5 mm and not considered to be gross pollutants include a proportion of litter and organic matter but are predominantly sediment particles, typically between the course sand to fine silt range, and sediment associated contaminants.

6.1 Gross Pollutants

Allison et al. (1997a) undertook an investigation into the types of gross pollutants derived from an urban catchment. The study found typical urban gross pollutants transported by stormwater to include litter (predominantly paper and plastics) and vegetation (leaves and twigs) as shown in Figure 6.1. Organic matter comprised the largest proportion by mass of the collected gross pollutants and therefore should be a major consideration in street cleaning programs. The data was based on field monitoring of gross pollutants retained in a Continuous Deflective Separation (CDS) unit treating a catchment area of 50 hectares in Coburg, an inner city suburb of Melbourne.

Only a small number of investigations have examined street sweeping effectiveness on gross pollutant removal. Nilson et al. (1997) conducted an investigation into source control of gross pollutants in Adelaide and attempted to assess the efficiency of street sweeping for gross pollutant removal in stormwater. This study sought to quantify the amount of gross pollutants entering the drainage network in three similar streets swept at different intervals. Catch baskets in side entry pits were used to collect gross pollutants which were not otherwise collected by the sweeper for a street swept every day, once a week, and not at all. Trapped pollutants in these

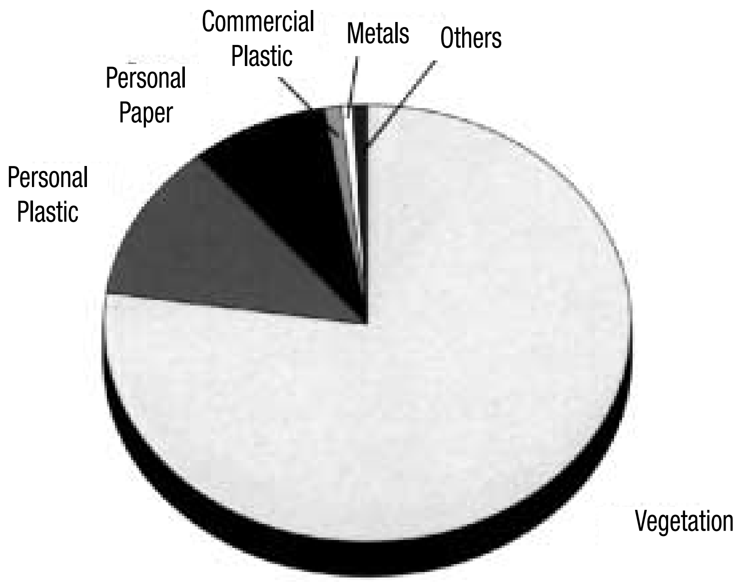

Figure 6.1 Composition of Gross Pollutants by Mass (Allison et al., 1998)

baskets were removed and quantified weekly during the study.

The results of the study by Nilson et al. (1997) show little correlation between the frequency of sweeping, rainfall or wind-run in the catchment with the gross pollutant load collected in the catch baskets. The study provided little conclusive information on the effectiveness of street sweeping with respect to gross pollutants. The study found that typically, a significant amount of gross pollutants were mobilised into the stormwater system from the street during bursts of rain, wind or both, irrespective of the nature of the street sweeping program implemented. These results suggest the amount of gross pollutants or street surface load does not limit the amount transported into the stormwater system regardless of the street sweeping frequency.

The observed composition of the gross pollutant material collected by Nilson et al. (1997) was consistent with other studies conducted by Sartor and Boyd (1972), O'Brien (1994) and Allison and Chiew (1995), where gross pollutant loads measured in dry mass comprised approximately 70-90% organic matter, and 10-30% litter.

Broad-based investigations into street sweeping conducted by the US-EPA suggest that street sweeping efficiency increases with particle size. Sartor and Boyd (1972) found sweeper efficiency to be nearly 80% for the collection of particles greater than 2 millimetres under 'test' conditions (ie. sweeping more frequently than the occurrence of rainfall events and effective use of parking restrictions). Ideal street cleaning conditions are unlikely to occur during normal street sweeping operations, and sweeper efficiencies for collecting gross pollutants would be expected to be considerably lower than the recorded 80% despite any improvements gained through refinements of equipment since the study. In practice, the effectiveness of street sweeping for gross pollutant removal is influenced by a number of factors including: access to the street load, operator skills and sweeping speed, sweeping mechanism, time of day sweeping is conducted and weather conditions.

Gross Pollutants:

- Typical urban gross pollutants transported by stormwater include litter (predominantly paper and plastics) and vegetation (leaves and twigs).
- Significant amounts of gross pollutants are mobilised into the stormwater system during bursts of rain, wind or both.
- There is little correlation between the frequency of sweeping and the transport of gross pollutants into the stormwater system.
- Street sweeping efficiency increases with particle size.
- Sweeper efficiency can be up to nearly 80% for particles greater than 2 millimetres under 'test' conditions (ie. Sweeping more frequently than the occurrence of rainfall events and effective use of parking restrictions).

6.2 Sediment and Other Suspended Solids

Street sweeping performance for smaller street surface particles depends considerably on the type of street sweeper used and also conditions such as the character of the street surface (texture, condition and type), street dirt characteristics (loadings and particle sizes), and other environmental factors (Pitt and Bissonnette, 1984).

Sartor and Boyd (1972) found the removal efficiencies of sediment by conventional street sweepers to be dependent upon the particle size range of the street surface loads as shown in Figure 6.2. Mechanical sweeper efficiency was found to be generally low for fine material. This finding was supported by two further studies conducted by Bender and Terstriep (1984) and Pitt and Bissonnette (1984), who reported that the proportion of the total street load smaller than 300 μm was less affected by street sweeping. Pitt and Bissonnette (1984) also demonstrated that no effective removal was evident for street dirt particles smaller than about 125 μm for the regenerative air sweeper.

Mechanical broom sweepers are found to be effective at collecting larger particles but less effective than regenerative-air vacuum sweepers in removing the smaller particles (Pitt and Shawley, 1982). The regenerative air vacuum sweeper, although regarded as more effective at collecting smaller particle sizes does not successfully control or remove fine particles. Problems are encountered with water-based dust suppression methods as they tend to resuspend the small micron particles and their associated attached pollutants, forming a slurry which either fills the cracks in the pavement or is discharged into the stormwater system. Similarly, fine particles can easily escape collection when they are re-mobilised into the air by the pavement blast used by the regenerative air sweeper to dislodge larger materials.

Studies by Pitt and Sutherland (1982) indicated that a significant proportion of the larger dirt particle sizes picked up by street sweepers are not easily transported by rain and that removal of these particles tends to expose the smaller sheltered particles. These smaller particles exposed by street sweeping are then more readily mobilised and transported into the stormwater drainage system during rainfall events. The small-micron surface sweeper sweeps dry, with no water being used, and thus overcomes problems associated with resuspension of fine particulates and associated pollutants by dust suppression sprays. These machines utilise strong vacuums in combination with uniquely-designed main and gutter brooms. The air filtration system, enables smaller particles to be removed from the street surface with the return of clean air to the atmosphere (ie. filters particles down to 2.9 microns). This relatively new technology is regarded to be a high-efficiency sweeper (Sutherland et al., 1998).

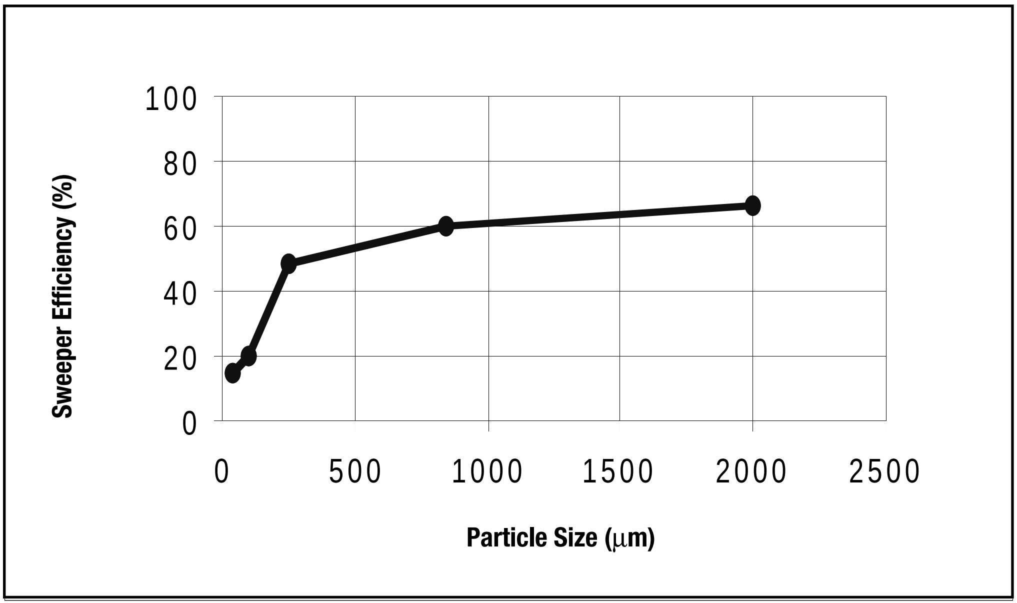

Figure 6.2 Street sweeping efficiency as a function of particle size (Sartor and Boyd, 1972)

The removal performance of street sweepers for sediment has been often determined from sampling accumulated street dirt before and after sweeping has been conducted. Initial street surface conditions are established and the street swept at a specified speed of 7-8 kilometres per hour before it is sampled to establish the residual condition. The difference between initial and residual loadings by specific particle size defines the removal performance of street sweeping operations. It was concluded from this method that sweeping removes little, if any, material below a certain threshold. This threshold load was found to vary by particle size range. A series of mathematical equations developed by Pitt (1979) to describe this removal performance have been recently calibrated and employed by Sutherland and Jelen (1996a and 1997) to evaluate and compare the removal performance of numerous street sweeping technologies.

Sutherland and Jelen (1997), using their Simplified Particle Transport Model, tested the removal performance of the small-micron sweeper, along with a regenerative air vacuum sweeper, a mechanical broom sweeper, and a tandem operation that involved a single pass by a mechanical broom followed by a vacuum sweeper. The small-micron sweeper was shown to be the most efficient, with average total removal efficiencies of 70% for particles less than 63 µm and between 77% and 96% for particle sizes ranging from 125 µm to larger than 6370 µm. The small-micron sweeper demonstrated an ability to efficiently remove particles without any threshold level unlike the other sweepers tested. The regenerative air sweeper was shown to be the second most efficient with overall removal efficiencies calculated to range from 32% for less than 63 µm range to 100% for larger particles between 600 and 2000 µm. However, the removal efficiency of the regenerative air sweeper for particles between 250 and 2000 µm can drop to zero, due to the necessity of large threshold loads for particles within this size range. The tandem operation and mechanical broom sweeper were found to be the least efficient despite some recorded high efficiencies. This can be mainly attributed to the high threshold loads required by these operations before any significant sediment removal is recorded.

6.3 Contaminants Associated with Sediment

It is well recognised that a significant amount of metals and nutrients are transported as sediment-bound contaminants. Many investigations have found the concentration of sediment-bound contaminants to vary with particle size, with high concentrations of contaminants attached to the finer particles (Sartor & Gaboury 1984, Sartor & Boyd 1972). Hvitved-Jacobsen et al. (1991, 1994) investigated road runoff pollutant characteristics and found 60-80% of phosphorous, 30-40% of zinc, 70-80% of lead, 30-40% copper and about 55% of total nitrogen in road

Sediment and Other Suspended Solids:

- The removal efficiency of sediment and other fine organic particles by conventional street sweepers was found to be dependent upon a threshold level of load on the surface and the particle size range of the surface loads.
- Material smaller than 300 µm was less affected by street sweeping.
- No effective removal (>50% removal efficiency) was evident for particle sizes smaller than 125 um for conventional street sweepers (excluding the new small-micron surface cleaning technology).

runoff to be associated with particulates. While most particulate matter found on street surfaces is in the fractions of sand and gravel. Approximately 6% of particles are in the silt and clay soil size and they were found to contain over half the phosphorous and some 25 percent of other pollutants, as indicated in Table 6.1, adapted by Shaver (1996) from results of Sartor et al. (1974).

Many other investigations have found the concentrations of sediment-bound contaminants in street dirt to be associated with the fine particle size fraction. Pitt & Amy (1973), NCDNRCD (1993) and Woodward-Clyde (1994) have all shown that higher concentrations of pollutants such as heavy metals are associated with the smallest particle size fractions of urban dust and dirt. These data indicate that almost half of the heavy metals (represented by copper, lead and zinc) found on street sediments are associated with particles of 60 to 200 µm in size and 75% are associated with particles finer than 500 µm in size. Dempsey et al. (1993) undertook an analysis of particle size distributions for urban dust and dirt, and partitioning of contaminants into a number of size fractions to determine the concentrations of contaminants in each particle size range. Results show the highest recorded concentrations of Cu, Zn and TP to be associated with sand particles between 74 and 250 µm in size.

Colwill et al. (1984) found 70% of oil and approximately 85% of polycyclic aromatic hydrocarbon (PAH) to be associated with solids in the stormwater. That study demonstrated that over a period of dry weather conditions, increasing proportions of oil become solid associated where the highest oil content was found in sediments of 200 to 400 µm in size.

Sansalone et al. (1997), Fergusson and Ryan (1984), Baker (1980) and Wilber and Hunter (1979) all reported that heavy metal concentrations increase with decreasing particle size. Results presented by Sansalone et al. (1997) from particle size distribution and metal analysis indicate that zinc, copper and lead concentrations increase with decreasing particle size or, equivalently, increasing specific surface area. The absorption of contaminants to particles is often regarded as being directly related to the surface area per unit mass available for ion absorption. Measured specific surface area results presented by Sansalone et al. (1997) indicated that the assumption of smooth spherical particles to estimate available surface area

Table 6.1 Percentage of Street Pollutants in Various Particle Size Ranges

	Particle Size (µm)					
Pollutant	**<43**	**43 - 104**	**104 - 246**	**246 - 840**	**840 - 2000**	**>2000**
Total Solids	5.9	9.7	27.8	24.6	7.6	24.4
Volitile Solids	25.6	17.9	16.1	12.0	17.4	11.0
COD	22.7	45.0	12.4	13.0	4.5	2.4
BOD	24.3	17.3	15.2	15.7	20.1	7.4
TKN	18.7	19.6	20.2	20.0	11.6	9.9
Phosphates	56.2	29.6	6.4	6.9	0.9	0.0
All Toxic Metals	27.8	-	23.5	14.9	17.5	16.3

(Source: Shaver; 1990; adapted from Sartor, Boyd, and Agardy, 1974) grossly underestimated the actual available surface area of particulates transported in stormwater. Specific surface area values were found to deviate from the monotonic pattern expected for spherical particles. Particles in the mid-range to coarser end (100 to 1000 μm) of the distribution were shown to contribute a larger surface area than would normally be expected.

The sediment binding behaviour of other toxicants such as polychlorinated biphenyls (PCB's) and polycyclic aromatic hyrdrocarbons (PAH's) is different to that of heavy metals. Schorer (1997) reported PCB's and PAH's to have no correlation with particle size distribution or surface area but rather with the abundance of organic material. Results indicated that the organic material content in different particle size fractions was bimodally distributed with maximum measurements recorded for fine silt (2 - 6.3 μm) and fine sand fractions (63 - 200 μm). Concentrations of PAH's would therefore be expected to be attached to these particle size fractions.

A substantial database, identifying particle size distributions and other parameters that relate to reactivity and mobility of contaminants, has resulted from data collected by a number of US-EPA studies. However, to date only limited information regarding the physical and chemical characteristics of urban stormwater runoff are available for Australian conditions. Results from an investigation by Mann and Hammerschmid (1989) on urban runoff from two catchments in the Hawkesbury/Nepean basin indicated the existence of high correlations between total suspended solids (TSS) with total phosphorus (TP), total kjeldahl nitrogen (TKN) and chemical oxygen demand (COD). Ball et al. (1995) found that TSS and TP show similar characteristics and correlations to other overseas studies.

In relation to street sweeper effectiveness, the association of pollutants with sediment, particularly the finer fractions, would suggest street sweeping needs to remove these particles in order to provide effective stormwater pollution control. However, street sweeping has to date been found to be generally effective only for material larger than 300 μm (see section 6.2).

Contaminants Associated with Sediment:

- Significant amounts of metals and nutrients are transported as sediment-bound contaminants.
- Most of the total mass of contaminants is associated with the fine particles.
- Conventional street sweeping is generally ineffective at removing particles smaller than 300 μm and therefore will not effectively reduce the export of sediment-bound contaminants such as nutrients, metals and PAHs.

6.4 Australian Conditions

Various studies undertaken by the US-EPA found the major constituents in street dirt to be consistently inorganic, mineral-like matter, similar to common sand and silt. This could be due to the fact that many of the US-EPA studies were conducted in cities where applications of screened sands are made to road surfaces. Street surface particulate matter has been described as having particle sizes ranging from about 3000 to 74 µm and less (Sartor and Gaboury, 1984).

A collation of reported particle size distribution curves for solids found on street surfaces and in street surface and highway runoff is shown in Figure 6.3. The collection of 20 particle size distribution curves presented in Figure 6.3 are derived from sampling solids from street surfaces and suspended sediment collected in road runoff from a number of overseas and Australian catchments.

It is evident from Figure 6.3 that despite the overseas data being collected from a variety of sources, locations and by various methods, they show a consistent distribution ranging from approximately 10 µm to approximately 10,000 µm. The particle size distributions derived from sampled road runoff from two Australian sites, one as part of an ongoing CRC project and the other by Ball and Abustan (1995), are also presented and appear to fall outside the range of the particle size distribution curves of the overseas catchments. The Australian data range from 2 µm to approximately 500 µm. There may be a number of possible explanations for this observed finer particle size distribution including differences in sampling and analysis techniques. However, it should be noted that the particle size distributions derived from overseas catchments were based on a variety of sampling and analysis techniques. The upper particle size limit can influence the position of the derived particle size distribution curve. Adjustments (Lloyd and Wong, 1999) to the overseas data to eliminate particles larger than 600 µm, to allow a common basis for comparison of these curves, still showed the Australian data sets to exhibit finer particle size characteristics. The significantly different particle size distribution of the Australian catchments may indicate fundamental differences in catchment characteristics.

The Australian sampled road runoff data displays a significantly finer particle size distribution, with a greater percentage of particles less than 125 µm (up to 70%). Although only based on sampling at two sites, the inefficiencies of street sweeping in removing particles less than 125 µm would result in little reduction of up to 70% of the particles found in runoff in these Australian catchments. The difficulty for Australian street sweeping is the fine nature of the sediment found on roads. Up to 70% of particles found on street surfaces are less than 125 µm compared to 20% for overseas road runoff data. The inefficiencies of street sweeping in the reduction of sediment-bound pollutants entering the stormwater system is therefore expected to have more severe implications under typical Australian conditions.

Removal of Sediment and Associated Contaminant:

- Limited sampling of sediment in street runoff in Australia indicates that 70% of particles are less than 125 µm compared to 20% for overseas data.
- The fine sediments found on Australian streets would suggest that conventional street sweeping will have a minimal effect on sediments and associated contaminants reaching stormwater systems.

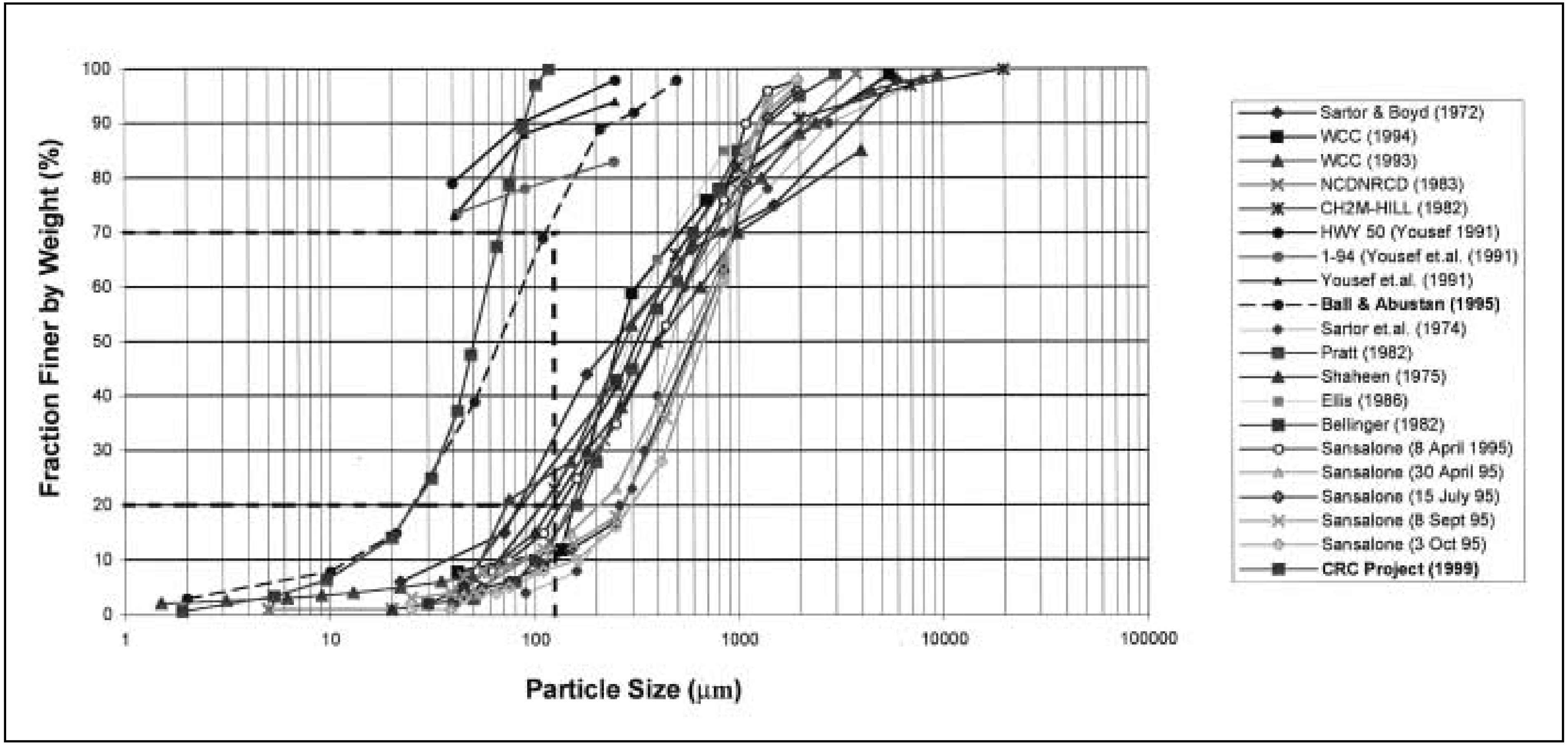

Figure 6.3 Particle Size Distribution of Suspended Solids in Road Runoff

7 Street Sweeping Frequency And Timing

7.1 Sweeping Frequency and Rainfall Patterns

Sartor and Gaboury (1984) concluded that the dominant influence on the effectiveness of street sweeping appears to be time intervals, ie. the relationship between the average interval between storm events (a function of local meteorological conditions) and the frequency at which streets are swept. Street sweeping operations are typically programmed for a fixed interval (eg. swept once per week). If the average time between rainfall events is much less than the sweeping interval, then much of the street surface load could be washed away by storm runoff, hence, making street sweeping relatively ineffective. In this context, analysis of rainfall statistics is important in the design of street sweeping programs to ensure street sweeping is compatible with the frequency of storm events and therefore optimise the effectiveness of street sweeping for removal of stormwater pollutants.

Generally street sweeping frequencies are determined according to land-use. Street sweeping frequencies, practiced by Melbourne metropolitan municipalities, generally range between daily sweeping for busy commercial areas and every six weeks for residential areas. The sweeping frequency in the CBD of Melbourne could however involve numerous sweeps throughout the day. Councils ordinarily stipulate sweeping specifications for the purpose of meeting community demands for aesthetic quality and amenity improvement. The inter-event dry period between storms is not often a factor considered when street sweeping programs are formulated. However, if municipalities are willing to incorporate stormwater management objectives into street sweeping programs, the occurrence of rainfall events should become a significant design factor.

The minimisation of pollutant washoff, particularly fine particulates and associated contaminants, from street surfaces requires compatibility of street sweeping frequency and timing with rainfall characteristics and the daily activities in the catchment. Fine particulates and associated contaminants are often mobilised with even the smallest amount of runoff while gross pollutants often require a minimum runoff rate to be reached before they are mobilised. In areas which are not swept daily, the selected street sweeping frequency should ideally reflect the relationship with the inter-event dry period (time between storm events) typical of the catchment. For those catchments currently on a daily street sweeping regime, the time of day when street sweeping is conducted should be selected to limit the period in which the pollutants deposited on street surfaces are exposed to the risk or likelihood of wash-off associated with a storm event.

7.2 Inter-Event Dry Period

It can be assumed that the majority of pollutants transported into the stormwater system occur during rainfall event periods. Therefore if the street cleaning frequency is longer than the average inter-event dry period it can be expected that the accumulated pollutants, on road surfaces, will have a higher likelihood of being washed into the stormwater system before being collected by the street sweeper.

Melbourne rainfall was characterised from analysis of rainfall over a 105 year period by Wong (1996). The analysis identified storm events as having a thirty minute minimum storm duration. A six hour minimum period of no rainfall to define the conclusion of a rainfall event. Using this definition for a storm event, the analysis found the mean period between storms in Melbourne to be 62.4 hours (2.6 days) with a standard deviation of 76.8 hours (3.2 days). There is an apparent trend in Melbourne of longer periods between storms in summer months, with a maximum mean period of 108 hours (4.5 days) in February and a minimum mean period of 45 hours (1.9 days) in August as shown in Figure 7.1. Wong (1996) also carried out an analysis of the rainfall data for a number of major cities in Australia, and the statistics according to their respective months are presented in Table 7.1. The influence of seasonality on the period between storms for the cities is shown in Figure 7.2.

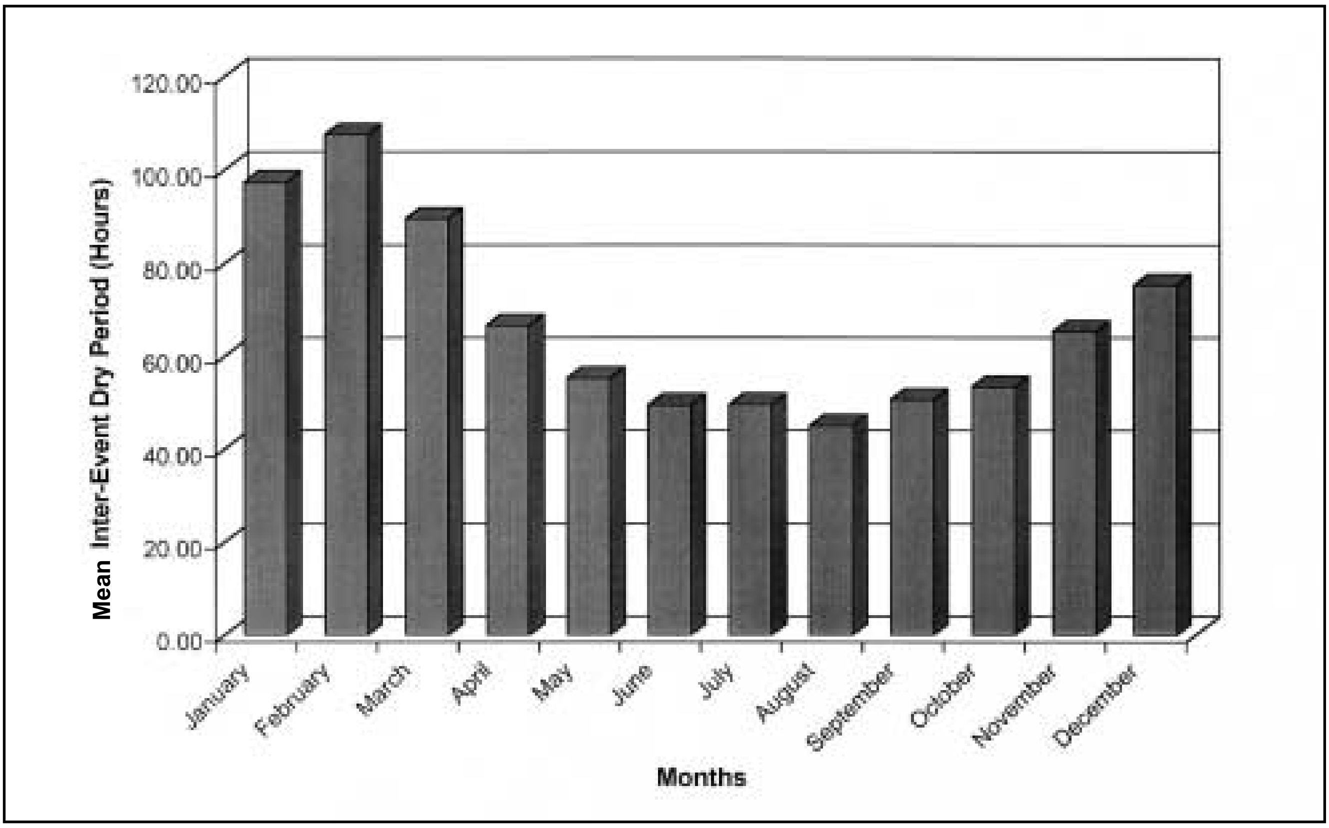

Figure 7.1 Melbourne Mean Monthly Inter-Event Dry Period

Table 7.1 Mean Inter-Event dry Periods (Hours).

CITIES	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE
Adelaide	165.93	189.42	156.52	94.81	61.07	51.16
Brisbane	65.39	57.28	58.08	74.48	93.68	111.03
Darwin	33.02	32.10	41.40	116.14	130.32	561.14
Hobart	72.33	83.26	74.79	60.86	56.24	50.69
Melbourne	97.38	107.55	89.56	66.68	55.21	49.46
Perth	250.70	238.29	200.54	89.21	58.02	39.91
Sydney	70.30	64.68	66.58	69.27	70.19	73.36

CITIES	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
Adelaide	44.02	44.45	54.94	69.63	93.96	128.95
Brisbane	133.87	141.20	126.21	90.91	81.91	72.38
Darwin	416.95	240.36	217.41	120.79	62.21	58.72
Hobart	47.94	46.93	50.47	47.26	49.03	59.92
Melbourne	49.57	45.01	50.63	53.39	65.32	75.32
Perth	39.96	53.79	62.20	88.16	141.96	193.17
Sydney	91.48	98.50	97.78	77.87	68.92	76.31

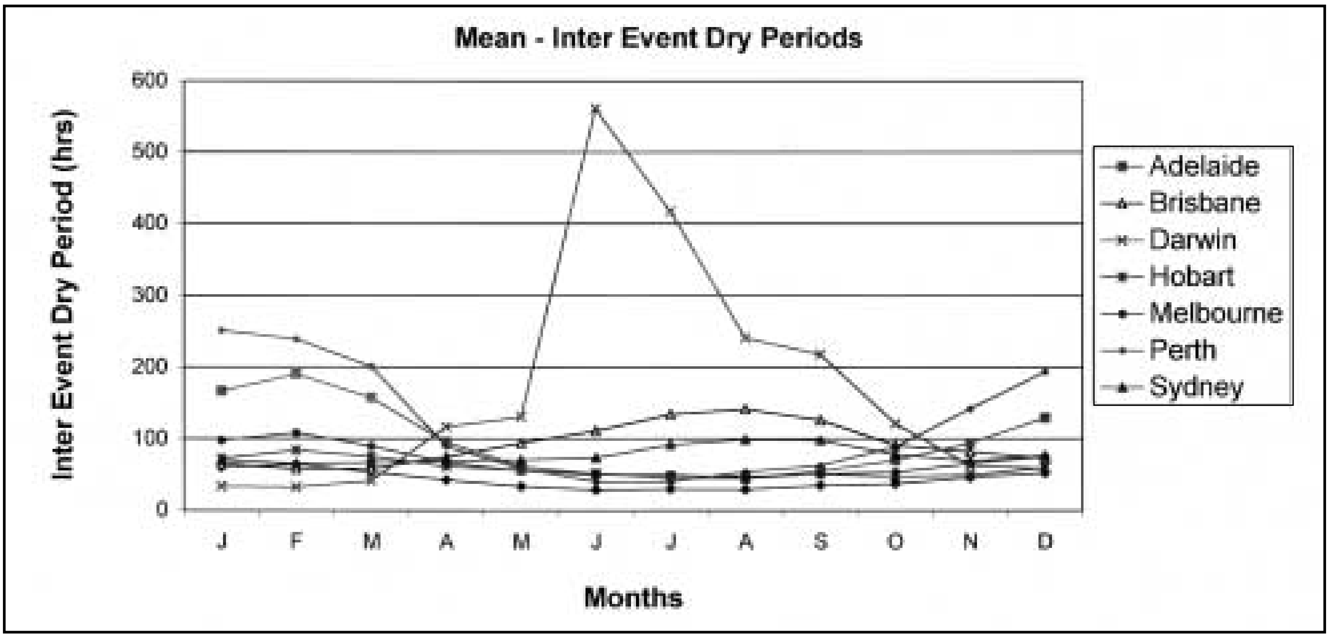

Figure 7.2 Mean Inter-Event Periods for Australian Cities

Of the cities analysed, Darwin shows the most inter-event dry period variability between seasons, ranging between 32 hours (1.3 days) and 561 hours (23.4 days), with the longer periods, unlike Melbourne, occurring during the winter months. The variable nature of inter-event dry periods, both between seasons and capital cities highlights the importance of street sweeping program design being specific to location and flexible to accommodate for season variability.

Based on consideration of typical inter-event dry periods, one would question the effectiveness of current Australian street sweeping practices in effectively preventing pollutants entering the stormwater system if the street sweeping frequency, designed for aesthetic objectives, is significantly lower than the frequency of storm events. If streets are only swept every six weeks then it is likely that storm events occurring within this period will flush a large proportion of the accumulated pollutants into stormwater drains before sweeping has the opportunity to collect it. In the case of gross pollutants, Allison et al. (1998) suggested a minimum rainfall amount before there is sufficient runoff to re-mobilise these larger size pollutants. As a gross pollutant export control, sweeping frequency equivalent to approximately three times the mean inter-event period appears to be appropriate (see Section 8.1).

Sweeping Frequency and Rainfall Patterns:

- The variable nature of inter-event dry periods, both in terms of seasonal variation and dependence on climatic locations, highlights the importance of street sweeping program designs which are specific to location and flexible to accommodate the local meteorological conditions and seasonal variability.
- It is anticipated that if street sweeping occurs at a longer interval than the inter-event dry period of the catchment, street surface pollutants will have a much higher likelihood of being flushed into the stormwater system before being collected by the street sweeper.

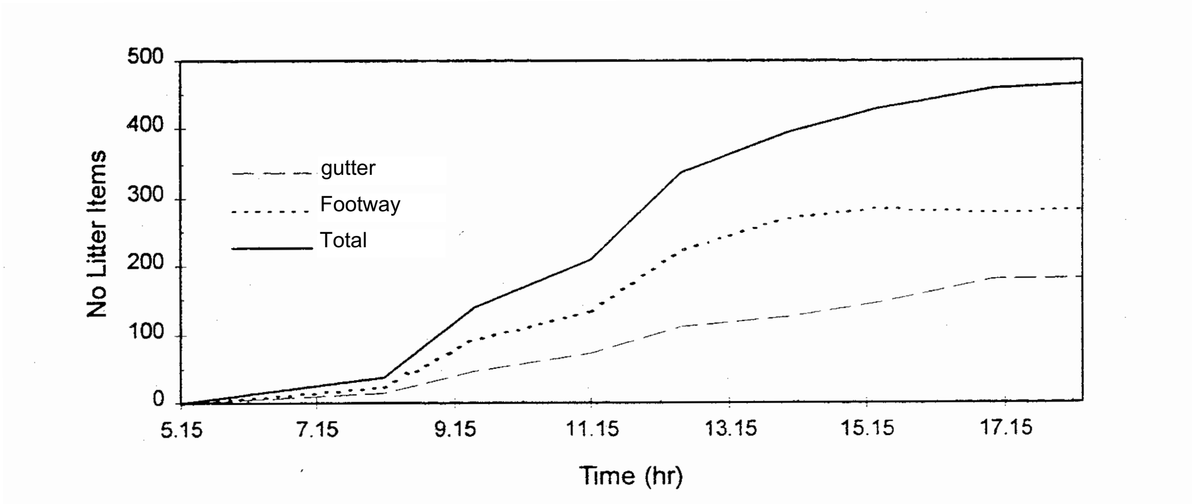

Figure 7.3 Daily Litter Generation (Hall and Phillips., 1997)

7.3 Street Sweeping Timing

Analysis of street and footpath litter accumulation along a 280 m section of strip shopping centre in the Melbourne suburb of Carnegie during a typical business day was conducted by Hall and Phillips (1997). This commercial land-use area is subject to typical street sweeping operations carried out daily by the Glen Eira municipality. Detailed recording of the gross pollutant load generated over a day from 5:15 to 18:30 commenced immediately after street sweeping and footpath cleaning and concluded when trade had effectively ended. The data indicates that the rate of accumulation of litter is highest between the times of 8:00 and 17:00 with litter accumulation effectively ending around 17:00 hours in the evening (see Figure 7.3).

The data plotted in Figure 7.3 suggest that the time of day a rainfall event occurs can alter the amount of litter available for re-mobilisation to the stormwater system. The time of day at which street sweeping is practiced is expected to have an effect on the amount of litter entering the stormwater system due to the exposure time of deposited pollutants to wash-off processes. Street sweeping is most commonly conducted in the early morning leaving the accumulated pollutants, especially litter from the day before, to a longer exposure period and the likelihood of over night rainfall events capable of flushing them into the stormwater system.

The study by Hall and Phillips (1997) also involved comparing accumulated litter items from street surfaces and side entry pit traps (SEPTs) in drains following rainfall events. The Carnegie urban catchment was monitored over a seven day period, and litter material was measured from bins, footpaths, street surfaces and SEPTs located in stormwater drain inlets. Footpath litter items were not considered when determining the effect of rainfall due to their surfaces being sheltered from rainfall and associated washoff mechanisms. When only street material is considered, up to 77% of the calculated street items entered the stormwater system during rainfall events. These data suggest that street washoff is the principal mechanism for transport of gross pollutants into the stormwater system.

Street Sweeping Timing:

- Recorded gross pollutant load generation over a typical day indicates that the accumulation of litter in a shopping strip begins at 8:00 and effectively ends around 17:00 hours.
- Early morning street sweeping allows the exposure of deposited street surface litter items to a higher likelihood of being transported into the stormwater drainage system.

8 Gross Pollutant Wash-Off Characteristics

8.1 Gross Pollutant Load Generation

The study by Allison et al. (1998) showed that stormwater runoff is the principal means by which gross pollutants are transported to the stormwater system. Ten storm events (larger than 3 mm of rainfall) and their transported gross pollutant loads in the Melbourne suburb of Coburg were monitored using the CDS unit from May to August 1996 (Allison et al., 1998). Monitoring was carried out in a 50 hectare catchment and the amount of gross pollutants transported during each of the 10 events was found to be correlated with the event rainfall depth as shown in Figure 8.1. A similarly high correlation between the gross pollutant load retained in the CDS unit and event runoff was also obtained as shown in Figure 8.2.

According to the fitted relationship between the wet gross pollutant load generated and the depth of rainfall (see Figure 8.1), events of less than 3.7 mm may be considered to be insufficient for re-mobilisation and transport of deposited street surface loads. The corresponding threshold for runoff (see Figure 8.2) is 0.70 mm. The fitted relationships between gross pollutant wet load and event rainfall depth or runoff show a trend of increasing gross pollutant load with increasing rainfall or runoff. Although the curves are monotonically increasing, the rate of increase in gross pollutant loads decreases with rainfall and runoff indicating a possible upper limit of gross pollutant load transported into the stormwater system during large rainfall or runoff events. The fitted curves in Figure 8.1 and 8.2 may be interpreted as indicating that the limiting mechanism for stormwater gross pollutant transport, in the majority of cases, is not the supply of gross pollutants but rather the processes (ie. the stormwater runoff rates and velocities) influencing the mobilisation and transport of these pollutants.

If the mobilisation and transportation of gross pollutants from the street surface depends on a rainfall depth greater than 3.7 mm, it is likely that the inter-event dry period for gross pollutant transporting storm events, in Melbourne will be longer than the calculated 2.6 days for all recorded storm events. Analysis of the cumulative frequency distribution of event rainfall depth for Melbourne over a 105 year record is presented in Figure 8.3. The analysis shows that approximately 35% of all recorded rainfall events are greater than 3.7 mm giving an average inter-event dry period of 178 hours (7.4 days) for gross pollutant transporting storm events.

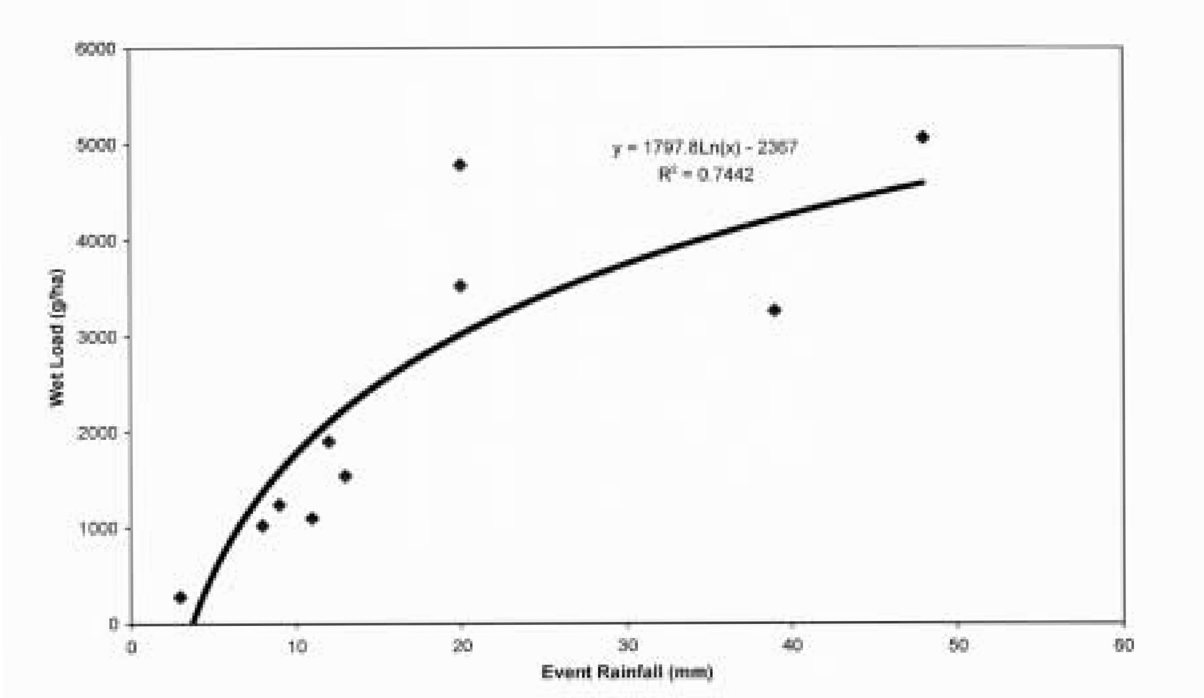

Figure 8.1 Gross Pollutant Wet Loads v's Rainfall (after Allison et al., 1998)

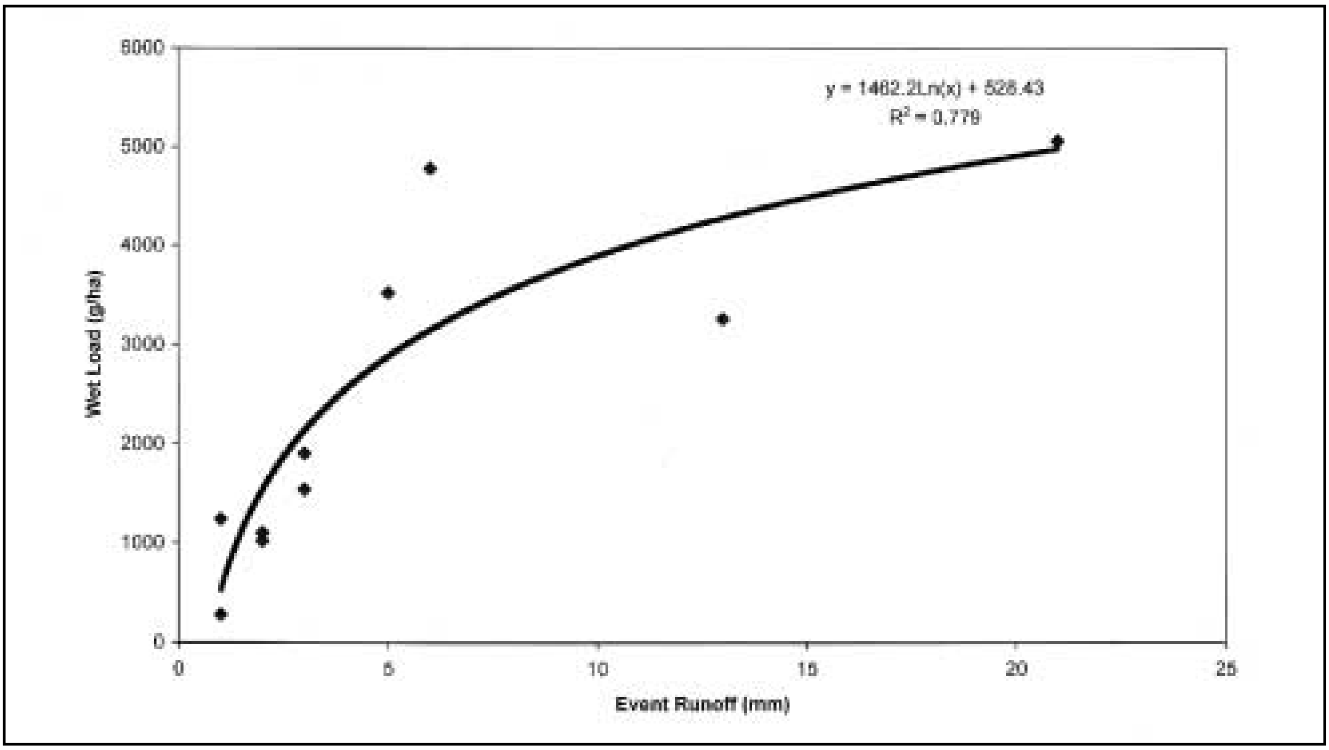

Figure 8.2 Gross Pollutant Wet Loads v's Runoff (after Allison et al., 1998)

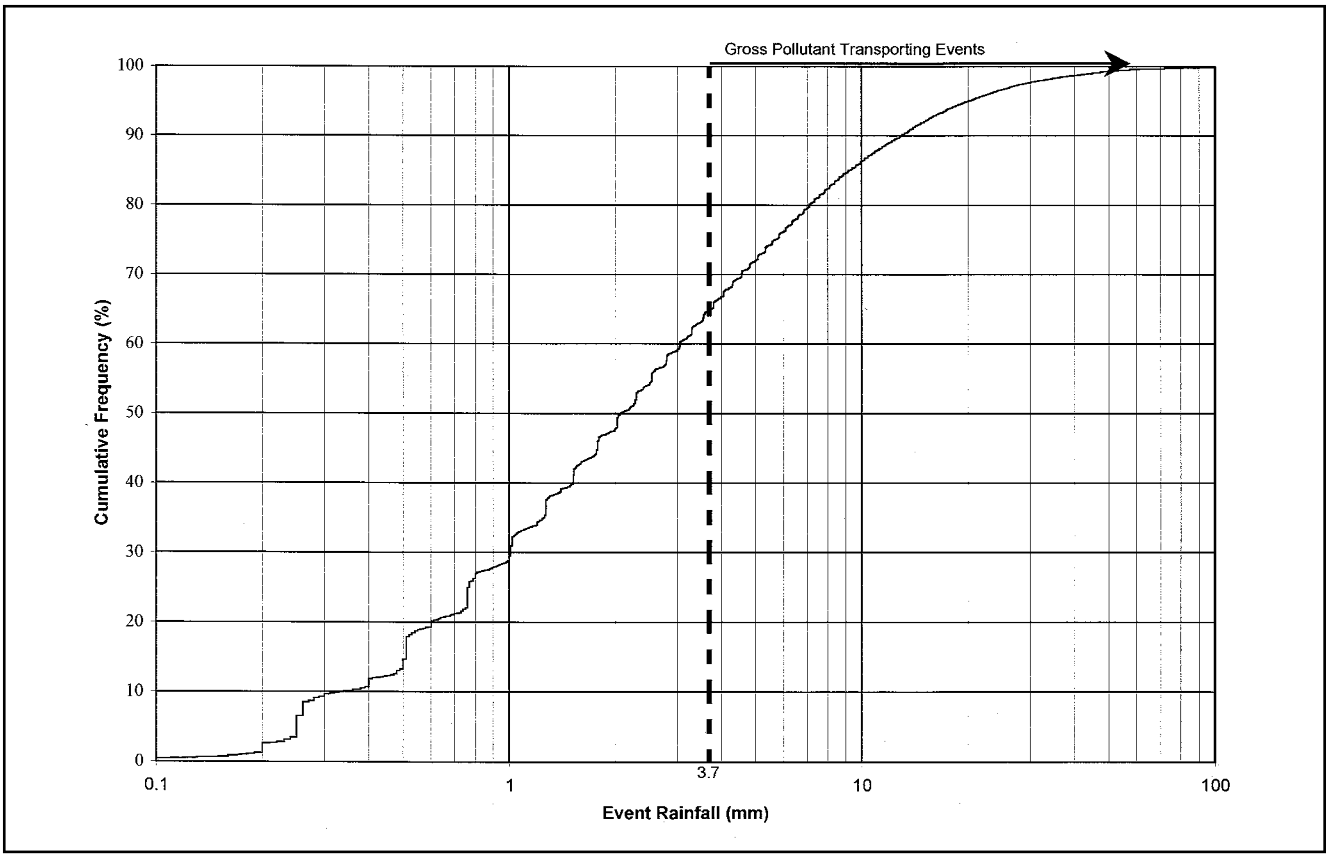

Figure 8.3 Cumulative Probability Distribution of Event Rainfall Depth for Melbourne

The Coburg gross pollutant wet load data have incorporated the effect of Moreland City Council's street sweeping practices which range from daily to fortnightly, depending on land-use. How exactly any alterations made to the street sweeping frequency would affect the gross pollutant load in stormwater (see Figure 8.2) is not known and cannot be ascertained from the data collected. However, it is possible for some inference of the effectiveness of street sweeping in limiting the export of gross pollutants from street surfaces to the stormwater system to be made, and this will be discussed in Section 9.2.

Despite rainfall wash-off being the dominant factor transporting gross pollutants from street surfaces, litter can also reach the stormwater system during dry weather periods. The litter monitoring study, conducted by Hall and Phillips (1997), in the Carnegie commercial catchment indicated that during dry days numerous gross pollutant items are transported into the stormwater system by factors other than stormwater runoff (eg. wind or direct dumping). That study focused on measuring the number of litter items as well as material composition collected daily over seven days, from identified catchment pollutant sources. SEPTs were placed in drain entry pits located in the study area to determine the number of litter items reaching the stormwater system from the identified catchment pollutant sources (including bins, footpaths and street surfaces). The results showed that up to 78 items of litter in total (per day) were collected in SEPTs during periods without rainfall. A substantial amount of the material trapped during recorded dry days were lighter items (polystyrene) although numerous heavier items were also found, indicating possible direct littering rather than wind blown transportation of street surface pollutants.

Gross Pollutant Load Generation:

- Data collected in the Coburg catchment indicated washoff of gross pollutants becomes significant for storm events greater than 3.7 mm of rainfall depth or 0.70 mm of runoff.
- The limiting mechanism affecting the transport of gross pollutants in the majority of cases appears to be re-mobilisation and transport processes (ie. stormwater runoff rates and velocities) and not the supply of gross pollutants.
- Approximately 35% of all recorded rainfall events in Melbourne are greater than 3.7 mm giving an average inter-event dry period of 178 hours (7.4 days) for gross pollutant transporting storm events.

8.2 Influence of Catchment Land-use

As part of the same project, Allison et al. (1997b) investigated the effectiveness of side entry pit traps (SEPT's) by monitoring 192 SEPTs installed in all publicly owned side entry pits of the 50 hectare Coburg catchment as shown in Figure 8.4. The study aimed to assess the effectiveness of SEPTs by using a CDS unit located at the outlet of the catchment to collect any gross pollutants which may pass the SEPTs. The SEPTs were monitored from 2 August 96 to 15 November 96. During these four months, the traps were cleaned out on four separate occasions. For each of these clean-outs the total SEPT load (wet & dry) for each trap was calculated. Gross pollutant load data from that study are used for further analysis in this study.

SEPT gross pollutant wet load data were grouped according to the practiced street sweeping regime defined by catchment land-use. Figure 8.5 displays the three identified land-use sub-catchments in the Coburg catchment (50ha) as the daily swept South East (SE) commercial sub-catchment (13ha), the fortnightly swept North West (NW) & South West (SW) residential sub-catchments (24.5ha) and the daily / fortnightly swept North East (NE) mixed land-use sub-catchment (12.5ha).

The total SEPT gross pollutant wet loads were calculated and categorised according to street sweeping regime, defined by the three sub-catchment land-use types and are presented in Table 8.1. The days between clean outs, total rainfall between clean outs and the number of storm events, are also presented in Table 8.1. For the purpose of this analysis a storm event was identified as a storm that had the potential to re-mobilise deposited solids from the road surfaces and is described as a gross pollutant transporting event (ie. greater than 3.7 mm after Allison et al., 1997b). The SEPT wet loads have been normalised into a load (g) per unit catchment area (ha) to enable gross pollutant loads from the sub-catchments to be compared.

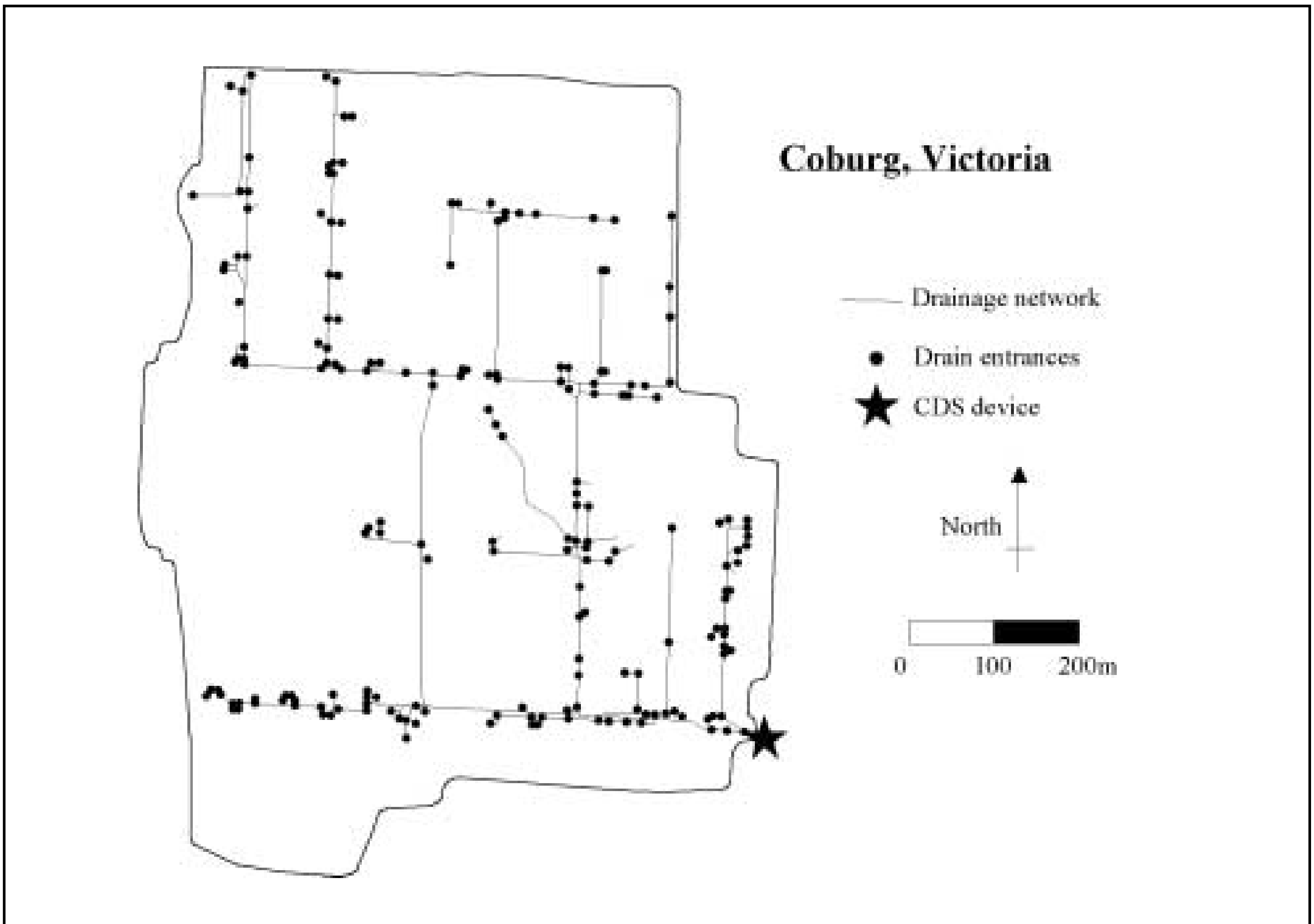

Figure 8.4 SEPT installations in the experimental 50ha Coburg Catchment (source Allison, 1998)

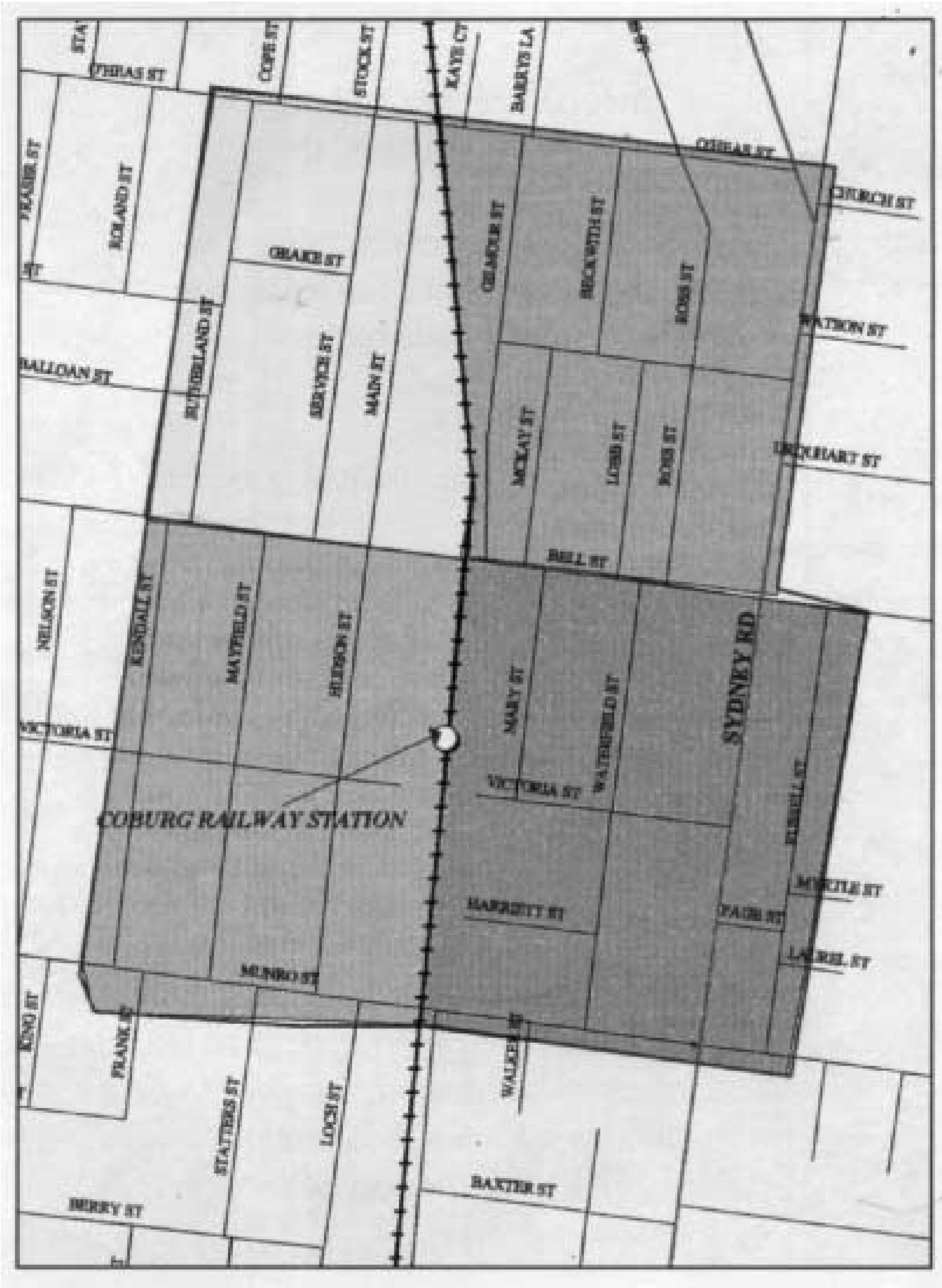

Figure 8.5 Land-use Sub-catchments in the 50ha Coburg Catchment
(source Moreland City Council and Merri Creek Management Committee, 1997)

Table 8.1 Event Rainfall and Related SEPT Total Gross Pollutant Wet Loads

Clean-out Date	Days between clean-outs	Total Rainfall (mm)	Storm Events (>3.7mm)	Single Event Rainfall (mm)	Event Rainfall (mm)	Commercial Wet Load (g/ha)	Residential Wet Load (g/ha)	Mixed Wet Load (g/ha)
29-Aug-96	27	55	5	(6.4) (10) (5) (15) (12)	48	5000	2408	1760
30-Sep-96	32	74	6	(11) (12.3) (16.4) (4.4) (9.4) (11.5)	65	20154	10041	6880
15-Oct-96	15	25	2	(8.2) (14)	22	6462	3143	1840
15-Nov-96	31	47	2	(7) (35.4)	42	6538	5878	1920

As indicated in Table 8.1, calculated total SEPT wet loads ranged from 1.8 kg/ha for the mixed land-use sub-catchment to as much as 20.2 kg/ha for the commercial sub-catchment. Figure 8.6 displays the comparison between land-use and total SEPT wet load, indicating commercial land-use contributes larger loads of gross pollutants per hectare compared to residential and mixed land-use catchments. This is in spite of daily street sweeping in the commercial sub-catchment compared to once every two weeks in residential and mixed land-use areas. Three of the four clean outs showed the ratio of gross pollutant load generation between the commercial and residential areas to be approximately 2.0. There was however, one clean out, that of the 15 November 96 which gave a significantly lower ratio of 1.1. It is interesting to note that the gross pollutant load generated from the mixed land-use was the lowest in all the four clean outs.

Many factors other than land-use contribute to the differences observed in the amount of gross pollutants exported from the different areas, including wind, traffic volume, topography, population density, community awareness and importantly the hydrologic conveyance system. Hydrologic conveyance factors which can influence gross pollutant export include the number of side entry pits in the stormwater system (ie. the average distance to entry pits from within the catchment), the degree of catchment area imperviousness and the extent of "supplementary areas" (defined as pervious areas over which runoff from impervious areas needs to traverse when discharging towards the stormwater drainage system) in these sub-catchments. Catchment topography, average distance along roadside kerbs and the extent of supplementary areas influence the required energy to re-mobilise and convey deposited gross pollutants to the stormwater system. The fraction imperviousness of the catchment influences the magnitude of the runoff from the catchment which in turn determines the energy available for re-mobilisation and transport of deposited gross pollutants in the catchment.

The results presented in Figure 8.6 are consistent with results from a separate study by Allison undertaken during 1995 to investigate the transport of gross pollutants from different land-uses within a 150 hectare catchment in Coburg. Gross pollutant loads from two storm events (27 January 95 and 31 May 95) were monitored at three locations representing mixed commercial/residential, residential and light industrial land-uses as shown in Figure 8.7 (Allison et al., 1998). On commencement of storm runoff, specifically designed gross pollutant samplers (Essery, 1994) were lowered, at varying time intervals, into the flow and used for gross pollutant sampling as illustrated in Figure 8.8.

Gross pollutant loads from the two storm events monitored for each land-use area are presented as dry mass per hectare of catchment area in Table 8.2. The computed unit area dry loads for the different land-uses were compared against the weighted average dry load for the three combined sub-catchments. These data indicate that commercial land-use catchments generate approximately twice the amount of gross pollutants compared to residential land-use and as much as three times the amount generated from light industrial land-use catchments.

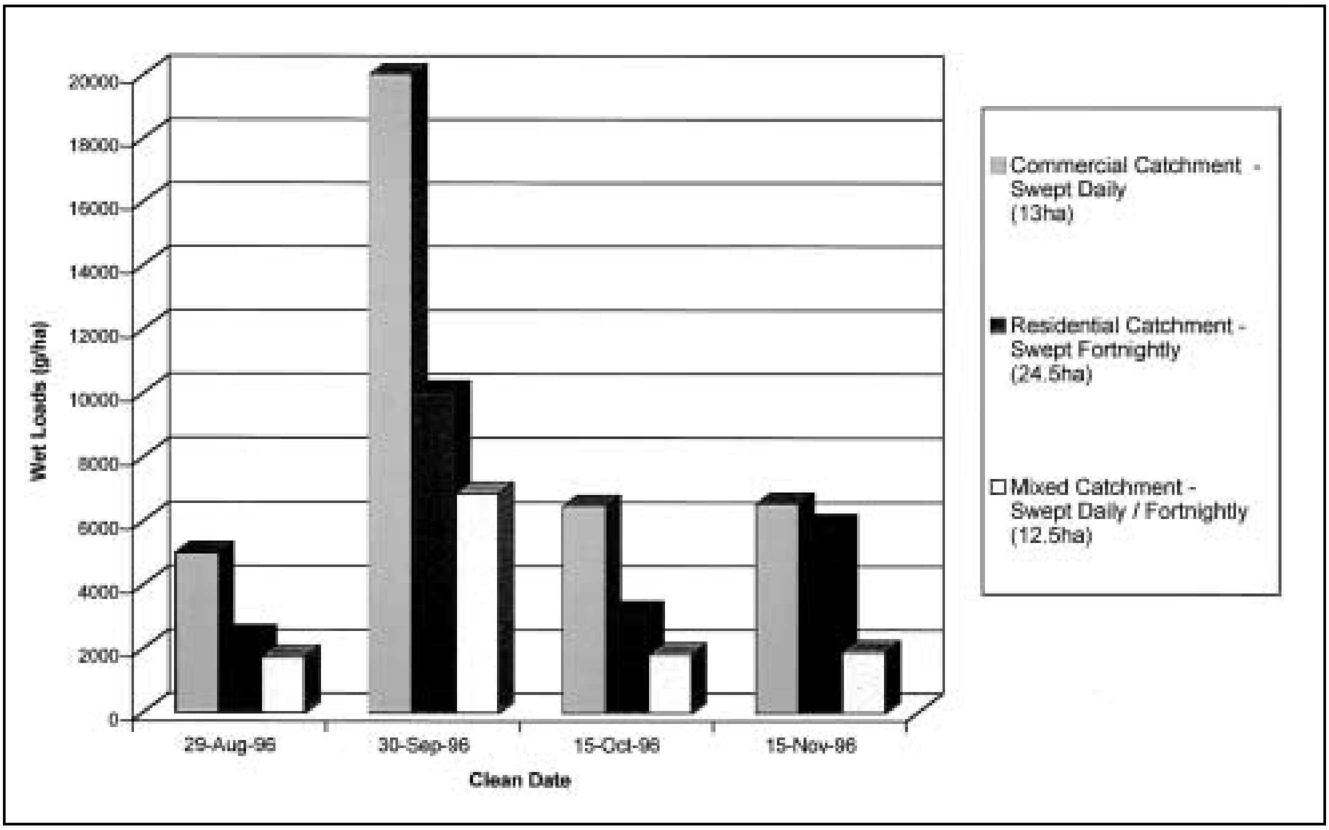

Figure 8.6 SEPT Wet Loads for Different Land use Catchment in Coburg.

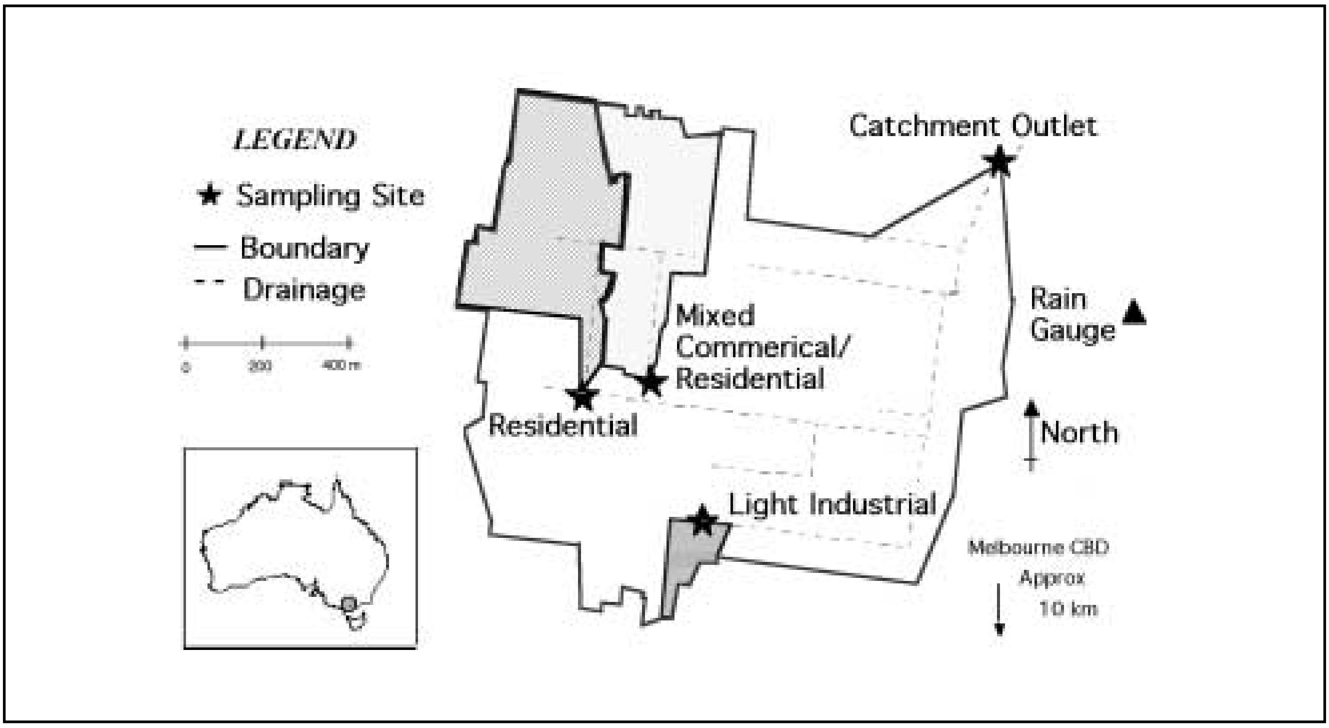

Figure 8.7 Coburg Land-use Monitoring Areas in the 150 ha Coburg Catchment
(source Allison et al. 1998)

Table 8.2 Gross Pollutant Dry Mass Loads and Weighted Averages (after Allison et al., 1998)

Land Use	Area (ha)	Total dry load per unit area		
		27-Jan-95 (g/ha)	31-May-95 (g/ha)	Value / Weighted Average
Commercial	9.5	423	747	1.6
Residential	26.5	292	308	0.8
Light Industrial	2.5	242	63	0.5
Total	38.5			
Weighted Average		321	400	

Allison (1997b) noted that material often blinded the SEPT basket pores, leading to overflows from the baskets and thus a reduction in trapping efficiencies. The field study into the efficiency of SEPTs, found the trapping efficiency of SEPTs to be between 60% and 70% (Allison et al. 1998). The SEPT total wet loads given in Table 8.1 can thus be assumed to be an under estimation of gross pollutant loads generated from the respective sub-catchments.

The gross pollutant loads for three of the four SEPT clean-outs (see Figure 8.6) show similar relative contributions from the different land-use catchments as that derived from the study by Allison (1998) and summarised in Table 8.2. The commercial catchment was found to have generated the most load of gross pollutants on each of the clean out dates in spite of daily street sweeping. As noted earlier, the ratio of commercial to residential land-use gross pollutant load from three of the four clean out dates is approximately 2.0 except for the data from the clean out of 15 November 96. The gross pollutant load transported from the commercial area preceding the clean out of the 15 November 96 was found to be significantly lower than expected when compared to corresponding data from the residential area.

The gross pollutant load from the clean-out of 15 November 1996 was transported by two gross pollutant transporting storm events (ie.<3.7 mm), one with an event rainfall of 6.8 mm and the other 35.4 mm.

Figure 8.8 Sampling Gross Pollutants from Different Land-use Sub-catchments in Coburg (source Allison et al, 1998)

The lower than expected gross pollutant load from the commercial area in this clean-out may be related to a possible "supply limiting condition" during the large 35.4 mm storm event (a trend not apparent in the fortnightly swept, residential catchment). This notion is explored in Section 9.3.

Influence of Catchment Land-use:

- The fraction imperviousness of a catchment influences the runoff during storm events which influence the available energy for mobilisation of deposited gross pollutants.
- Commercial land-uses contribute larger loads of gross pollutants despite more intensive street sweeping frequencies.
- Relative gross pollutant loads generated from different land-uses show that commercial areas produce approximately twice the amount of gross pollutants than residential and three times as much as light industrial, despite a daily street sweeping regime in the commercial area compared to fortnightly in the residential and industrial areas.
- A number of transport factors are thought to also influence gross pollutant loads from different land-uses. Some of these factors include:-
    - Number of entrances to the stormwater system,
    - Fraction of catchment imperviousness,
    - Extent of pervious area over which runoff needs to traverse towards the stormwater drainage system.

9 Discussion

9.1 Gross Pollutant Load and Rainfall Depth Relationship

The relationships between the gross pollutant load and rainfall depth (Figure 8.1) and runoff (Figure 8.2) derived from the Coburg data incorporate the effect of a typical Melbourne municipal street sweeping program, ranging in frequency from daily to fortnightly sweeping depending on catchment land-use. The relationships clearly show a trend of increasing gross pollutant load to the stormwater system with increasing rainfall or runoff, indicating that the limiting mechanism for stormwater gross pollutant transport in the majority of cases is stormwater runoff rates and velocities. While the curves are monotonically increasing, the rate of increase in gross pollutant loads entering the stormwater system decreases with rainfall and runoff indicating a possible upper limit of gross pollutant load transported into the stormwater system at relatively high rainfall depths or runoff. This possible upper limit of gross pollutant load may reflect the gross pollutant load deposited on street surfaces which is available for re-mobilisation into the stormwater system. A modification of the street sweeping frequency could potentially adjust this upper limit value, thereby altering the shape of the gross pollutant export curve as conceptualised in Figure 9.1.

9.2 Impact of Street Sweeping on Gross Pollutant Loads

It is not known how exactly any further alterations made to the street sweeping frequency will affect the gross pollutant export curve. Nevertheless the illustration in Figure 9.1 postulates that if street sweeping effort were reduced it can be expected that the gross pollutant load will increase, initially for those events with large rainfall depths. Further reduction in street sweeping frequency will ultimately lead to the increase of gross pollutants in stormwater systems becoming evident for even smaller storm events. Similarly, by increasing street sweeping effort, the reduction in gross pollutant load would essentially be confined to events of large rainfall depths. Figure 9.1 postulates that in most gross pollutant export events, the export load is defined by the size of the storm event rather than the available pollutant surface load.

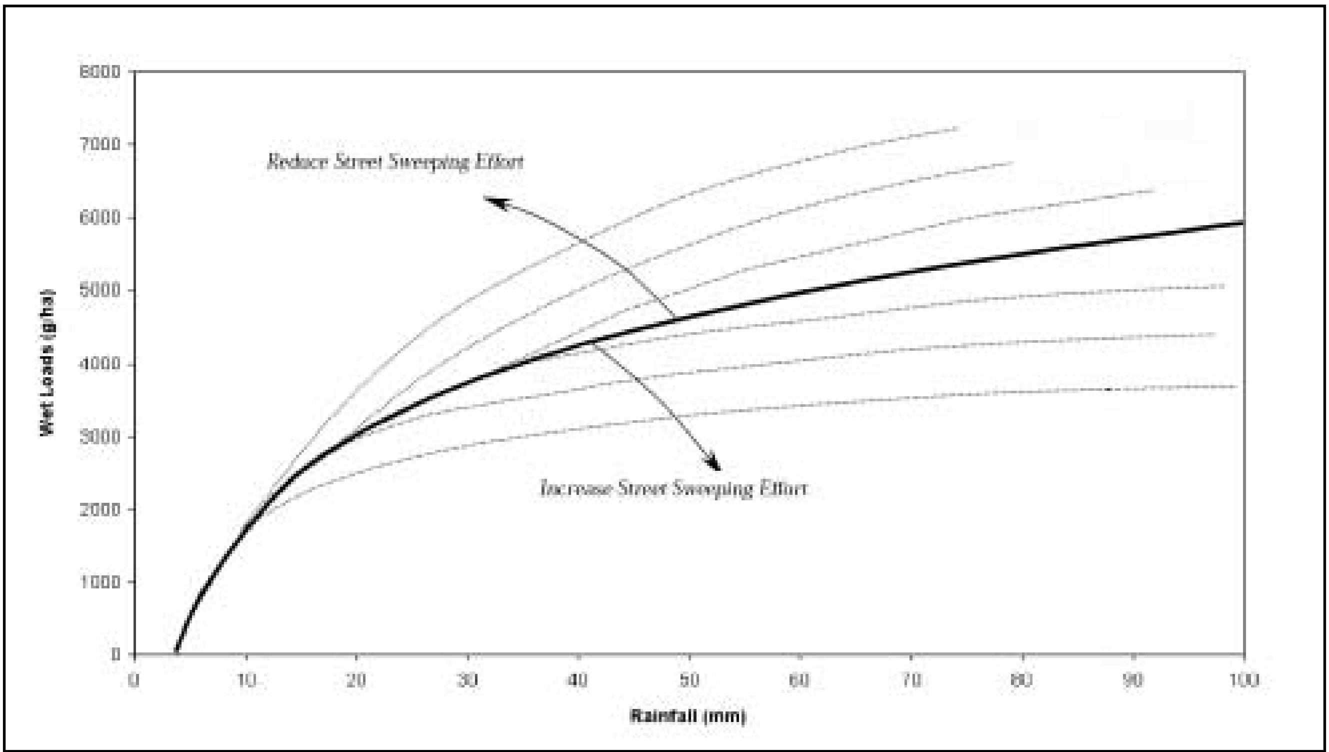

Figure 9.1 Hypothetical Gross Pollutant Load and Street Sweeping Effort

9.3 Supply Limiting Condition

The lower than expected gross pollutant load from the commercial area for the clean-out of the 15 November 96 noted in Table 8.1 of the previous section of this report may be explained by a possible "supply limiting condition" occurring during the large 35.4 mm storm event. It is possible that during this large event the available gross pollutants in the catchment have been substantially removed from the street surface and mobilised into the stormwater system, a trend not apparent in the fortnightly swept, residential catchment.

Based on the results of this investigation, it is postulated that a source limiting storm condition may have occurred during the 35 mm storm event. Storm events greater than 35 mm occur less than 3% of the time in Melbourne (see Figure 8.3) indicating that the occurrence of such a gross pollutant supply limiting condition would be very rare. This may have important implications for assessing the effectiveness of street sweeping. The incremental benefits of increasing the present street sweeping effort in the Coburg catchment (from the daily frequency of the commercial areas and fortnightly frequency in the residential areas) are expected to be low. The limiting factor affecting the transport of gross pollutants in the majority of cases appears not to be the supply of gross pollutants but instead the pollutant mobilisation and transport processes (ie. rainfall patterns and depths, runoff rates and velocities).

9.4 Street Sweeping Efficiency Issues

The use of new street sweeping technologies may contribute to reducing pollutant loads in the stormwater system as advocated by Sutherland and Jelen (1997). Taking into account influencing factors such as the inter-event dry period and catchment characteristics may enable the frequency and timing of street sweeping operations to be redesigned to meet specified stormwater improvement objectives for specific conditions. Street sweeping frequencies that are equivalent to three times the mean inter-event period (approximately 8 days for Melbourne) is considered to be appropriate as approximately 35% of storm events are considered to be gross pollutant transporting events. Also, conducting street sweeping at a time of day which enables the collection of pollutants when the rate of load acummulation of street surface has reached its highest would reduce the time pollutants are potentially exposed to the likelihood of rainfall events.

Factors contributing to inefficiencies in street sweeping are not confined to rainfall patterns (affecting the build-up and wash-off processes), frequency and timing of sweeping, size of pollutants and the sweeper mechanism. Street sweeping inefficiencies are further exacerbated by everyday practice limitations. Significant practice limitations associated with street sweeping include the inability of sweepers to access the street surface load due to parked vehicles (see Figure 9.2), inappropriate street design, poor road surface conditions and operator speed. Street sweeping program specifications must address these influencing factors as well as improving sweeper mechanisms before stormwater quality improvements may be realised from street sweeping practices.

The principle objective of street sweeping in meeting community demand for a standard of street cleanliness, and the perceived success of sweeping to fulfil this objective makes street sweeping an important municipal operation. However, there is little evidence to suggest significant incremental benefits in stormwater quality, particularly the removal of contaminants associated with the fine particulates, can be gained with increased street sweeping frequency.

The use of new street sweeping equipment may lead to increased effectiveness particularly for gross pollutants and coarse to medium sized sediment. There are however other operational limitations which will reduce the actual effectiveness of street sweeping from that determined under controlled test conditions. Furthermore, the use of new equipment will need to be associated with a street sweeping frequency that matches the catchment meteorological characteristics. Their cost effectiveness will need to be evaluated against the cost of installing and maintaining end-of-pipe or in-transit gross pollutant traps.

Figure 9.2 Street sweeping pollutant removal effectiveness is limited by parked cars

10 Conclusions

This study has investigated the effectiveness of street sweeping for stormwater quality improvement. A number of factors are identified as influencing the effectiveness of street sweeping for the collection of street surface pollutants for stormwater pollution control rather than just aesthetic requirements. These factors include street sweeping mechanism, pollutant type, sweeping frequency and timing and also pollutant wash-off characteristics.

The most important conclusion from this study is that current Australian street sweeping practices are generally ineffective as an at source stormwater pollution control measure. Current street sweeping practices are found to be not only ineffective for the reduction of fine sediment and sediment-bound contaminants but also for larger gross pollutants capable of entering the stormwater system. Current Australian street sweeping mechanisms and practices are therefore regarded as providing very little benefit for stormwater quality improvements, due to inefficiencies at reducing a variety of pollutants from entering the stormwater system over a range of conditions. Street sweeping should be therefore accompanied by structural pollutant treatment measures to effectively reduce the discharge of gross and sediment associated pollutants in stormwater.

Increasing the frequency of current street sweeping practices beyond what is required to meet aesthetic objectives is not expected to yield substantial incremental benefits in relation to receiving water quality improvements. There seems little benefit in conducting detailed field monitoring investigations into quantifying the effectiveness of street sweeping as a stormwater pollution control measure for current Australian street sweeping mechanisms or operations. Other specific observations from this study are listed below.

Sweeping Mechanisms

- Mechanical and regenerative air street sweeping equipment requires a minium threshold load of sediment on the street surface before they become effective.
- The threshold load can be three times higher for the mechanical sweeper compared to the regenerative air system.
- Overall the regenerative air sweeper exhibits a substantially better performance than the regular mechanical sweeper.
- Street sweeping technology is developing and improving to remove finer street surface particles for a variety of street surface loads.

Gross Pollutants

- Significant amounts of gross pollutants are mobilised into the stormwater system during bursts of rain, wind or both.
- There is little correlation between the frequency of sweeping and the transport of gross pollutants into the stormwater system.
- Street sweeping efficiency increases with particle size.
- Sweeper efficiency can be up to nearly 80% for particles greater than 2 millimetres under ‘test’ conditions (ie. sweeping more frequently than the occurrence of rainfall events and effective use of parking restrictions).

Sediment and Other Suspended Solids

- The removal efficiency of sediment and other fine organic particles by conventional street sweepers was found to be dependent upon a threshold level of load on the surface and the particle size range of the surface loads.
- Material smaller than 300 µm was less affected by street sweeping.
- No effective removal (>50% removal efficiency) was evident for particle sizes smaller than 125 µm for conventional street sweepers (excluding the new small-micron surface cleaning technology).

Contaminants Associated with Sediment

- Significant amounts of metals and nutrients are transported as sediment-bound contaminants.
- Most of the total mass of contaminants is associated with the fine particles.
- Conventional street sweeping is generally ineffective at removing particles smaller that 300 µm and therefore will not effectively reduce the export of sediment-bound contaminants such as nutrients, metals and PAHs.

Removal of Sediment and Associated Contaminant

- Limited sampling of sediment in street runoff in Australia indicates that 70% of particles are less than 125µm compared to 20% for overseas data.
- The fine sediments found on Australian streets would suggest that conventional street sweeping will have a minimal effect on sediments and associated contaminants reaching stormwater systems.

Street Sweeping Frequency

- The variable nature of inter-event dry periods, both in terms of seasonal variation and dependence on climatic locations, highlights the importance of street sweeping program design which are specific to location and flexible to accommodate the local meteorological conditions and seasonal variability.
- It is anticipated that if street sweeping occurs at a longer interval than the inter-event dry period of the catchment, street surface pollutants will have a much higher likelihood of being flushed into the stormwater system before being collected by the street sweeper.

Street Sweeping Timing

- Recorded gross pollutant load generation over a typical day indicates that the accumulation of litter in a shopping strip begins at 8:00 am and effectively ends around 5:00 pm.
- Early morning street sweeping allows the exposure of deposited street surface litter items to a higher likelihood of being transported into the stormwater drainage system.

Gross Pollutant Load Generation

- Data collected in the Coburg catchment indicated washoff of gross pollutants becomes significant for storm events greater than 3.7 mm of rainfall depth and 0.70 mm of runoff.
- The limiting mechanism affecting the transport of gross pollutants in the majority of cases appears to be re-mobilisation and transport processes (ie. stormwater runoff rates and velocities) and not the supply of gross pollutants.
- Approximately 35% of all recorded rainfall events in Melbourne are greater than 3.7 mm giving an average inter-event dry period of 178 hours (7.4 days) for gross pollutant transporting storm events.

Influence of Catchment Land-use

- The fraction imperviousness of a catchment influences the runoff during storm events which influence the available energy for mobilisation of deposited gross pollutants.
- Commercial land-uses contribute larger loads of gross pollutants despite more intensive street sweeping frequencies.
- Relative gross pollutant loads generated from different land-uses show that commercial areas produce approximately twice the amount of gross pollutants than residential and three times as much as light industrial, despite a daily street sweeping regime in the commercial area compared to fortnightly in the residential and industrial areas.
- A number of transport factors are thought to also influence gross pollutant loads from different land-uses. Some of these factors include:-
  - number of entrances to the stormwater system,
  - fraction of catchment imperviousness,
  - extent of pervious area over which runoff needs to traverse towards the stormwater drainage system.

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