Classification of Stormwater-borne Solids: A Literature Review

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Classification of Stormwater-borne solids: A Literature Review

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NIWA

Executive Summary

Auckland Council has engaged NIWA to provide a literature review on international definitions of solids found in stormwater in order to recommend a threshold particle size between total suspended solids (TSS), settleable solids and gross pollutants. The council is updating existing and producing new guidelines for stormwater management best practice. A key issue in the preparation of these guidelines is the sampling, analysis and classification of stormwater solids in order to evaluate stormwater quality and determine the performance of stormwater treatment devices.

The current target for water treatment at the council is for 75% removal of TSS which is defined by the council according to the American Public Health Association (APHA) Standard Methods for the Examination of Water and Wastewater (SM 2540 D). There are two primary concerns regarding this definition:

- The definition does not specify how TSS samples are collected, despite the fact that sampling methods are known to influence the particle size, and consequently the concentration, of suspended solids in a sample; and
- The definition refers to neither the particle size distribution (**PSD**) nor the maximum particle size for suspended solids, that is, there is no clear boundary between TSS, settleable solids and gross pollutants.

This review was commissioned in response to these concerns. The review has five objectives (the sections where the objectives are met are in parentheses):

1. To provide a literature review of studies which characterise stormwater-borne solids consisting of:
    a. An overview of definitions for stormwater-borne solids with respect to particle size (Section 2.0 ,Definitions of stormwater solids);
    b. An overview of sampling and analytical methods used to determine the concentration and size of solids transported in stormwater (Section 3.0, Sampling methods); and
2. To overview the Water Environment Research Foundation (WERF) protocol for the classification and analysis of stormwater-borne solids (Roesner et al., 2007; Section 5.0, WERF protocol recommendations).
3. To compare the total range of particle sizes found in Auckland stormwater, including data collected by NIWA, with those reported in the international literature (Section 6.0, Size range of stormwater solids);
4. To examine the implication of particle size on the choice of stormwater treatment options for the removal of stormwater solids (Section 7, Impact of particle size on stormwater treatment); and
5. To recommend a particle size definition for Auckland that can be used to refine the current council definition of TSS based on the literature review. The definition should set a maximum particle size for TSS (Section 9.0, Recommendations).

A primary source for this review is the WERF protocol (Roesner et al., 2007). The protocol notes that there is no single, internationally recognised classification for stormwater solids and that field sampling and analytical methods are inconsistent between studies. This lack of consistency makes it difficult to compare water quality between studies and to evaluate the relative performance of treatment options. The aim of the protocol was to produce a set of consistent, reproducible, pragmatic and cost effective methods for sampling and characterising stormwater solids so that agencies charged with water quality management could better understand the issues surrounding solids removal, specifically TSS which has become an indicator for water quality in general, and have the means for practical and affordable solids collection and analysis.

The key findings of this literature review are provided in Section 8.0 and are summarised below:

- The definitions of stormwater solids size classes are many and varied. The WERF protocol proposes dividing stormwater solids into four particle size classes:
  - gross (>5000 µm);
  - coarse (75-5000 µm);
  - fine (2-75 µm); and
  - dissolved (<2 µm) solids.
- The Auckland Council marine ecology and sediment monitoring programmes classify sediment grain sizes using a scale similar to the Wentworth grade scale for soils which separates coarse from fine solids at 63 µm.
- Suspended and settleable solids are found in the fine and coarse size classes.
- The size boundary between suspended and settleable solids is blurred as settleability depends on a range of factors in addition to particle grain size, notably particle density and shape, and stormwater flow characteristics such as flow rate and turbulence.
- There is no one method of determining PSD that can be applied across the range of particle sizes for solids found in stormwater. The most common method of determining PSD is serial sieving and filtration, often in combination with light scattering or light obscuration sensors for fine particles.
- The size range of particles found in stormwater differs spatially and temporally both due to local differences in sources and flow conditions.
- Non-isokinetic sampling and the use of automatic water samplers may result in an over-representation of fine particles in water samples of suspended solids.
- Samples of stormwater solids which include street dust or bed load or which have been made close to sediment sources generally have a higher fraction of coarse, readily settleable particles than commonly reported in the literature for stormwater solids.
- Sediment sizes reported for Auckland are varied but are within the size ranges reported internationally. The size ranges for solids reported for Auckland are given in Table Exec-1.

Table Exec-1 Size range of solids sampled in Auckland

Study	Size range
Leersnyder (1993)	79 % of solids in 20 to 63 µm range; 79 % for Pacific Steel and 49.8% for Hayman Park. Only 0.7 % of particles were >1000 µm at Pacific Steel. Hayman Park had 6.7 % of particles >1000 µm.
Metrowater stormwater monitoring (Reed and Timperley, 2004; Timperley et al., 2004 a and b)	Most particles in the range 1-275 µm, median particle size ranges between 30-75 µm depending on site
Catchpits by traffic count (Moores et al., 2009a, TR2009-119)	Proportion of particles in the 1 mm – 1 cm size range varies between 27 to 85 %
Richardson Rd catchpits (Moores et al., 2009b, TR2009-123)	Around half of solids are in the 1 mm to 1 cm size class.
Catchpits by industry (Gadd et al., 2010, TR2010-02)	Proportion of particles in the 1 mm – 1 cm size range varies between 10 to 61 %
Filter study (Moores et al., 2012)	Median grain size in the 62.5-125 µm size band for Albany and Esmonde Rd. Median grain size for Silverdale site is in the 31.2-62.5 µm size band.

- The particle size distributions and the fractionation of particulate contaminants are important factors which should be considered in the planning, design and evaluation of stormwater treatment devices. However, there are currently few guidelines or tools available which take these factors into account.
- The lack of guidance available reflects a knowledge gap in our understanding of stormwater treatment. That is, most investigations on the performance of stormwater treatment devices report solids removal for TSS only and do not consider PSD.

The following recommendations are made:

- The size range for sampling TSS or SSC in stormwater should be 2-250 µm. Below this range, solids are generally considered dissolved. The upper bound of 250 µm reflects the limit for reliable sampling of suspended solids in stormwater using automatic water samplers.
- If coarser solids (i.e., > 250 µm) are required for analysis, auto-sampling should be complemented with other sampling techniques such as bed load sampling or collection in sediment traps or drainage infrastructure (e.g., catchpits).
- To minimise sampling bias when taking either manual or automatic water sampling, isokinetic sampling techniques should ideally be used to avoid under- or over-representation

of the solid concentration and the size of particle collected. However, this ideal can be difficult to achieve. In cases where isokinetic sampling is not feasible or practical, it is important that those collecting and analysing samples are aware of possible bias in both the determination of solid concentration and PSD. To this end, Auckland Council has developed a protocol for sediment monitoring in freshwater streams which minimises bias, this document should be consulted prior to stormwater sampling.

- The council should consider adopting the WERF definitions for dissolved, fine, coarse and gross solids with the amendment that the separation between fine and coarse sediments be made at 63 µm rather than 75 µm with reference to current council practice
- The council should consider adopting the amendments to APHA SM 2540 D for determining the relative concentration of TSS and settleable solids proposed by WERF. The amendments make the standard method, which was developed for waste water, more compatible with the size range of solids found in stormwater. The method also allows calculation of SSC as well as TSS. Where SSC is analysed using standard methods (ASTM D3977-97), samples should be first split to allow the determination of settleability and PSD.
- The method chosen for determining PSD should reflect the nature of the solids and the purpose of the study.

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Glossary of abbreviations

Abbreviations included in this glossary appear in **bold** the first time they are used in the text.

ANZECC	Australian and New Zealand Environment and Conservation Council
APHA	American Public Health Association
ARC	Auckland Regional Council
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
BMP	Best Management Practices – usually refers to drainage infrastructure intended for water quantity and quality control
CALTRANS	California Department of Transportation,
C-CALM	Catchment Contaminant Annual Loads Model (NIWA)
CLM	Auckland Council Contaminant Load Model
CRCCH	Cooperative Research Centre for Catchment Hydrology
EMC	Event Mean Concentration
ISO	International Organization for Standardization
NURP	US National Urban Runoff Program
PDEP	Auckland Council Proprietary Devices Evaluation Protocol
PSD	Particle Size Distribution
SSA	Specific Surface Area
SSC	Suspended Sediment Concentration
TDS	Total Dissolved Solids
TS	Total Solids - sum of TDS and TSS
TSiS	Total Solids in Suspension, alternative measure of suspended sediment concentration proposed by WERF
TSS	Total Suspended Solids
US EPA	US Environmental Protection Agency
USGS	United States Geological Survey
WERF	Water Environment Research Foundation

Glossary of technical terms

Terms included in this glossary appear in **bold** the first time they are used in the text.

Term	Definition
Automatic (auto-) sample	Sample taken using an automatic water sampler.
Automatic (auto-) sampler	Device used to automatically take either discrete or composite water samples. Can refer to both passive and pumped auto samplers.
Bed load	Coarse and gross solids which are in almost constant contact with the channel bed and are subject to downstream transport.
Composite sample	Mixed sample whereby discrete water samples are composited proportionally either on the basis of time, flow or volume.
Discrete sample	Single water samples taken at one point in time and space using either an automatic or manual sampler
Dissolved solids	Solids in aqueous solution
Granulometric analysis	Particle analysis which considers the size distribution and physical and chemical properties of particles.
Gravimetric method	Method of determining the concentration of a residue following filtration of a known sample volume whereby the residue is dried and weighed.
Gross solids	Large particles such as litter, debris and coarse sediment.
Imhoff cone	Conical glass container with marked volumes used to determine the concentration of settleable solids in a water sample.
Isokinetic sampling	Water samples taken whereby the velocity of flow into the sampler intake is the same as the in-stream flow rate. Isokinetic samples can be made using both manual and automatic samplers.
Manual sample	Discrete water sample taken using a manual water sampler. Often referred to as a grab-sample.

Term	Definition
Manual sampler	Hand held sampler used to take manual samples consisting of a sample container which is lowered into the water stream to take samples.
Particle size distribution (PSD)	Distribution of the grain sizes in a sample of mixed solids expressed as the fraction or percentage of the total solid mass of solids in each of a set of specified size classes.
Passive auto-sampler	Automatic water sampler for taking composite water samplers where the inflow rate is controlled by the placement of the sampler.
Pumped auto-sampler	Automatic water sampler equipped with a pump for taking discrete or composite water samples by suction following some pre-determined trigger (e.g., flow rate or water stage).
Quiescent settling	Settling in a still, non-turbulent fluid.
Saltation	Bed load transport mechanism where particles bounce along the stream bed.
Settleable solids	Solids which are subject to gravitational settling.
Stokes' law	Formula for determining the quiescent fall velocity of a spherical particle. The fall velocity is a function of the fluid viscosity and the radius and density of the particle (see TR 2009/035)
Street dirt or dust	Solids accumulated on an urban surface prior to wash-off following rainfall.
Suspended solids	Solids held in a fluid suspension.

1.0 Introduction

1.1 Background

Auckland Council has engaged NIWA to provide a literature review on international definitions of solids found in stormwater in order to recommend a threshold particle size between total suspended solids, settleable soilds and gross pollutants. The council is updating existing and producing new guidelines for stormwater management best practice. A key issue in the preparation of these guidelines is the sampling, analysis and classification of stormwater solids in order to evaluate stormwater quality and determine the performance of stormwater treatment devices.

The presence of solids in urban runoff is a major concern for stormwater management. Suspended solids in freshwater and marine receiving environments can increase turbidity thereby reducing light penetration and settled solids can potentially damage fresh water and marine benthic communities by smothering or changing substrate grain size (Norkko, 1999). Moreover, contaminants from urban land uses such as heavy metals and polycyclic aromatic hydrocarbons tend to bind to sediments (e.g., Bibby and Webster-Brown, 2005 and 2006) leading to further habitat degradation. Stormwater solids have a size range from colloidal material to sands and gravels. They come from a variety of sources including eroded soil particles, animal waste, vegetation (twigs and leaves, grass clippings), litter, and traffic (vehicle emissions, road and tyre wear and tear). Solids from different sources have different physical and chemical properties which affects the choice and efficacy of treatment options to improve stormwater quality.

Since solids in stormwater are associated with other contaminants, solids removal, namely TSS, has been used by the council and its predecessor, Auckland Regional Council (**ARC**), as an indicator of the performance of stormwater treatment devices. The target in existing council guidelines (e.g., TP 10, ARC, 2003) is for devices to remove at least 75 % of TSS.

The Auckland Council *Air Land Water Plan* currently defines TSS as:

The total amount of particulate matter that is suspended in the water column that can be captured using the standard method defined in the American Public Health Association, Standard Methods for the Examination of Water and Wastewater, 19th Edition, Topic 2540 Solids, APHA, Washington DC, 1995 or equivalent.

The **APHA** standard method (SM 2540 D) was developed for waste water and uses the **gravimetric** method whereby TSS is the residual after filtering and drying of solids in an aliquot taken from a well-mixed water sample (see Section **Error! Reference source not found.**). There are two issues arising from this definition that have been identified by the council which have implications for assessing the efficacy of stormwater treatment:

1. The definition does not specify how samples are collected, despite the fact that sampling methods and inherent biases are known to influence the particle size, and consequently the concentration, of solids in a sample; and

2. The definition refers to neither the particle size distribution (**PSD**) nor the maximum particle size for suspended solids, that is, there is no clear boundary between TSS and gross pollutants.

The design criteria for non-proprietary stormwater treatment devices in TP10 have been determined on the analysis of stormwater sediments that were collected from ponds in Pakuranga by the then Auckland Regional Water Board (ARWB, 1991; overviewed in TP 4, ARC, 1992). The particle sizes of these sediments were calculated using **Stokes' Law** from the settling rates determined from a sediment column experiment. The similarity between the Pakuranga settling rates with those cited in Driscoll et al. (1986) for the US National Urban Runoff Program (**NURP**) led to adoption of the NURP values in TP 4 rather than using the Pakuranga results directly. Leersnyder (1993) found similar settling characteristics for sediments sampled from ponds in Otahuhu and Manukau to those from Pakuranga, which has lent weight to the use of NURP sediment classifications for modelling and design.

Over the 20 years since the initial sediment sampling cited above, there have been further studies on the nature of solids found in Auckland stormwater and the fractionation of particulate contaminants. There have also been advances in sampling and analytical methods and the introduction of new stormwater treatment devices to the New Zealand market. Furthermore, there is concern that the current treatment criteria may not result in desired improvements to water quality. That is, if a device targets a coarse sediment size, while it may meet the target of 75% TSS removal, it may not be effective at removing fine sediments and associated particulate contaminants. Moreover, identical devices located at different sites may have different removal efficiencies as a result of differing relative proportions of fine to coarse solids in runoff to be treated rather than their ability to function as designed. This report has been prepared in response to the above concerns.

1.2 This report

1.2.1 Objectives

The objective of this report is to provide the council with:

1. A literature review of studies which characterise stormwater-borne solids consisting of:
    a. An overview of definitions for TSS and gross solids with respect to particle size, the overview has an emphasis on standards and guidelines, and includes relevant publications on the characterisation of stormwater solids (Section 2.0,Definitions of stormwater solids)
    b. An overview of sampling and analytical methods used to determine the concentration and size of solids in stormwater (Sections 3.0,Sampling methods, and 4.0,Sample analysis). Limitations of the methods are discussed with respect to their ability to capture the full size range of solids. Sampling and analysis of floatables and separation of volatile and non-volatile solids are not discussed.
    c. An overview of the Water Environment Research Foundation (**WERF**) protocol for the classification and analysis of stormwater-borne solids (Roesner et al., 2007; Section 5.0, WERF protocol recommendations).
2. A comparison of the total range of particle sizes found in Auckland stormwater, including data collected by NIWA, with those reported in the international literature (Section 6.0, Size range of stormwater solids);

3. A discussion on the choice of stormwater treatment options for the removal of particles of different sizes (Section 7, Impact of particle size on stormwater treatment); and
4. A recommendation for a particle size definition for Auckland that can be used to refine the current council definition based on the literature review. The definition sets a maximum particle size for TSS above which solids are considered gross pollutants (Section 9.0, Recommendations).

1.2.2 literature sources

The primary source for this review is the WERF protocol for the classification and analysis of stormwater-borne solids (Roesner et al., 2007; henceforth referred to as the WERF protocol).

The protocol covers the impacts of stormwater solids on receiving environments and sampling and analytical methods as well as a proposed classification of solids into size classes. The protocol was prepared in response to similar concerns in the United States as those expressed by Auckland Council. It was noted that there is no single, internationally recognised classification for stormwater solids and that field sampling and analytical methods are inconsistent between studies. This lack of consistency makes it difficult to compare water quality between studies and to evaluate the relative performance of treatment options. The aim was to produce a set of consistent, reproducible, pragmatic and cost effective methods for sampling and characterising stormwater solids so that agencies charged with water quality management could better understand the issues surrounding solids removal, specifically TSS which has become an indicator for water quality in general, and have the means for practical and affordable solids collection and analysis. Moreover, by following the protocol, different agencies have the ability to compare the results of their monitoring, particularly with respect to the efficacy of stormwater treatment devices.

The report also makes reference to a literature review of stormwater solid settling rates prepared by NIWA for the ARC (Semadeni-Davies, 2009), henceforth referred to as TR-2009/035, which contained a synopsis of settling theory and investigated the relationship between settling rates and particle size, along with other particle physical properties. Settling rate data reported in both international and local literature were also presented; these data are reproduced here with respect to particle size. It should be noted that many of the sediment sizes reported in the literature, including TP4 (Beca Carter Hollings and Ferner, 1992) which informed TP10 design criteria, were back calculated from settling rates determined on the basis of settling column experiments. The review also included a discussion on the relationship between particulate contaminant fractionation and the physical and chemical properties of particles, including particle size, which is not repeated here. Many of the documents reviewed in TR-2009/035 are also cited within the WERF protocol.

Finally, readers are directed to the Auckland Council guidelines on water sampling for sediment monitoring (Hicks, 2011; TR2012/012) for supplementary information on taking automatic and manual water samples, the content of this document is overviewed in Section 3.1.4.

2.0 Definitions of stormwater solids

This section contains a review of international literature, including Chapter 3 (Current Solids Classification) of the WERF protocol, on the classification of solids found in stormwater according to particle size. Unless otherwise stated, particle size in this report refers to the sieve diameter, which is equivalent to the smallest mesh size through which a particle is able to pass during sieving or filtration. Other metrics of particle size are the fall and sedimentation diameters, which are determined from the settling rate of the particle, the nominal diameter, which is determined from the particle weight and density, and the geometric average diameter which is determined from the particle' dimensions across its width, breadth and length. The choice of measure largely reflects the analytical method used to determine particle size, furthermore, the reported particle sizes vary depending on the metric used and underlying assumptions with respect to particle shape and density.

Stormwater solids cover a size range from nanometre-sized colloidal organic material to millimetre-sized gravels - more than six orders of magnitude (Grant et al., 2003, Makepeace 1995). There are a number of different grain size classifications for soils and sediments derived from soils such as the American Society for Testing and Materials (**ASTM** D 2487-92, 1992), International Organization for Standardization, (**ISO** 14688-1, 2002) and Wentworth (1922) grade scales. The latter two scales are similar, for instance; ISO 14688-1 separates soil sediments into fine and coarse grains at 63 µm while the Wentworth scale separates muds and fine sands at 62.5 µm. The Wentworth scale has been adopted by the United States Geological Survey (**USGS**) and is widely cited in literature. The 63 µm separation is also commonly used in Australia and New Zealand, including by NIWA for classifying sediments and stormwater solids alike (as can be seen in Table 1 and Section 6.0). The ASTM classification makes the equivalent separation for silt/clay and fine sand at 75 µm. The Auckland Council uses the following classification marine and freshwater sediments which is similar to the Wentworth scale (personal communication, Fiona Curran Cournane, soil scientist at Auckland Council):

- > 2 mm, gravel
- 500 µm – 2 mm, coarse sand;
- 250 - 500 µm, medium sand;
- 63 – 250 µm, fine sand; and
- <63 µm, mud (i.e., silt and clay).

A generic classification for stormwater solids, as set out in the WERF protocol, is given in Figure 1 while Table 1 summarises classifications found in stormwater literature. These classifications differ from the scales cited above in that they take factors other than grain size, such as origin and settling behaviour, into account.

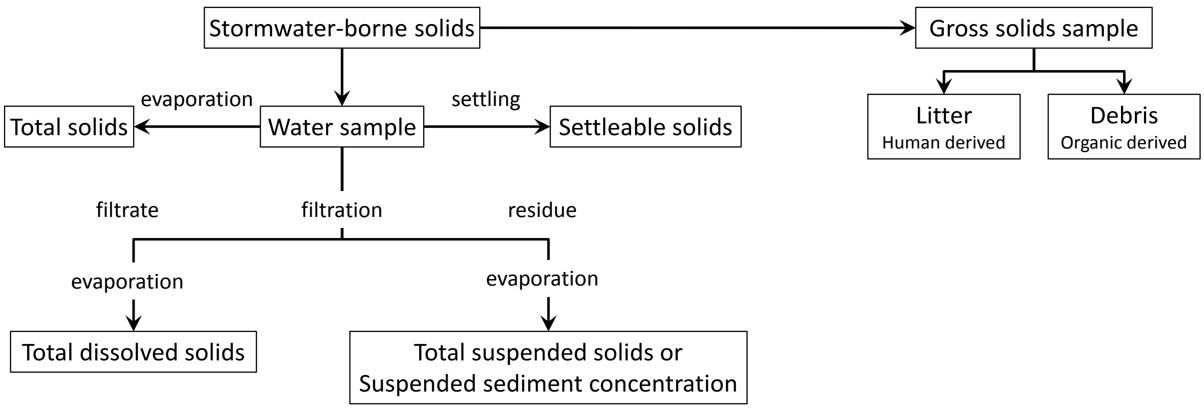


Figure 1Generic classification of stormwater solids. Adapted from WERF protocol Figure 3-1

In addition to TSS and suspended sediment concentration (**SSC**) for suspended solids, common terminology which describes solids found in stormwater includes:

- Total solids (**TS**) – total mass of solid matter in stormwater including both dissolved and suspended sediments and excluding gross solids
- Total dissolved solids (**TDS**) – solids in aqueous solution
- Colloidal solids – solids which are able to escape from aqueous solution and can be affected by coagulation-breakup mechanisms, as opposed to removal by settling (Grant et al., 2003)
- Settleable solids – quantity of solids that will settle out of suspension in a water-solid mixture within a specified period of time, usually determined using the Imhoff cone test (APHA SM 2540 F, see Section 4.1).
- Gross solids - large particles such as litter, debris and coarse sediment. Litter is defined as human derived solids including plastic, metal, cloth paper, glass, cigarette butts, and other trash. Litter can be further classified according to the ability to float (i.e., floatables) and biodegrade. Debris includes organic materials such as animal waste, twigs, leaves, grass clippings and seeds.

Table 1 Summary of literature definitions for stormwater solids in order of grain-size.
The fraction name is that used in the respective source

Reference	**Solid fraction**	**Size range (µm)**	**Comments**
CALTRANS (2003)[a]	Dissolved	<0.001	
CSIRO (1999; 2006)	Dissolved	NA	No size range given, defined according to content, listed as generally consisting of nutrients, metals and salts
Vignati et al. (2005)	Colloidal	0.001-1	
CALTRANS (2003)[a]	Colloidal	0.001-1	

Reference	Solid fraction	Size range (µm)	Comments
CALTRANS (2003)[a]	Turbidity causing	0.001-10	
CALTRANS (2003)[a]	TDS	<0.45	
APHA Standard method, 2540D (1998)[c]	Dissolved	<2	TDS is the proportion of total solids able to pass through a 1-2 micron filter from an aliquot taken from a well-mixed sample.
CALTRANS (2003)[a]	Suspended	>0.45	
ASCE (2010)	Suspended	<1-25	Based on definition by J. Sansalone (e.g., Barretta and Sansalone, 2011)
Barretta and Sansalone (2011)[b]	Suspended	1-25	This definition is used throughout publications by J. Sansalone
APHA Standard method, 2540D (2000)[c]	TSS	>2	TSS is the proportion of total solids retained by a 1-2 micron filter from an aliquot taken from a well-mixed sample.
CALTRANS (2003)[a]	Settleable	>10	
ASCE (2010)	Settleable	25-75	Based on definition by J. Sansalone
Barretta and Sansalone (2011)[b]	Settleable	25-75	This definition is used throughout publications by J. Sansalone
CSIRO (1999; 2006)	Fine	<62	No lower size limit given
CSIRO (1999; 2006)	Medium	62-500	
CSIRO (1999; 2006)	Coarse	500-5,000	
ASCE (2010)	Coarse sediment	75-4,750	Inorganic breakdown products from soil, pavements or building materials, can include fragments of litter and organic debris. 75 µm was chosen as the upper size limit of sediments that can be reliably sampled using an auto-sampler.
Barretta and Sansalone (2011) [b]	Sediment	>75	Determined by wet sieving through a No 200 US sieve. This definition is used throughout publications by J. Sansalone

Reference	Solid fraction	Size range (µm)	Comments
Dallmer (2002)	Gross pollutants	>2,000	
ASCE (2010)	Gross solids and organic debris	>4,750	Cut-off equivalent to a No 4 US Standard sieve. Consists of litter, floatables, and natural debris including leaves, branches, seeds, grass clippings.
Allison et al. (1998)	Gross pollutants	>5,000	Litter and debris > 5 mm
CSIRO (1999; 2006)	Gross pollutants	>5,000	Trash, litter and debris > 5 mm
CALTRANS (2000)	Litter	>5,000	Any man-made object that can be captured by a ¼ inch mesh
Butler et al. (2002)	Gross pollutants	>6,000	Solids with a specific gravity close to unity that can be captured by a 6 mm screen
Lloyd et al. (2001)	Litter	>6,350	Manufactured items that can retained by a 6.35 mm mesh
Kayhanian et al. (2005b)	Litter	>6,350	Non-biodegradable – litter waste that does not break down naturally Biodegradable – litter waste that does break down naturally
Armitage and Rooseboom (2000 a and b) Armitage (2007)	Litter	>10,000	Visible solid waste emanating from the urban environment with an average dimension > 10 mm Includes plastic, paper, metal, glass, vegetation, sediment, building materials, fabric, and animal waste and carcasses

a. Three classification systems are listed by CALTRANS (2003) based on particle behaviour (listed below)

b. This classification is used throughout research papers by John Sansalone and his associates

c. Current definition used in Auckland Council *Air, Land and Water Plan*

Table 1 shows that the terminology and size ranges for different size fractions vary from study to study and there is no common size class definition. In some cases, notably the separation between **dissolved** and **suspended** solids and between **settleable** and **gross** solids, the size range is determined on the basis of available standard sieve or filter sizes. In others, such as suspended and settleable solids, the division has been determined by physical behaviour, in this case settleability.

The American Society of Civil Engineers (ASCE, Rushton et al., 2010; 2006) definition of gross solids has largely been based on the **granulometric** studies by John Sansalone which separate solids into dissolved, suspended and settleable fractions based on their behaviour. A recent example of this definition (Barretta and Sansalone, 2011) is listed in Table 1.

The California Department of Transportation, **CALTRANS** (2003), gives three sets of particle classification based on particle size and behaviour:

- dissolved (<0.001 µm), colloidal (0.001-1 µm) and suspended solids (< 1 µm);
- turbidity causing (0.001-10 µm) and settleable solids (>10 µm); and
- TDS (<0.45 µm) and TSS (>0.45µm).

They note that the division between these classes will vary depending on parameters such as particle density, flow rate and turbulence.

Another CALTRANS report (Grant et al., 2003), which is not listed in Table 1, advocates separation of stormwater solids on their behaviour in water rather than on particle size citing Gustafsson and Gschwend (1997). Their argument is most pertinent to the determination of dissolved and colloidal solids rather than larger suspended solids, though it is noted that the separation of colloidal and gravitational (or settleable) solids is influenced by the solids concentration. The definitions are as follows:

- Dissolved pool - *any constituent that lacks an internal environment and whose fate is not affected by coagulation-breakup mechanisms nor gravitational settling*
- Colloidal pool - *any constituent that provides a molecular milieu into and onto which chemicals can escape from the aqueous solution and whose environmental fate is predominantly affected by coagulation-breakup mechanisms, as opposed to removal by settling*
- Gravitational pool - *any constituents that can bind chemical contaminants and rapidly settles through water by gravitational sedimentation.*
- Sediment pool is defined as *all particulates associated with sediment deposited on highway surfaces, or in the storm sewer system*

3.0 Sampling methods

Obtaining representative samples of solids transported in stormwater is difficult not only because of the uncertainty surrounding the timing and intensity of rainfall and therefore flow events, but also as the size and concentration of solids can change over the course of an event as accumulated sediments and litter are progressively washed off. Moreover, the tendency for larger, heavier particles to settle out means that the concentration and size of particles in stormwater is spatially variable both vertically in the water column and laterally along the flow channel. Whether a particle settles or remains in suspension is dependent on the physical properties of the particle (namely density and shape) as well as flow conditions (flow velocity, ambient water temperature and turbulence) and even the presence of other particles (i.e., particle concentration) which can entrain nearby particles as they settle. Flocs are a special case and can exhibit both increased and reduced settling rates depending on their size and make-up. Thus the same particle may exhibit different settling behaviour in different parts of the stormwater network and between field and laboratory settling conditions. An overview of settling theory is given in Semadeni-Davies (2009).

Due to the spatial and temporal variability of solids in stormwater, the sampling method chosen can have a profound effect on the concentration and **particle size distribution** (**PSD**) of sampled solids. Indeed, the WERF protocol notes that there is no standard method for either collecting or analysing solids, which can lead to differences in the determination of both solids concentrations and particle size distributions between studies. Their concern over a lack of standard methods has subsequently been noted by others (e.g., Clark and Pitt, 2008, Clark and Siu, 2008; Kim and Sansalone, 2008; Kayhanian and Givens, 2011). The following section overviews sampling methods and their limitations with respect to their ability to represent different particle sizes. The WERF guidelines for sampling are overviewed in Section 5.2.

3.1 Water sampling for suspended solids

This section discusses the relative merits and disadvantages associated with manual (grab) and automatic water sampling to obtain samples of suspended sediments. In addition to the WERF protocol, guidelines for the selection, use and maintenance of water sampling equipment can be found, amongst others, in the USGS (on-line resource) National Field Manual for the Collection of Water-Quality Data (http://water.usgs.gov/owq/FieldManual/ - date of last access 3 April 2013), the US Environmental Protection Agency guidelines for performance monitoring of best management practices (**US EPA**, 2002), the Stormwater Effects Handbook (Burton and Pitt, 2002) and the Australian and New Zealand Environment and Conservation Council guidelines for water quality monitoring and reporting (**ANZECC**, 2000). Guidelines for sampling gross solids have also been published by the American Society of Civil Engineers (**ASCE**, 2006, 2010).

Whether automatic or manual sampling is undertaken, most of the guidelines cited above state that **isokinetic** sampling, whereby the rate of flow entering a sampler is the same as the ambient velocity of the stream, is preferential to non-isokinetic sampling. This is to avoid either under- or over-representation of the solid concentration and the size of particle collected (Edwards and Glysson, 1999). If the velocity into the sampler is less than the stream flow velocity, eddies can form around the sample nozzle which divert particles away from the sampler. In contrasts, if the nozzle inflow velocity is greater than the stream flow velocity, particles can be entrained, pulling them out of the water stream into the nozzle.

3.1.1 Type of water sample

The WERF protocol names two types of water sample - discrete samples and composite samples - both can be made using either manual sampling or automatic samplers. These are described below:

- **Discrete samples** are single samples made over a short period of time which give a snapshot of water quality at a given time and discharge. They can be taken both manually or automatically. Discrete samples cannot be used to calculate event mean concentrations (**EMC**) unless flow monitoring is also performed.
- **Composite samples** provide an estimate of average concentrations, there are four methods which can be used to combine samples:
    - Time-weighted composites, samples are taken at equal time increments and are combined in equal measures, the WERF protocol does not recommend this combination method as it can result in un-representative sediment concentrations.
    - Flow-weighted composites can be made using one of three methods:
        - Samples taken after equal time intervals are combined proportionally according to the volume of flow between samples.
        - Samples taken after equal time intervals are combined proportionally according to the flow rate at the time of sampling
        - Samples of equal volume are taken after equal increments of flow volume and are combined. This is the method recommended by the WERF protocol which states that it is the most commonly employed compositing method for stormwater sampling. Auckland Council too generally uses this method.

Flow-weighted composites can be used to determine the EMC. Flow weighting requires either a flow meter (e.g., Doppler velocity / area meter) or stage recording, with a known rating curve, to determine flow rates.

3.1.2 Manual or grab sampling

Using **manual samplers** to take discrete samples has the advantage over automatic sampling as the samplers are suitable for all contaminants and sampling can be cheaper to undertake if long term monitoring is not required. Moreover, sampling equipment can be less bulky than automatic samplers and therefore more practical to transport to remote locations. The disadvantages are:

- sampling can be inconsistent between events;
- it can be difficult to obtain representative samples over the course of an event, particularly if monitoring staff are not on-site at the onset of the event when there may be a first flush of stormwater contaminants;
- care must be taken not splash or disturb the water as the sampler is lowered into the water column to avoid local turbulence around the sampler;
- sampling is labour intensive for on-going monitoring; and
- sampling can be impractical or hazardous at some locations.

The WERF protocol lists three main kinds of grab-samplers, these are summarised below:

- Non-Isokinetic samplers are the simplest form of sampler and consist of a container, usually a bottle, which is lowered into the water stream to collect a sample. They include hand held samplers and dippers where the container is attached to a long pole so that the sample can be made at a fixed depth. Modifications include mechanisms to avoid sample aeration and pivots so that the sample container can be rotated to take a sample at a specific depth.
- Depth integrated samplers consist of a container which is lowered to the channel bed and then raised to the surface at a constant rate. The container nozzle should be orientated into the flow stream. The samplers can have an air valve allowing isokinetic sampling, that is air is displaced by water at the same rate as stream flow while the sampler is raised.
- Point integrated samplers consist of a container with inflow and outflow covers that are opened and closed remotely once the sampler is at the desired sampling depth. The sampler should be orientated into the water stream. The samplers can be used to take time integrated samples at a specific depth, or can be raised to obtain depth integrated samples. Burton and Pitt (2002) note that the design allows unhindered flow through the sample container allowing flow equilibrium with the surrounding waters and therefore isokinetic sampling. They also note that samplers are available in horizontal (for shallow water) or vertical models, several of the latter can be attached on a single line allowing simultaneous samples at different depths in the flow stream.

In addition to these samplers, Burton and Pitt (2002) note the use of manual pump samplers, primarily designed for well sampling, where a nozzle attached to a hand-held pump unit is lowered to a specified depth in the water column for sampling.

3.1.3 Automatic samplers

Automatic samplers (or auto-samplers) can be passive, whereby water is sampled at a specified rate which is controlled by the placement, orientation and design of the water intake, or pumped, whereby a sample is taken after the sampler is triggered, usually by flow rate or water stage. Of the two, pumped auto-samplers are most commonly used for stormwater sampling in New Zealand.

3.1.3.1 Passive auto-samplers

Passive auto-samplers are varied in design and are more common for taking samples in rural locations. They are either placed in the water column or flow path as appropriate to the sample design. Brodie and Porter (2004) evaluated the use of passive samplers for sampling stormwater and stormwater-borne solids and particulates with particular regard to subsequent calculation of EMCs. Samplers overviewed included gravity flow, siphon, rotational (Coshocton) and flow splitting and direct sieving samplers. They concluded that each has limitations. For instance, flow splitting samplers, which divert a small portion of the stormwater discharge to a flume for collection in a sample container, are large and require a steep flow gradient making them unsuitable for most urban locations. Siphon samplers, which are also discussed by Burton and Pitt (2002) with respect to stormwater sampling, suck water into the sample container when the flow stream rises over a pre-determined stage; these samplers are not suitable for particles >62 µm and are unable to function during the falling limb of the hydrograph. Gravity fed samplers, which consist of housing embedded into the flow path (e.g., gutter) containing a removable sample bottle, are subject to by-pass and may fill before the end of an event. Waschbusch et al. (1999) used several variants of gravity flow sampler to determine the sources of phosphorus in Wisconsin stormwater.

Brodie (2005) further evaluated the ability of two passive samplers, a gravity flow and a flow splitting sampler, to take flow proportional samples of suspended sediments which are representative of the PSD for sediments in the size range 0.45-500 µm. The gravity flow sampler was modified to have a side orifice along the wall of the flow channel rather than lying beneath the channel bed. It was found that the flow splitter sampler had the best performance of the two and was able to provide representative flow-proportional composite samples for solids with a particle size <63 µm.

3.1.3.2 Pumped auto-samplers.

Pumped auto-samplers consist of an intake tube with a nozzle which is placed in the water column, either a peristaltic or a vacuum pump and single or multiple sampling bottles housed in a sample chamber. Pumped automatic samplers can be programmed to take samples over the course of a flow event either on the basis of pre-set time intervals time or flow volumes. The sampler is usually triggered by the flow rate (or water stage), however sampling can also be triggered by other environmental factors such as the initiation of rainfall or the physical properties (e.g., turbidity, conductivity, temperature pH) of stormwater. Citing the US EPA (EPA 600/4-82/209; US EPA (1982)), Burton and Pitt (2002) list the following advantages and disadvantages of automatic sampling taken with a pumped auto-sampler over grab sampling:

- Advantages
  - Consistent samples;
  - Reduction in handling lowers possibility of sample variability;
  - Less labour intensive, particularly for long term sampling; and
  - Ability to take multiple samples throughout a flow event, samples can be collected in single composite sample bottles or multiple bottles for discrete analysis of time or flow weighted compositing.
- Disadvantages
  - Require either mains electricity or battery packs;
  - Subject to vandalism requiring secure housing;
  - Requires maintenance such cleaning, replacement of worn parts and unclogging suction tubing;
  - Restricted in size to general specifications; and
  - Can require replacement sample bottles during extreme events.

There has been increasing concern that there is an apparent bias towards smaller particle sizes being collected in stormwater samples taken with pumped auto-samplers which is voiced in the WERF protocol amongst others. For instance, ASCE (2010) state that automatic samplers may not capture representative samples for solids >75 µm requiring bed-load sampling as a complement to water sampling. In a comparison of automatic peristaltic pump samplers, Clark et al. (2009) found that while the samplers had fairly consistent performance for particles <250 µm, they were less consistent for coarser particles. One of the problems they identify is the lack of sufficient turbulence in pipes to ensure a well-mixed sample. That is, sediments >100 µm with a specific gravity equivalent to sand will rapidly settle out of stormwater. They note that larger sediments may be found at source or trapped in grit chambers or catchpits, but are rarely present in outfall discharge. Kayhanian et al. (2005 a) compared flow weighted composite samples collected by automatic and grab sampling; they found that samples collected by auto sampler have lower particle concentration, presumably due to unrepresentative sampling, which prompted them to suggest that samples taken by auto-sampler should not be used to determine PSD. They further state that auto-samplers probably collect the most representative samples when the sampling pipe is not full, the flow is turbulent, and sediments are uniformly suspended through the water. Therefore, this issue could potentially be addressed by introducing artificial baffles to increase mixing in front of the auto sampler inlet so that larger particles are re-suspended and can be sampled more effectively.

URS Greiner Woodward Clyde (1999) cites a study carried out by the USGS (1973) that related sample representativity against the ratio of stream flow to intake velocity. They found that representative samples of sediments smaller than sand (<62 µm) can be collected when ratios range from 0.25 to 3. When velocity ratios are less than one (i.e., intake velocity > stream velocity), there is a bias towards sand and larger sized particles in the sample. When velocity ratios are 3.0, up to 25% lower concentrations of sand and larger sized sediment are collected. Of chief concern to URS Greiner Woodward Clyde (1999) is the possibility of overestimating the removal efficiency of treatment devices which rely on sedimentation if non-isokinetic samples are taken at the inlet and outlet as these facilities are designed to have a higher inflow velocity than outflow velocity.

The ideal for obtaining representative samples is for isokinetic sampling, however, most intakes have a velocity less than stream velocity which means they are unable to entrain larger particles with greater settling rates (Burton and Pitt, 2002). Citing James (1999), the WERF protocol adds that placing the sample nozzle above the channel bed to prevent clogging excludes the collection of bed-load. Similarly, floatables are also absent from water samples. Lin (2003) further states that there is no assurance that the intake tube can capture a representative sample with all particles sizes present as:

- The suction tube intake cross-sectional area is many times smaller than the total cross-section of flow yet not much larger than the median diameter of the largest sediment particles to be sampled;
- The intake location may not be representative of the channel flow or the size distribution of particles with respect to the entire channel cross-section. This issue has been addressed for sampling in freshwater streams by the Auckland Council Monitoring programme (see Section 3.1.4).

In addition to isokinetic sampling, WERF cite other recommendations from the literature to minimise sampling bias. For instance, the nozzle intake should be orientated parallel to the flow stream pointing downstream. This orientation causes the formation of an eddy behind the intake which allows for a more representative sample of coarse solids. Burton and Pitt (2000) suggest that multiple intake (depth integrated) sampling can be used where there is a vertical gradient of particle sizes such that samples can be taken simultaneously from different points in the water column. Bent et al. (2001) list the following criteria for pumped automatic samplers to ensure representative sediment samples in stormwater:

- A suspended-sediment sample should be delivered from the water column to the sample container without a change in sediment concentration or PSD.
- Cross contamination of a sample caused by residual sediments in the system between sample collection periods should be minimized – that is, suction tubes should be purged between samples.
- The sampler should be capable of sample collection over the full range of sediment concentrations and particle sizes up to about 4 mm.
- Sample-container volumes should meet minimum sample analysis volume requirements.
- The inside diameter of the suction tube intake should be maximized to facilitate representative concentrations and PSD of samples (typically 9.5 or 19.0 mm diameter intakes depending on the minimum pumping rate of the sampler used). The sampler should be capable of vertical lifts large enough to maintain sample PSD integrity from the sample point to the sampler storage chamber.
- The sampler should be capable of collecting a reasonable number of samples, depending on the purpose of sample collection and the flow conditions.
- Some provision should be made to protect against freezing, evaporation, and dust contamination.
- The sample-container unit should be constructed to facilitate removal and transport as a unit.
- The sampling cycle should be initiated in response to a timing device, flow change, or external signal.
- The capability of recording the sample-collection date and time should exist.
- The provision for operation using alternating current power or direct current (battery) power should exist.

The sampling approach recommended by the Auckland Council sediment monitoring programme largely follows these criteria. Bent et al. (2001) state that pumped automatic samplers that pre-date 1993 were unable to satisfy these criteria leaving the findings of many earlier studies of sediments in stormwater in question. This cut-off time includes all the samples used to determine sediment sizes and fall speeds for ARC design criteria (i.e., the US EPA NURP samples, Driscoll et al.*,* 1986; ARWB, 1991; and Leersnyder, 1993).

3.1.4 Auckland sediment monitoring programme water sampling guidelines

Further information on taking automatic and manual water samples for monitoring suspended sediments can be found in recent guidelines (Hicks, 2011) prepared as part of Auckland Council's sediment monitoring programme. This document is tailored to conditions found in streams and rivers in the region. The report includes guidelines on:

- Choice of sampling locations and placement of automatic sampler intakes;
- Setting up automatic samplers for flow-proportional composite sampling of in-stream suspended sediments during flow events, including calculation techniques to determine

sampling intervals and determination of seasonally adjusted trigger flow values to initiate sampling;

- Manual depth-integrated sampling and sediment gauging techniques to determine cross channel mean sediment concentrations and PSD;
- Sample handling methods from preparation of bottles to collection and analysis;
- Data management strategies including documentation of metadata, raw and processed data and preparation of data reports and plots.

While the guidelines have not considered stormwater solids *per se*, the information is relevant to stormwater monitoring within urban streams, and readers are advised to consult the guidelines when setting up a water sampling programme.

3.2 Sampling street dirt

Street dirt, or dust, refers to the solids accumulated on the street surface between flow events that is mobilised following rainfall. It consists of particulate matter, debris and litter covering the entire spectrum of stormwater-borne solids including coarse settleable solids. Studies cited in this report which have investigated street dirt have used either vacuuming (Waschbusch et al., 1999; Zander, 2005) or collection of solids from sweeping including by street sweepers (German and Svensson, 2002, Fan, 2004). Vacuuming has the advantage that sampling can be carried out more often in controlled areas – Zander (2005) for instance sampled a 30 cm wide strip of gutter along a 60.7 m section of road at two-day intervals over a two-week dry-period to both characterise street dirt and to determine accumulation rates. On the other hand, street sweeping can give an indication of solids found over a wider area. In either case, the PSD of solids collected in street dirt are generally coarser than those found in stormwater samples.

3.3 Sampling unsuspended coarse solids

A number of the authors cited above (e.g., Clark et al., 2009) suggest that while water sampling alone may be adequate for sampling suspended solids up to 250 µm, other sampling techniques should be used to supplement automatic water sampling where samples of coarse, readily settleable solids are required. ASCE (2010) go as far to say that sampling only the water column has led to the notion that most particulate contaminants found in stormwater are suspended. While these coarse particles may not be suspended, their presence in the stormwater network and treatment devices show they are none-the-less transported with stormwater. Despite this recommendation, very few studies were found which have sampled settleable solids *per se*. Examples which have include Waschbusch et al. (1999) who embedded a slot-type bed load sampler within a reticulated network and Kayhanian et al. (2012) and Walker and Hurl (2002) who used sediment traps to collect sediments settling in a stormwater detention pond and a vegetated wetland respectively in order to evaluate the settling behaviour of stormwater solids and associated particulates.

The guidelines for sampling settleable coarse solids overviewed below have largely been summarised from Burton and Pitt (2002) and Edwards and Glysson (1998), both of which are cited by other stormwater sampling guidelines including Bent et al. (2001), ASCE (2010) and the WERF protocol. In addition to sediment traps and bed load samplers, coarse solids can also be retained, along with gross solids in stormwater flow structures such as catchpits (see Section 3.4 and Section 6.14.2 for

Auckland examples). Sampling solids that have accumulated in aquatic receiving environments with either surface sediment samplers or corers is outside the scope of this report. That is, a distinction is made between settleable solids which are subject to further transport in the stormwater system and accumulated settled solids, although it is noted that scour and resuspension can mobilise the latter.

3.3.1 Settleable solid samplers

Settleable solids samplers are described by Burton and Pitt (2002) as glass bottles topped with wide funnels which act as sediment traps. The bottles are suspended at different depths in the water column. Sediments settled on the funnels are directed into the bottles giving a depth-integrated picture of settleable solids in the water column. These samplers are most suited to large water bodies with slow to moderate currents as they are susceptible to turbulence in swifter moving waters. The samplers should be left in place for prolonged periods (several weeks) which means that they are not suitable for event sampling.

3.3.2 Bed load samplers

Bed load material consists of settleable solids which are in almost constant contact with the channel bed and are transported by rolling, sliding and **saltation** along the bed. Whereas suspended solids are transported at the mean flow rate, the rate of transport for bed load is affected by local velocity distribution and is much slower. With respect to stormwater-borne solids, bed load material is equated to unsuspended coarse solids and gross solids.

Burton and Pitt (2002) describe a simple bed load sampler as a container placed on the channel bed which is opened at the upstream end such that material transported into the sampler is trapped within the container. Another form of sampler is a container with a slotted lid which is embedded in the channel bed so that the lid is flush with the bed surface. The width and length of the slots should be adjusted for local conditions and should be wide enough so that bed load transported over the sampler falls through the slots and is trapped in the container below. Edwards and Glysson (1998) add pressure-difference samplers which create a pressure drop at the sampler's exit that maintains entrance velocities approximating the ambient stream velocity. Bed load grab samples can also be taken with hand-held or cable suspended samplers which are suspended above the stream bed – although Edwards and Glysson (1998) state that these samplers can be subject to error due to the relatively small area sampled and the short collection period.

Irrespective of the sampler type, Edwards and Glysson (1998) state that obtaining representative samples of bed load material is difficult as any device placed on or near the channel bed may disturb the flow and rate of bed load transport. Moreover, since flow velocity, and therefore bed load transport rates are highly variable in time and space, any sample obtained at a given point may not be representative of the mean flow conditions. For this reason, bed load samplers must able to representatively sample the mass or volume of particles moving along the bed through a given width over a specified period of time. To minimise sampling error, Burton and Pitt (2002) recommend the slot-type sampler and state that several samplers be used in close proximity. If a sampler is full upon retrieval, the sample may not represent actual conditions, in which case, either the slots widths should be reduced to exclude large particles or the exposure time shortened. Slot widths should be at least 6 mm wide to capture coarse solids. The length of the slot should be as long as possible for the container lid to avoid particles bouncing over the slots.

3.4 Sampling gross solids

The WERF protocol states that gross solids can be collected from roads (i.e., as part of street dirt) between rain events, in drainage structures including treatment facilities and proprietary devices, such as hydrodynamic separators, or by using traps such as screens and catchpit inserts. CALTRANS (2003) state the sampling method used is dependent on the location of the sampling site within the drainage network. For instance, end-of-pipe samples can be taken by attaching a mesh bag (mesh size 5 mm) to the outfall of stormwater pipes. They also suggest the use of nets to capture gross solids in open channels. Since gross solids can include a wide range of materials (i.e., organic debris and litter), some of which are buoyant, and some of which settle, it can be difficult to obtain representative samples. Moreover, the amount and type of gross solids are highly variable both in time and space. For this reason, yearly data accumulation measurements are more meaningful than shorter time frequency comparisons.

3.5 Sampling total solids

One of the challenges when analysing stormwater solids collected from water and sediment traps of bed-load samplers is combining the two or more sets of data to give an overall picture of total sediment loads and PSD (ASCE, 2010). In the first case, suspended solids (and consequently particulate contaminants) present in stormwater samples are measured as a mass to volume concentration (e.g., mg/l). In contrast, sediment samples collected from street dirt, sediment traps and bed-load samplers are presented as a net mass or load and the contaminant content is expresses as mass to mass concentration (e.g., mg/kg). This leads to the question of how samples taken using two or more sampling techniques should be combined to obtain a meaningful PSD for total solids. There are two possible solutions, either report the results separately, which is the usual case in the studies cited in this report, or use a sampling method that captures all solids transported past a particular point in the flow stream over the sampling period.

The granulometric studies undertaken by John Sansalone and his research students, some of which are cited in this report, have employed concurrent sampling methods to capture representative samples of all solids transported by stormwater. These sampling methods have made use of specially constructed sampling installations which are generally unsuited to stormwater monitoring outside specific research programmes.

Lin (2003) and Kim and Sansalone (2008) are two examples which are overviewed further in Section 6.0 with respect to PSD. Lin (2003) collected coarse and gross solids in a grit chamber (i.e., hydraulic separation), the outflow of the chamber was collected in a settling tank and water samples drawn off to evaluate settleable and suspended solids respectively. Kim and Sansalone (2008) used a specially constructed catchpit with divert to a flume to similarly collect representative sediment samples. By capturing all solids transported with stormwater concurrently, the methods employed by Lin (2003) and Kim and Sansalone (2008) have the advantage that concentrations can be reported as mg/l the sediments can be combined to give a representative PSD.

For information on undertaking depth-integrated water sampling to obtain representative samples of suspended sediments for the determination of average in-stream PSD, consult Hicks (2011).

4.0 Sample analysis

This section summarises methods for determining the concentration, PSD and fractions of settled and suspended solids in stormwater.

4.1 Concentration of suspended solids

The concentration of suspended sediments is most commonly reported as TSS, although, as noted in the WERF protocol, SSC has been reported in a number of stormwater studies. Gravimetric methods are used to determine both TSS and SSC; the two measures differ fundamentally in that TSS is determined for an aliquot of a water sample whereas SSC is determined for the entire sample. Of the two, the WERF protocol, amongst others (e.g., Kayhanian et al., 2005a; Gray et al., 2000) states that TSS tends to under-represent the mass of solids in the water column. For example, in a study where TSS and SSC were determined for known concentrations of two silica-based standards (median grain sizes of 100 and 500 µm respectively), Clark and Sui (2008) found that SSC was best able to represent the known concentration and that the results were independent of the sample PSD. Similarly, the Auckland Council sediment monitoring programme advocates determining SSC rather than TSS in order to avoid the risk of underestimating the concentration of suspended solids (Guo, 2006). SSC analysis has accordingly become the council standard method since 2012, and SSC is reported for the region's freshwater sediment monitoring sites in the most recent council sediment monitoring report (Curran-Cournane et al., in preparation). A TSS to SSC relationship was developed as part of the monitoring programme to enable previously collected TSS data to be converted to SSC for comparison between data sets.

The two most commonly cited methods for determining TSS concentration are APHA SM 2540 D, as cited in the Auckland Council *Air Land Water Plan*, or the similar EPA 160.2 method (USEPA, 1983), these are summarised in Table 2. In both methods, TSS concentration is determined for an aliquot from a well-mixed sample, however, the methods of mixing and drawing off the aliquot differ. Once obtained, the aliquot is passed through a filter and the residual dried and weighed. Kayhanian et al. (2005a) note that both methods can result in bias caused by one or more of the following:

The orifice of the pipette may limit the size of particles that can be drawn off the sample and may cause clogging. The WERF protocol adds that if the orifice is too large, heavier solids may be settle out from the pipette when the energy of mixing is lost.

The variation in depth of the pipette in the sample container may affect the sampled particle sizes.

Sample mixing is not sufficient to keep sand and other heavier material in suspension when drawing the aliquot. In regard to this point, the WERF protocol states that the mixing speed is not specified in SM 2540 D.

Table 2 Summary of standard gravimetric methods for determination of TSS.

Method	Filter pore size	Sample handling	Drying temperature	Detection limit
APHA SM 2540 D	<2 µm	Stir plate to mix. Sufficient volume to yield a residue of 2.5-200 mg Pipette at mid-depth in sample bottle mid-way between wall and vortex	103-105 °C	Residue no more than 200 mg
EPA 160.2	Not specified, noted that absolute pore sizes of glass filter discs can neither be controlled nor measured.	Shake to mix Pour 100 ml or more aliquot into graduated cylinder	103-105 °C	Must capture at least 1 mg residue

SSC is commonly determined using one of three American Society for Testing and Materials (ASTM) D3977-97 tests which are summarised in Table 3. For methods A and C, bias corrections may be required if the dissolved solids concentration exceeds around 10% of the SSC value. For this reason, Auckland Council recommends using method B. While SSC is becoming accepted as an alternative to TSS, there are some problems with the analytical method listed by Kayhanian et al. (2005a):

- The method is not widely recognised or reported and is not often performed by commercial laboratories;
- The analysis is more expensive than that for TSS;
- The bias correction for method A may introduce error;
- Filters used for Test Method B are subject to clogging, resulting in the use of multiple filters or a reduction in the applied sample volume; and
- The test requires the entire sample volume to be analysed.

Some of the limitations of this method have been overcome as laboratories have increased their level of service in response to increased demand for SSC analysis. Moreover, samples can be split to create duplicates to enable determination of PSD and settleability.

Table 3 Summary of ASTM method D 3977-97 for determination of SSC.

Method	Sample handling	Applicability
A Evaporation	Sample placed in an evaporating dish and heated at 105 °C until all water has evaporated.	May only be used on sediment which settles within an allotted storage time which can range from days to weeks. Sample size between 0.2-20 l. Sample concentration from 5-550,000 mg/l and with less than 35,000 mg/l dissolved solids
B Filtration	Entire sample is filtered through a glass-fibre filter disk. Filter and residue are dried and weighed.	May only be used on samples containing sand concentrations < 10,000 mg/l and clay concentration less than 200 mg/l. Sediment need not be settleable because filters are used to separate water from sediment.
C Wet-sieving	Entire sample poured through a 62 or 63 µm sieve and retained material weighed. 300-500 ml sample of the filtrate is analysed using methods A or B to obtain the silt/clay fraction.	Used if two concentration values are required – i.e., sand sized particles and silt/clay sized particles. The silt/clay fraction need not be settleable.

4.2 Separation of settled and suspended solids

Both the USEPA (160.5) and APHA (2540 F) methods to determine settleable solids in water samples use the **Imhoff cone** test whereby solids in a well-mixed 1 l water sample are left in an Imhoff cone to settle quiescently for an hour and are then measured volumetrically as the depth of settled solids in the base of the cone (i.e. ml/l). The APHA standard method also includes a gravimetric option which is recommended for use where flocs are present and which is cited in the WERF protocol for use in the analysis of stormwater solids. Under this option, the water sample is first split into two sub-samples. TSS is determined for one sub-sample without settling following SM 2540 D (see Section 4.3 below). The second sample is allowed to settle for an hour and an aliquot is siphoned off and analysed for TSS. The TSS concentration of the aliquot is equivalent to the concentration of non-settleable solids. The concentration of settleable solids is thus calculated as the difference between the TSS concentrations with and without settling. This method has the advantage of reporting settleable solids in mg/l making the concentration comparable to TSS.

The Imhoff cone test has been used in a number of the studies cited in Table 1 (e.g., Berretta and Sansalone, 2011). However, the WERF protocol makes the point that quiescent conditions are not typical of stormwater systems and that the size of settled particles is related to the length of time the sample is left to settle.

4.3 Size determination

This section gives a brief description of the main methods used to determine grain size and PSD, namely serial sieving, settling analysis and use of light scattering or light obscuration sensors. Other methods include microscopy, electrical resistance counters and gravitational photo-sedimentation counters. More detail can be found Semadeni-Davies (2009); Grant et al (2003); Bent et al. (2001) or Skinner (2000). It should be noted that there is no standard method for determining grain size and that no one method can be used to analyse the entire range of particle sizes found in stormwater (Grant et al., 2003). The US EPA (2002) states that the choice of analytical method must be suited to the expected size range of the particles. Particle sizes for which the methods reported in the WERF protocol are applicable are presented in Table 1. In the case of treatment devices, such as ponds, which have sedimentation as the main removal mechanism, determining the settling velocity of stormwater solids is more meaningful than particle grain size.

4.3.1 Wet and dry sieving

Wet and dry sieving is the most common method of determining the PSD for stormwater sediments as it is simple and inexpensive to carry out. In this method, sediments are shaken mechanically through a stack of sieves with progressively smaller mesh sizes. Both sediment and stormwater samples can be sieved. Stormwater samples are poured directly onto the sieve for the wet sieve technique, and for the dry sieve process, the sediment sample is dried in an oven before sieving. Both methods produce reliable particle size distribution results and are easy to perform on stormwater samples. However, each method has its own disadvantages. Dry sieving can be time intensive as the liquid in the runoff sample must be evaporated to obtain the sediment. Some of the fine particles can clump together and act as larger particles during the evaporation step. Wet sieving, on the other hand, can be hampered by the formation of a mucous layer that clogs the sieve holes of the smaller meshes.

As the smallest sieve mesh size is around 20-25 µm, particles passing through the sieve stack can be filtered to further determine the size of finer sediments. In order to assess the reliability of processing micro particles (<20 µm) in roadway runoff, Kayhanian and Givens (2011) compared particle concentrations for both real and synthetic runoff water samples measured using a light scattering sensor to estimates obtained using the gravimetric method with two types of filter, each with a pore size of 20 µm; wet sieving (equivalent to a No 400 US standard mesh) and suction filtration through filter paper. Water samples were first passed through a 38 µm sieve and then split into identical sub-samples for the comparison. For each water sample, PSD was determined using the sensor before and after wet sieving and again after filtration. Theoretically, the concentration of particles less than 20 microns should be the same for each analytical method, that is, it is assumed that the deviance from the estimated concentration gives a measure of reliability. It was found that the suction filtered sub-sample consistently had lower micro-particle concentrations than the raw water samples; the difference ranged between 28 and 91% with an average of 59%. This discrepancy resulted in an average under prediction of TSS concentration of 70%. This reduction was not seen for the wet-sieved sub-samples leading the authors to conclude that wet-sieving is preferred when determining the concentration of micro-particles and, consequently, estimating TSS. In addition to determination of TSS, the impact of filtration method on the determination of metal fractionation (copper, iron, lead, nickel and zinc) was discussed. Likewise, it was found that the filtered sample underestimated the fraction of metals bound to micro-particles.

Table 4 Particle size determination methods showing applicable size range.

Method	Range reported in WERF protocol	Range reported elsewhere
Serial wet and dry sieving (including filtration)	> 75 µm (equivalent to a No 200 US standard sieve)	> 20 µm (e.g., Kayhanian and Givens, 2011)
Hydrometer analysis	1 – 75 µm	
Settling analysis (Pipette procedure)	< 62 µm	2-62 µm (Bent et al., 2001)
Light scattering counters	0.1 – 50 µm	0.1 – 8,750 µm depending on counter (Grant et al., 2003)
Light obscuration counters	0.1 – 500 µm	0.1 – 5,000 µm depending on counter (Grant et al., 2003)
Electrical resistance counters	Range not given	0.4 – 1,200 µm depending on counter (Grant et al., 2003)
Gravitational photo-sedimentation*	0.1 – 300 µm	0.1 – 500 µm depending on counter (Grant et al., 2003)
Microscopy	0.01 – 5,000 µm depending on sensor	

* called x-ray sedimentation in the WERF protocol

Other problems reported in the literature for serial sieving include the break-up of aggregated particles and flocs and difficulty obtaining aliquots (see the discussion above for TSS determination) with representative sediments sizes.

4.3.2 Settling analysis

There are several methods which determine sediment size on the basis of settling rate including hydrometer analysis and settling column experiments. In either case, the methods are based on the relationship between settling rates and particle size. Grain size (i.e., either the sedimentation or fall diameter) is calculated from the settling velocity using Stoke's law, usually with an assumed specific gravity of 2.65, equivalent to quartz sand (See Semadeni-Davies, 2009) for a discussion on stormwater particle densities). The settling velocity is determined from the rate of change in sediment concentration in the water column over time.

Hydrometer analysis relates the concentration of particles in suspension to the depth of the hydrometer floating in a water sample. A hydrometer consists of a weighted glass bulb and is used to determine the specific gravity or relative density of a fluid. The change in depth over time is thus related to the change in sediment concentration due to settling which is in turn used to determine the average fall velocity of the settled particles for each time step.

In column tests, like hydrometer analysis, the change in the concentration of suspended solids at different depths in the column over time is related to the average fall velocity of the settled solid. Settling column tests can be split into two types (Lin, 2003):

- homogeneous suspension method – the solids are thoroughly mixed with the liquid to form a suspension with solids homogeneously divided throughout the depth of settling column at the start of measurement; and
- floating layer method – the solids sample is distributed in a thin uniform layer at the surface of the fluid at the start of measurement.

Of the two methods, the first is most common and is known as the pipette procedure. As part of the NURP investigation, Driscoll et al. (1986) gave a protocol for the pipette procedure to determine fall velocities for stormwater sediments (summarised in TR2009-035). This method was used to determine the PSD of sediments in Auckland stormwater by the Auckland Regional Water Board (ARWB, 1991); Leersnyder (1993), and, more recently by Semadeni-Davies et al. (2008).

4.3.3 Light scattering counters

Light scattering counters shine a light or laser beam through a water sample and measure the light scattered over a fixed angle on the principle that smaller particles scatter light through a wider angle than larger particles. There are three types of sensor – diffraction, time averaged (static) and time dependant (dynamic) instruments.

4.3.4 Light obscuration counters

In light obscuration counters, a light or laser beam with a known intensity is shone through a water sample, as particles pass through the zone, the beam is blocked and there is a decrease in intensity which is related to the particle concentration and grain size.

The NIWA Hamilton site, which has analysed stormwater solids from Auckland, often determines PSD using a Galai CIS-100 time-of-transition stream-scanning laser system. This is a *time-of-flight* instrument in which the size and shape of a particle is determined as it crosses a laser beam. Millions of particles are measured in each sample and the frequency of occurrence of particles in a range of size bands is recorded. The frequency is reported in terms of the number, area and volume of the particles. The laser beam scans the particles of a suspended sample and the time scale of this interaction, that is, the obscuration of the laser beam is detected by a photodiode. Image analysis using a high-resolution digital video camera, microscopic lenses and powerful software is able to capture and analyse particle images many times a second. Because the laser beam rotates with a constant angular velocity and the time of interaction is directly measured, the software can estimate the particle size. The Galai counter quickly counts large numbers of particles, providing good statistics on size and shape populations.

5.0 WERF protocol recommendations

This section lists the main recommendation for sampling and analysing stormwater solids given in Chapters 7 (Proposed Stormwater Solids Classification), 8 (Proposed Stormwater Solids Analysis) and 9 (Guidance for Sampling) of the WERF protocol.

5.1 Proposed stormwater solids definition

The WERF protocol contains a synthesis of classifications by size, including many of the reports cited in Table 1, for solids found in stormwater which is reproduced in Table 5. The summary clearly illustrates the wide range in particle sizes found in stormwater and the boundaries for different size fractions varies greatly from study to study.

Table 5 Synthesis size limitations for defining stormwater solids. Reproduced from Table 3-1 of the WERF protocol.

Size classification	Total dissolved solids	Total suspended solids	Gross solids
Lower limit	NA	0.45-2 µm	75-20,000 µm
Upper limit	0.45-2 µm	75-20,000 µm	NA

Given the diversity in classifications, in order to allow comparisons between studies, WERF protocol proposes dividing stormwater solids into four particle size classes – gross, coarse, fine and dissolved solids. All the size classes can be physically separated using serial sieving, for instance, the 75 µm separation between fine and coarse sediments has been made with reference to the No 200 US standard sieve. The definitions for each class are given in Table 6 and are represented visually in Figure 2. The classes are based on the ASTM Soil Classification System (ASTM, 1992) for the fine, coarse and gross solids and APHA Standard Method 2540 C for dissolved solids. The classes can be further split into a number of different sub-classes relevant to stormwater management based on their ability to float (i.e., floatables) or settle, volatility (i.e., organic content), material make-up and impact on the receiving environment.

Table 6 WERF protocol proposed definitions for solids found in stormwater.

Solid Class	**Size range (µm)**	**Comments**
Gross solids	>5,000	Solid material that can be captured on a 5 mm screen, which is roughly equivalent to solids retained by a No 4 US standard sieve (4,760 µm) – the ASTM separation between coarse sand and gravel. The Can be further divided into sub-classes based on source material: Litter – human derived trash including paper, cigarette butts, plastic, metal, Styrofoam and glass. Debris – organic material including leaves, branches, seeds, twigs and grass clippings. Coarse sediments – inorganic breakdown of soil, pavement and building materials These solids have a wide range of aesthetic, operational and environmental impacts such as causing blockages in the drainage network and being potentially damaging to wildlife, plastics for example, can be ingested by fish and birds.
Coarse solids	75-5,000	75 µm corresponds to No 200 US standard sieve, the ASTM separation between clay/silt and fine sand. These solids are associated with sedimentation destroying habitats, smothering of benthic organisms and transport of toxic elements into ecosystems. Since auto-samplers may not take representative samples of solids larger than 75 µm, water sampling should be combined with bed-load sampling to capture particles in this size group.
Fine Solids	2-75	Solids which are able to pass through a No 200 sieve but are retained by a 2 µm filter. Fine solids are commonly transported as suspended solids and attributed to increased turbidity resulting in reduction of light penetration. They are associated with the transport of toxic elements into ecosystems and can cause gill clogging, and choking of the filter mechanisms of filter feeders and some zoo-plankton. Fine solids may settle depending on their density and size; 2µm represents the lower limit of sediments that will normally settle out in a stormwater detention pond.
Dissolved solids	<2	Particles that will pass through a 2 µm filter (following APHA Standard Method 2540 C). This size class includes fine clays, colloidal materials, microorganisms and dissolved chemicals. Due to their large specific surface area for bonding, solids in this size class can be associated with high contaminant concentrations. Thus they are associated with the transport of toxic elements into receiving waters.

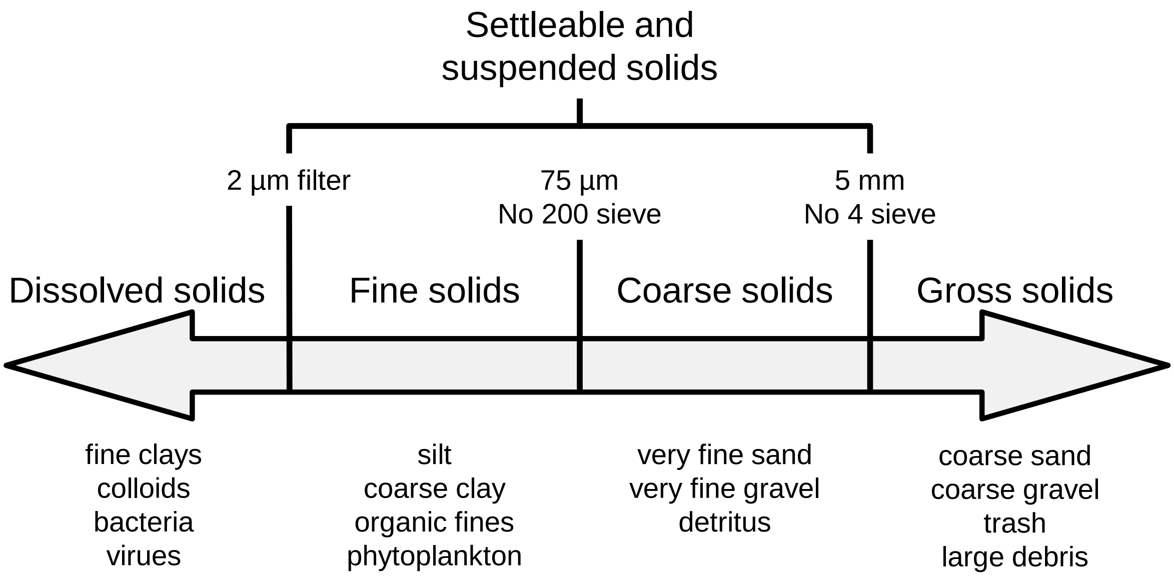


Figure 2Graphical representation of stormwater solids classification. Adapted from Figure 7-2 in the WERF protocol.

Suspended solids are found in the coarse and fine solids size classes (i.e., 2-5,000 µm), however, since solids in these classes are also able to settle depending on physical properties such as grain density and shape, the protocol gives no size definition for suspended solids. Instead, it is stated that the concentrations of TSS, SSC and settleable solids should be determined analytically from water samples containing fine and coarse solids, the recommended methodology is summarised here in Section 5.3.1.

5.2 Guidance for sampling

The WERF protocol recommends developing a sampling plan along the same lines as the US EPA Data Quality Objectives (US EPA, 1994). A key task is to identify the impacts associated with different sized particles in order to determine which sized solids are of most concern and should be targeted for removal and are therefore of most relevance to sampling. That is, the sampling technique used will depend on the situation. This is because the particle size will influence the sampling method and, subsequently, the choice of analytical method. In general, the recommended sampling methods by size class are:

- gross solids – trapping device to retain solids;
- coarse solids – bed-load sampling recommended to supplement water sampling using automatic or manual samplers; and
- fine and dissolved solids – water sampling using automatic or manual sampling.

The concern that water sampling with auto-samplers may lead to an under representation of coarser particles is reiterated in the protocol which states that the potential bias should be taken into account at the planning stage. For instance, if the key issue is the degradation of fresh water habitats due to increased particulate metals and toxins transported in stormwater, both coarse and fine sediments may need to be sampled using a combination of automatic water sampling and bedload sampling. However, if the issue is a decrease in aquatic plants due to reduced light penetration as a consequence of increased turbidity, sampling of suspended solids using an automatic water sampler is adequate. And, if the issue is decreased aesthetics due to the accumulation of litter, collection of gross solids is warranted.

With respect to determining the efficiency of stormwater management devices for the removal of suspended solids, the protocol recommends following appropriate sampling guidelines such as those given in the US EPA Urban Stormwater BMP Performance Monitoring Manual (2002) or the Stormwater Effects Handbook (Burton and Pitt, 2002). For gross solids sampling, the ASCE guidelines (ASCE, 2006; 2010) are recommended. There are no specific recommendations for bed load sampling. In addition to these documents, Auckland Council has recently published guidelines for water sampling as part of its sediment monitoring programme (TR 2011/012, Hicks, 2011, see Section 3.1.4) which gives recommendations that are also relevant to stormwater sampling from urban streams.

The protocol notes that precipitation and flow should also be recorded to allow calculation of sediment and contaminant EMCs and loads. Flow monitoring is essential for flow-weighted auto-sampling.

The second task is to decide where to sample both in terms of site location and the position of sampler at that location. The objective is to obtain a sample which is representative of solids found in stormwater given that particle sizes vary laterally along the water channel, horizontally across the water channel and vertically through the water column due to settling of larger sediments. The ideal is for turbulent well-mixed flow. The choice of location will also be influenced by the practicality of sampling, for instance, whether the site is suitable for the construction of a weir for flow monitoring. Recommendations are given in the protocol for sampling from open channels and streams, treatment devices and within pipes. These recommendations are similar to those listed in Section 3.1.

The choice of when to sample and how many samples to take is dependent on the purpose of the study. For instance, if a worst case scenario is required, samples should be taken after a long antecedent dry period to allow maximum accumulation of solids.

Once samples are collected, they should be analysed as quickly as possible. It is noted that for solids in water samples, the holding time should be no more than six hours and that samples should be cooled to 4 °C. In NIWA’s experience, an effective way of achieving this is to place samples in an ice slurry in a light-proof, insulated storage container immediately upon collection. For gross solids, the protocol suggests following the handling recommendations given in Rushton et al (2006) which suggest a holding time of no longer than 72 hours. If anaerobic conditions need to be maintained, the samples should be stored in an oxygen free, airtight container and refrigerated until analysis which should be within 24 hours.

5.3 Proposed stormwater solids analysis

5.3.1 Dissolved solids

The WERF protocol has no proposed amendments for the analysis of dissolved solids noting that TDS should be determined using either US EPA Method 160.1 or APHA SM 2540 C. In either case, the filtrate obtained after filtering through a 2 µm filter is dried at 180 °C and weighed. Dissolved solids should be reported as mass to volume concentrations (mg/l).

5.3.2 Settled and suspended solids

The WERF protocol guidance on the analysis of settled and suspended solids covers fine (2-75 µm) and coarse (75 µm – 5 mm) solids as defined in the proposed WERF classification for solids based on particle size. The protocol has proposed a number of amendments to the analytical methods for determining the concentrations of suspended and settled solids overviewed in Section 4.0 noting that the methods were developed for wastewater and are not directly applicable to stormwater. This is because wastewater and stormwater have different settling environments and different sources of water-borne solids resulting in particles with different settling behaviour. The amendments are summarised in the following sections.

5.3.2.1 Total solids in suspension with mixing

Amongst others (e.g., Glysson and Gray, 2002, Clark and Siu, 2008), the WERF protocol notes that SSC is a preferable measure of solid concentration than TSS due to possible under representation of the mass concentration of solids of the latter. However, the analytical methods used to determine either of these measures do not address the settleability potential of these solids which is important for describing the transport potential and fate of particulate contaminants. Knowing settleability is also essential for the choice and design of treatment devices. It is noted that since organic particles larger than 75 µm can have lower densities than finer inorganic particles, it is important to include coarse solids in suspended solids testing.

WERF proposes a new measure, called Total Solids in Suspension (**TSiS**). The proposed method is similar to the APHA standard method (2540 D) for determining TSS; the main differences are that the mixing speed, time period for mixing and the pipette size are prescribed. They propose that the standard method be modified as follows:

- Mix the sample with a magnetic stirrer for one minute at 600 rpm;
- Use a large bore pipette (e.g., 3 mm orifice) to obtain aliquots; and
- Withdraw the aliquot from mid-depth and midway between the vortex and the wall of the container.

It is worth noting that the Auckland Council Proprietary Devices Evaluation Protocol (**PDEP**, Wong et al., 2012) has adopted WERF amendments to the standard method for analysing TSS.

5.3.2.2 Total suspended solids with settling

The current method used to determine settleability is set out in APHA SM 2540 F which has both volumetric and gravimetric options. In either case, a 1-hour settling time is prescribed. The protocol states that this method may not be suitable for stormwater studies as the settling time of one hour defines the particle size. That is, coarser solids typically settle under quiescent conditions, however, these solids may be in suspension in the stormwater network .

Accordingly, the WERF protocol proposes a new analytical procedure which will yield estimates of SSC, TSS, total settleable solids and TDS (Figure 3). In the procedure, the water sample is first split using a churn or cone splitter into identical sub-samples; one is used to determine SSC (using ASTM method D 3977-97; ASTM 1997) while the other is analysed for TSS (or rather TSiS) and settleability following the proposed method above with the addition of a 5 minute settling period before taking a 250 ml aliquot from the middle of the sample at mid depth. This aliquot is then filtered and dried following the standard method. The settleable solids are calculated as the difference between SSC and TSS.

5.3.2.3 Separation of coarse and fine solids

The separation of coarse and fine solids requires an extra sieving procedure using a No. 200 standard US sieve, as shown in Figure 3, during the determination of SSC and TSS. Using this procedure, TSS and SSC are determined for the entire sample and for sediments <75 µm (i.e. fines). Mass balance equations are used to determine coarse fractions of SSC and TSS as well as the total and fine and coarse fractions of settleable solids.

5.3.3 Gross solids

The WERF protocol advocates following the ASCE guidelines set out in ASCE (2006) for gross solids. The basic analysis should include measurement of the volume collected in the trapping device between clean-outs and the determination of the range in particle sizes. Additionally, the solids can be characterised by material content, this step can give an indication of the source of gross solids and can aid in the development of prevention plans. The proposed guideline for the analysis of gross solids is summarised below:

- Volume – Determine the appropriate volume and mass of the sample to ensure a representative sample, large samples may be required. Volume should be estimated at the time of collection by either;
    - calculating from the dimensions of the trap (i.e., length and width of the device multiplied by the depth of the solids in the trap),
    - placing the gross samples in containers of known volume, or
    - recording the volume occupied by the solids in the vacuum or haul truck used to clean out the trap.
- Characterisation. Gross solids can be characterised by the proportion of litter to debris, the type and number of items (e.g., leaves vs. litter) and particle size. The level of analysis is dependent on the monitoring goals.
- Mass. Wet and dry weights. A record should be made on how solids were dried, the length of drying time and temperature and humidity at the time of weighting.
- Volatile solids to determine organic content.

Gross solids analysed should be reported as a mass (kg) and/or volume (m^3) over time. The pollutants associated with gross solids should be reported as mass/volume (kg/m^3).

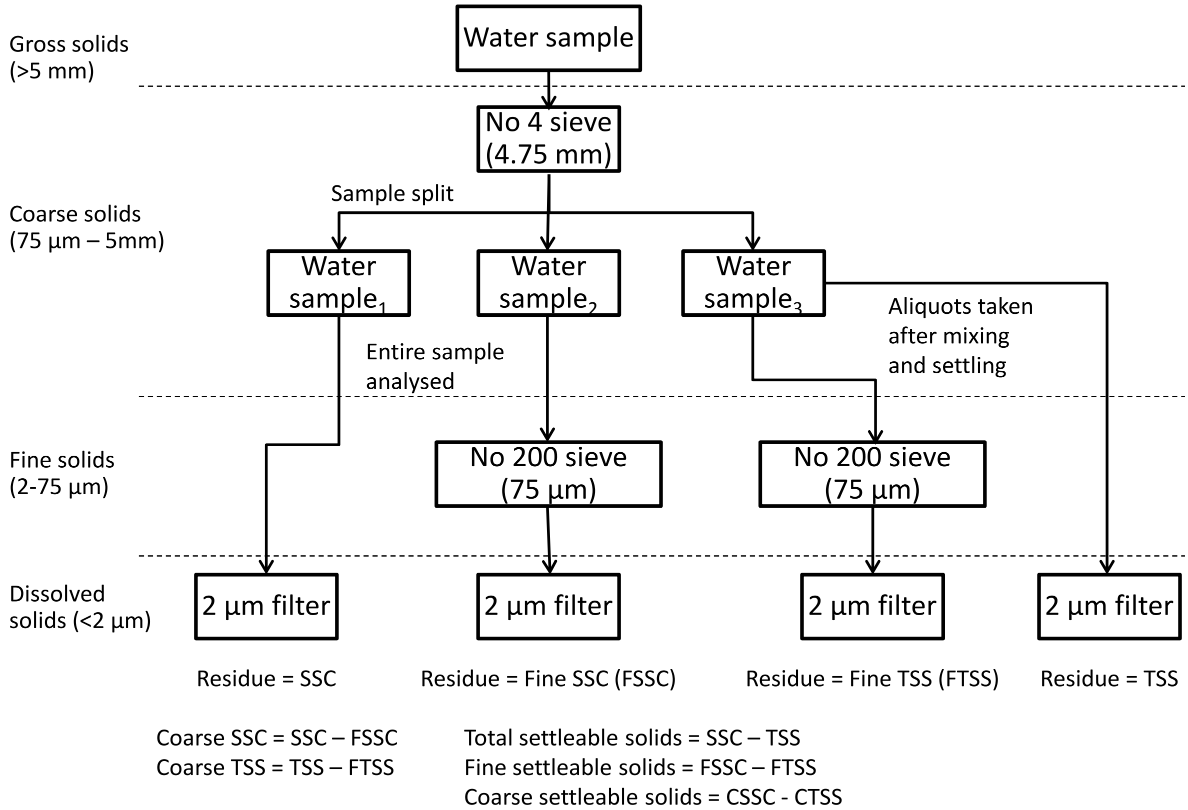


Figure 3Separation of fine and coarse solids during analysis of TSS, SSC and settleable solids. Adapted from Figure 8-6 of the WERF protocol.

5.3.4 Particle size distribution

The WERF protocol recommends that particle size be analysed as a standard part of sample analysis. PSD should be determined using an appropriate method, as listed in Table 4, depending on site specific factors (see guidelines in Grant et al., 2003). It is cautioned that some methods, such as microscopy which uses very small samples, may result in PSDs which are not representative of solids found in stormwater. The protocol also recommends that samples be analysed as soon after collection as possible. Similarly Kayhanian et al. (2005 a) state that since particle size can increase with time due to natural aggregation, analysis should be carried out within six hours of sample collection

6.0 Size range of stormwater solids

This section presents the range of particle sizes for solids found in stormwater reported in a selection of both international and local studies. Many of the data below were also presented in TR2009-035 with respect to settling rates.

6.1 Driscoll et al. (1986)

The Nationwide Urban Runoff Program (NURP) completed by the US EPA (1983) is often used as an industry standard for stormwater quality and presents a historical snapshot of urban water quality and treatment methods from this time period. Under the NURP umbrella, Driscoll et al. (1986) carried out a further investigation into the settling properties of stormwater sediments as part of a methodology to design and evaluate stormwater detention ponds. All samples were taken using automatic water samplers which pre-date the 1993 threshold for reliable water sampling recommended by Bent et al. (2001, cited in Section 3.1.3). The summary was intended as a guide for determining sedimentation rates in detention basins in the absence of local column experiments. It is noted that there is a wide range of particle sizes and settling velocities in any sample of stormwater and local data collection is recommended.

The ARC design criteria for sedimentation devices (TP 4 and TP 10) adopted the NURP findings stating that the settling behaviour for Auckland stormwater solids (ARWB, 1991; Leersnyder, 1993) was similar to that given in Driscoll et al. (1986). The PSD derived from the settling velocities, as calculated using Stokes' Law by the ARC, are given in Table 7.

Table 7 Pooled fall velocity distribution recommended for pond performance simulation by Driscoll et al. (1986). Particle sizes calculated by ARC for use in TP4 and TP10.

Size Band	Proportion of total particle mass (%)	Settling velocity		Particle size* (µm)
		(ft/h)	(m/h)	
1	20	0.03	0.009	2
2	20	0.3	0.091	5
3	20	1.5	0.457	12
4	20	7	2.134	35
5	20	65	19.812	82

*Calculated for spherical particles, density = 2680 kg/m^3, water temperature = 20°C

6.2 Leersnyder (1993)

The MSc thesis work carried out by Leersnyder (1993) for the ARC has been used to support the use of NURP particle settling velocity bands by the ARC. Stormwater was sampled at two stormwater wet detention ponds in South Auckland, one at an industrial site (Pacific Steel, Otahuhu) and the other for a commercial site (Hayman Park, Manukau). Samples of bottom sediments from both ponds were taken at the inlet, outlet and mid-point under the assumption that these represent the integration over time of the quality of settleable solids deposited in the ponds. It should be noted that Pacific Steel is typical of neither stormwater pond design nor urban hydrology (the pond receives both stormwater and industrial water used to wash the site). Moreover, the sediments originate from the industrial activity which means their physical characteristics and accumulation rates could be very different to urban sediments.

The PSD of particles in water entering the ponds was determined by sieving the stormwater samples (1,000 - 20 µm). Of the sediments trapped by the sieve, the majority had particle sizes in the 20 to 63 µm range; 79% for Pacific Steel and 49.8% for Hayman Park. The combined PSD of the sieved particles and those less than 20 µm are given in Table 8. Of note is that the particles in the Pacific Steel stormwater samples tend to be finer than those from Hayman Park. Column experiments were used to determine the settling velocity of the particles.

Table 8 PSDs for stormwater sediments reaching two South Auckland detention ponds. Leersnyder (1993).

Size band (µm)	Percentage particles in band	
	Pacific steel	Hayman Park
0-20	66	34
20-63	26.9	32.9
63-125	4.4	11.6
125-250	1.4	7.2
250-500	0.4	4.6
500-1,000	0.2	3
>1,000	0.7	6.7

6.3 Sansalone et al. (1998)

This granulometric study investigated sediments in highway runoff from a section of interstate in Cincinnati. There were three main objectives:

1. to characterise the mass delivery of sediments during the first-flush;
2. to determine the PSD and specific surface area (**SSA**) of stormwater sediments; and
3. to integrate the SSA results over the PSD in order to determine the contribution of different sediment size classes to total surface area.

Lateral flow from the road was sampled during 13 separate storms from 1995 to 1997. Samples collected over the course of each storm were analysed for PSD; particles greater than 25 µm were sieved (mesh size from 9.25 mm to 20 µm) while those finer were counted and sized using a light obscuration particle counter.

The PSDs were similar across the 13 storm events, summary statistics are given in Table 9 for the median (d_{50}), 60th, 30th and 10th percentiles. Perhaps the most interesting results were for the analysis of SSA as a function of particle size. Although SSA increases with decreasing particle diameter and particles in the size range 2-8 µm had the greatest count, coarse, readily settleable particles in the 425–850 µm range had the highest contribution to the SA. With the exception of two events, the median grain size by mass for the sampled events was in this coarse range (between 370 – 785 µm); however, most of the sediments counted had a diameter less than 25 µm. Sediments less than 100 µm made up a relatively small portion of the SA.

Table 9 Particle size summary statistics for sediment samples taken during 13 flow events. Data reported in Sansalone et al. (1998).

Summary statistics for 13 events	Grain size (µm)			
	d_{60}	d_{50} (median)	d_{30}	d_{10}
Mean	742	555	320	117
Median	700	570	350	110
Standard deviation	184	120	85	41
Relative standard deviation (%)	24.8	21.6	26.6	35.0

6.4 Andral et al. (1999)

Andral et al. (1999) analysed particle sizes and particle fall velocities in stormwater samples collected from eight storm events from the A9 motorway in the Kerault Region of France. The motorway is located near a road pollution prevention system that protects a water supply catchment. Stormwater flows from the motorway via tiled chutes into a sloping collection channel which acts as a settling basin. Sediments were collected from a channel and from stormwater generated by eight storm events in 1993 and 1994. Two sampling methods were used: 1. at the end of each rainfall, bottom sediment samples were taken by hand over the 30 m length of the channel; and 2. suspended solids contained in runoff were collected with a water sampler, settled and filtered. The first method was used to reveal the particle size of solid matter carried in runoff and the second to calculate the load of TSS in runoff during the rainfall event.

PSD was determined using dry sieving and filtering for coarse particles above 50 µm in diameter (maximum sieve size 1 mm) and using a laser counter for fine particles. The fall velocity was found using a settling column (pipette procedure) for the coarse sediments and calculated with Stokes' Law for the fines.

For the <100 µm fraction of the sediment, the PSDs and fall velocity distributions for the settled and suspended particles were remarkably similar. The median grain size for the different samples ranged from approximately 10-15 µm. However, 90% by weight of the sediment accumulated in the collecting basin were larger than 100 µm. They state that these coarse sediments are easily settled and are not carried as suspended solids in runoff. In contrast to the settled sediments, 75% by weight and volume of the suspended sediments in the runoff were smaller than 50 µm. For < 50 µm particles , the calculated fall velocity ranges from 2.5 to 3.3 m/h with a mean of 2.98 m/h. The corresponding fall velocities for particles in the 50-100 µm size range are 5.7 (minimum), 13.1 (maximum) and 9.8 m/h (mean) respectively.

6.5 Cristina et al. (2002)

Cristina et al. (2002) presented a granulometric analysis of particles within snowmelt water from 10 highway shoulder sites in urban Cincinnati generated from a 46 cm snowfall. While this study is concerned with melt water, the techniques used are relevant to stormwater runoff in general. Each site was exposed to traffic and maintenance activities (ploughing and de-icing salts only). Variables analysed were PSD, particle counts, particle density. Particle size was determined using mechanical sieving and PSD was expressed in terms of the proportion of total surface area of each particle size band. They found that 98% of the total surface area was associated with particles > 75 µm in size.

6.6 Furumai et al. (2002)

The PSD of suspended sediments from water sampled using an automatic sampler installed at the inlet of a highway treatment pond was compared to street dust collected in catchpits along the same stretch of highway in order to investigate sediment and particulate pollutant transport. The street dust was sampled from solids cleaned from the catchpits. PSD was determined by sieving (mesh for stormwater particles - 20-250 µm, mesh for street dust up to 800 µm). Nine events were sampled, mostly during the first flush.

It was found that particle size of the suspended sediments varied between events, the median grain size ranged from 106 to <20 µm. However, there were indications that the PSD was related to TSS concentration. The samples with the highest TSS concentrations also had the coarsest size fractions. The street dust tended to be coarser than the suspended sediments and was mostly larger than 125 µm. The conclusion was drawn that finer particles are readily washed off road surface leaving coarser grains. There appeared to be step-wise wash-off processes driven by runoff flow rates, but the relationship between flow rate and grain size was not linear suggesting that fine (<20 µm) particles may have different wash-off behaviour to coarse particles.

6.7 German and Svensson (2002)

German and Svensson (2002) investigated the PSD and metal concentration of street dust collected in Gothenburg, Sweden, prior to and after sweeping and sediments from the sweeper waste tank. The PSD was determined by sieving using Swedish standard sieve sizes from 250 µm to 75 µm. They found that sweeping removed coarse sediments leaving fines available for wash-off. The pre-sweeping fraction of sediments finer than 250 µm was 26%, this increased to 40% after sweeping.

6.8 Lin (2003)

Lin (2003) compared PSDs derived from two settling devices (settling column and Imhoff cone) against PSD analysed using a laser diffraction counter.

In order to sample the full range of particles during specific flow events, Lin collected stormwater in a grit chamber and settling basin concurrently. Samples were collected in three ways. First, coarse sediments were collected from the grit chamber. Second, sediments reaching the sedimentation basin were resuspended and mixed by recycling pumps during water sampling to obtain ensure a representative PSD from the water column. Third, the sediments in the settling basin were allowed to settle for two days after which the water was siphoned off and the settled sediments collected. Samples were collected at two sites for a total of 12 events.

It was found that the grain size of settleable solids was coarser than that reported in other studies and that most of the sediment in the sedimentation basin was in the fine sand to sand range; over 50% of particles had a size greater than 250 µm. Lin notes that over 90% of non-colloidal particulate matter (1.25 – 250 µm), in terms of volume concentration, can be removed with one hour of settling in the settling column. Particles remaining in suspension after 1-hour sedimentation were generally less than 40 µm.

6.9 Fan (2004)

Fan (2004) is a reference guide for sediment control in sanitary sewers which includes sediments from stormwater entering combined sewers and was prepared for the US EPA. This report has amalgamated PSDs (calculated and measured) and settling velocities for stormwater particles from a range of sources including the original NURP study described above, the Construction Industry Research and Information Association (CIRIA) in the UK, and Pisano and Brombach (1996). The latter presented the results of several hundred solids settling curves for a wide variety of waste types (dry weather flow, combined sewer overflow, stormwater, street solids, sediment scraping, pipe slime) collected across North America and Germany over the last two decades.

The results of the review of sediment sizes are given in Table 10; it can be seen that most particles reported are in the range 16 to 62 µm. There are two sets of results to reflect the fact that some areas will have fewer coarse particles in the stormwater network due to street sweeping and sediment trapping in catchpits. Fan (2004) cites the NURP results to state that regular street sweeping (e.g., monthly) can reduce TSS by 15 to 20 %. Further sediment reductions are made by Fan (2004) for catchpits.

Table 10 Summary of sediment sizes reported in the literature showing potential removal of sediments by street sweeping and catchpits. Compiled by Fan (2004).

Particle Size (µm)	**Initial proportion mass in category (% mass)**	**Effectiveness of street sweeping (% reduction)**	**Effectiveness of catchpits (% reduction)**	**Proportion of mass remaining after sweeping and catchpits (% mass)**
>2,000	1	80	100	0
>1,000	2	70	90	0.1
>500	4	60	80	0.3
>250	5	55	60	0.9
>125	14	45	40	4.6
>62	20	30	20	11.2
>31	26	15	10	19.9
>16	18	0	0	18
>8	6	0	0	6
>4	2	0	0	2

6.10 Zanders (2005)

Zanders (2005) is one of the few internationally-published New Zealand studies of stormwater solids which includes PSD. She investigated street dust vacuumed from a length of gutter running next to a major intersection in Hamilton (Cobham Dr / Normandy Ave; 25000 vehicles per day). The site is subject to monthly street sweeping. Samples were taken at 2-day intervals over a two week dry period. The objective to assess the potential for pollutant removal using road-side vegetated strips.

Sediment had an average accumulation rate of 0.55 g/m kerb/day and the particle sizes became finer over the course of the sampling period in comparison to the initial sample. Particle size was determined by sieving (mesh sizes: 2000-32 µm). The PSDs for the initial sample and a composite of the 2-day samples is given in Table 11. The 2-day samples were found to contain predominantly fine particles compared to the initial sample; however, the sediments were comparatively large compared with studies of particles in stormwater – which is consistent with the other studies of street dust reported here.

Table 11 PSDs for street dust reported by Zanders (2005).

Size range (µm)	Percentage of total solids	
	Initial sample	Composite of subsequent 2-day samples
500-2000	55	30
< 500	45	70
< 250	28	52
< 125	16	36
< 63	9	23
< 32	1.5	6

6.11 Cooperative Research Centre for Catchment Hydrology, CRCCH (2005)

The default PSD (Table 12) for the widely used Australian stormwater planning model, MUSIC, was been derived from studies of urban stormwater particles collected in Melbourne (Lloyd et al., 1998; Lloyd and Wong, 1999).

Lloyd and Wong (1999) took samples of road runoff from a fully developed urban catchment. The road is a major transport route which carries around 32,000 vehicles per day. The catchment is 100% impervious, approximately 100 x 15 m in size and is not subject to street sweeping. Grab samples of runoff were collected at five minute intervals over two events. For each sample, the PSD was determined using vacuum filtration and sieving (maximum mesh = 118 µm). The proportion of suspended solids with a particle size less than 118 µm varied between 74 and 100%. Interestingly, the smaller of the two events had the greater proportion of coarse particles, which suggests a longer pre-event accumulation time. For each event the rising limb had a greater proportion of coarse material which is consistent with a first-flush effect. Lloyd and Wong (1999) compared the PSDs for Melbourne with other Australian studies (Sydney - Ball and Abustan, 1995; Queensland – Drapper et al., 2000) and found broad agreement. The Australian PSDs were also compared to PSDs from the United States and Europe (collated by Walker et al., 1999) and it was found that particles in stormwater runoff from roads and highways in Australia were relatively finely graded.

Table 12 MUSIC model default PSD determined from literature values. Compiled by CRCCH (2004).

Sediment size band (µm)	Proportion of total sediment (%)
< 1	0
1-2	2
2-4	1
4-8	2
8-16	5
16-32	10
32-64	25
64-128	32
128-256	18
256-500	5

6.12 Kim and Sansalone (2008)

Kim and Sansalone (2008) investigated the PSD of the non-colloidal fraction of solids in stormwater sampled from a catchpit in Baton Rouge. They collected water and sediment samples over the course of eight flow events using a PVC pipe to divert discharge through the catchpit to a specially constructed sampling rig which allowed sampling of inflow, outflow and settled sediments. They ensured that influent water samples were well mixed by taking samples directly downstream of a Parshal flume and a drop-box to create turbulence. The aim was to analyse the entire range of non-colloidal solids reaching the catchpit. Since it was hypothesized that particle delivery and PSD are related to hydrology, samples were taken over the course of eight flow events.

The solids were first separated into coarse and eluted fractions on site. PSD was determined by sieving for coarse particulate matter and laser diffraction for the fines. The PSD differs for the eight events; the median particle size ranged from 43 µm to 300 µm (mean 136 µm) though non-colloidal solids ranged from 1 to 24000 µm. The coarse fraction accounted for between 85-95% of the stormwater solids for all but one event where the coarse fraction was 56%. For the eluted sediments, between 65-99% (mean of 81%) was less than 75 µm and only 3% was larger than 250 µm respectively.

The PSDs were compared to other PSDs reported in the literature, including most of the reports cited here, for particles on urban paved surfaces (i.e., street dust) and in urban runoff. It was found that the street dirt and coarse fraction PSDs were generally comparable; however, there was variance in the PSDs reported for stormwater. This variance was attributed to disparate sampling and analytical methods. It is noted that water sampling alone does not result in samples which contain the coarse particles seen in either the coarse fraction reaching the catchpit or street dust.

6.13 Kayhanian et al. (2012)

In order to evaluate changes in the properties of sediments derived from traffic, including grain size, particle density, shape, surface area and contaminant fractionation, Kayhanian et al. (2012) analysed three sets of sediments from different sources. Each source relates to a different location in the highway runoff flow pathway:

- dry particles from the surface pavement of a parking lot and a highway shoulder;
- centrifuged solids from highway runoff; and
- settled sediment from the bottom of three detention basins.

Altogether, 38 samples were collected and analysed.

The surface particles were collected using a vacuum with a 0.3 µm filter. Samples were taken from three sites. Highway runoff was sampled at three sites with varying traffic densities (130,000, 5,000 and 800 vehicles per day) over between two or three events per site. Grab samples, made over equal time intervals, were composited for each event. These samples were passed through a continuous centrifuge to obtain sediments >0.7 µm. Samples of settled solids were obtained in three detention basins. The samples were made by installing sample containers on the bed of each pond at three points (i.e., at the inflow, mid-point and outflow). The containers were retrieved after the stormwater flow subsided and the ponds drained.

The PSD of each sediment sample was determined using serial sieving (38 – 1,000 µm) and a laser diffraction counter for particles <38 µm. The PSD varied both by sediment type and sampling site and is reported graphically in terms of the particle percentage by mass and volume. The runoff samples had the greatest proportion of fine particles with 67.4 % if the sediment mass <38 µm. The vacuumed dry particles and detention basin sediments had 0.7% and 32.3% by mass <38 µm.

It was found that particles were not smooth or spherical and that metal concentration increased with decreasing particle size. However, the distributions of metal mass across the sieved size fractions generally followed patterns of particle mass distributions.

6.14 NIWA Auckland stormwater monitoring

6.14.1 Metrowater stormwater monitoring (2002-2003)

NIWA collected extensive data on sediment sizes as part of stormwater monitoring programme commissioned by Metrowater and Auckland City during 2002-3 (Reed and Timperley, 2004; Timperley et al*.,* 2004 a and b). The data has been compiled from dozens of samples for between 7 and 15 events per site (Table 13). The average distributions for samples collected from eight of the sites are given in Figure 4. With the exception of samples from Oakley Creek, samples were taken by automatic sampler from the reticulated stormwater network, which, in the case of Cox’s Bay was a combined network. It must be added that the catchments are all in the central city, other urban areas in the city may have different sediment sizes and characteristics due to differences in local geology and therefore soil type. Particle sizes for the sediments in Auckland stormwater were determined at NIWA Hamilton using a Galai WCIS-100 particle size analyser (see Section 4.3).

There is a considerable range of particle sizes for different events at each site and between sites. There seems to be two geographic groups of PSDs; representing fine and coarse sediment respectively. Mission Bay (coarse) and Oakley Creek (fine) represent the extremes; Mayoral site has a PSD close to the arithmetic mean (that is, the average percentage of particles finer for each size group). As stormwater passes down the City's streams, the particle size distribution changes with a general reduction in the proportion of coarse particles. For example, for Tamaki, Mission Bay and the Aotea Square, 30 % (by volume) of the particles were less than 50 µm compared with 65 % in Oakley Creek water. Similarly only 10 % was less than 20 µm at the stormwater sites compared with 40 % in Oakley Creek.

Table 13 Sample summary for Auckland catchments analysed for stormwater particle sizes by NIWA.

	CBD	**Mission Bay**	**Orakei**	**Mayoral**	**Tamaki**	**Cox's Bay**	**Remuera**	**Oakley Creek**
Land use	mixed	mixed	residential	commercial	industrial	mixed	residential	mixed
No of events	15	15	14	16	16	9	7	8
No of samples	160	153	164	134	134	143	95	182

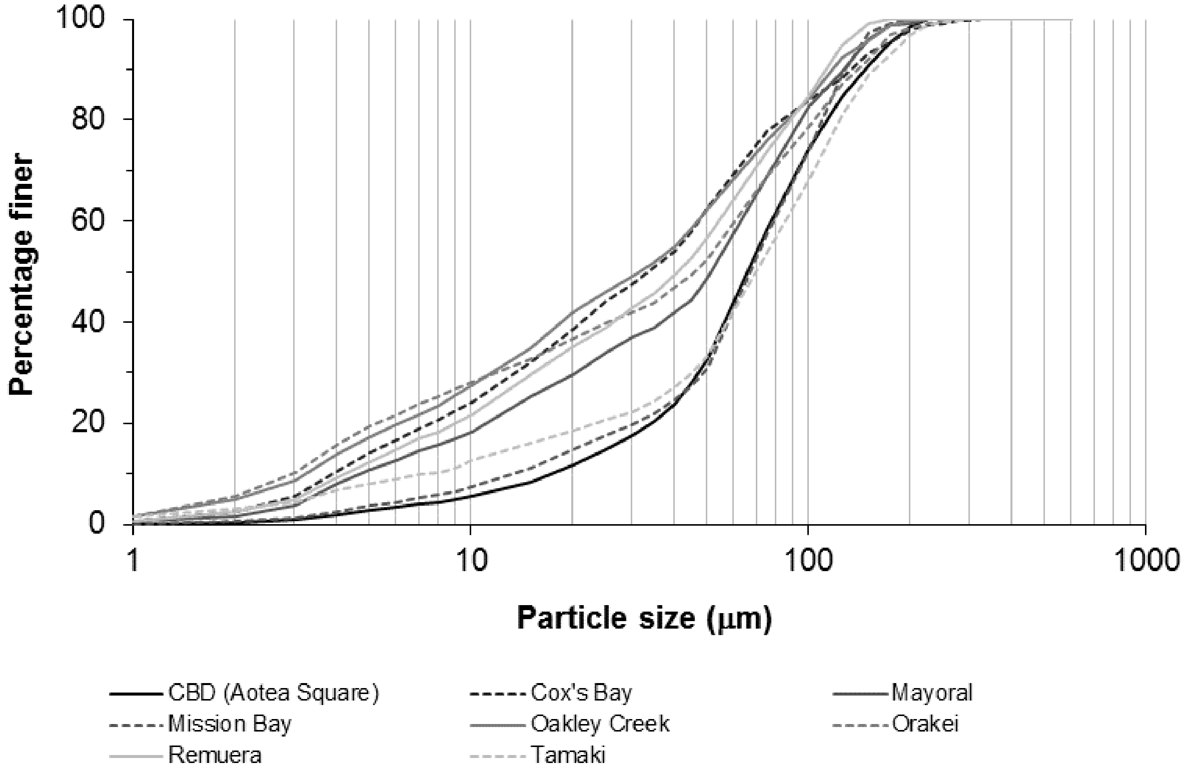
6.14.2 Catchpit solids sampling and analysis

NIWA has carried out three studies into the characterisation of solids collected in stormwater catchpits for the ARC (Moores et al., 2009 a and b; Gadd et al., 2010, hitherto referred to as TR2009-119, TR2009-123, and TR2010-002). The studies differed in the way in which samples were taken and analysed.

6.14.2.1 Richardson Road (TR2009-119)

This study sampled solids accumulated in two pairs of catchpits located on opposite sides of a 200 m long section of Richardson Road. The primary aim was to estimate the loads of solids and associated particulate copper, lead and zinc entering roadside catchpits. In addition to sampling collected solids, flow to the catchpits was monitored and road runoff was sampled and analysed. Only the results pertaining to the PSD of collected solids are reported here.

There were two solids accumulation periods, 25 October 2007 – 6 August 2008 and 19 August 2008 – 9 March 2009. During the first period, maintenance contractors attempted to clean out a pair of the catchpits despite "No Clean" signage. The second period of collection was therefore conducted to allow measurement of undisturbed quantities of catchpit solids. The catchpits were cleaned and lined with heavy-duty PVC bags prior to each period. These were secured by bolting an aluminium strip over the bolt rope and into the wall of each catchpit slightly below the invert of the catchpit outlet pipe. Given the pliable nature of aluminium, this ensured a good, tight seal which prevented leakage of runoff and solids down the sides of the bag. Upon the completion of each accumulation period, stormwater in the catchpit sumps was pumped away until between 10-20 mm of water remained above the accumulated solids. The catchpit bags were then removed for analysis.



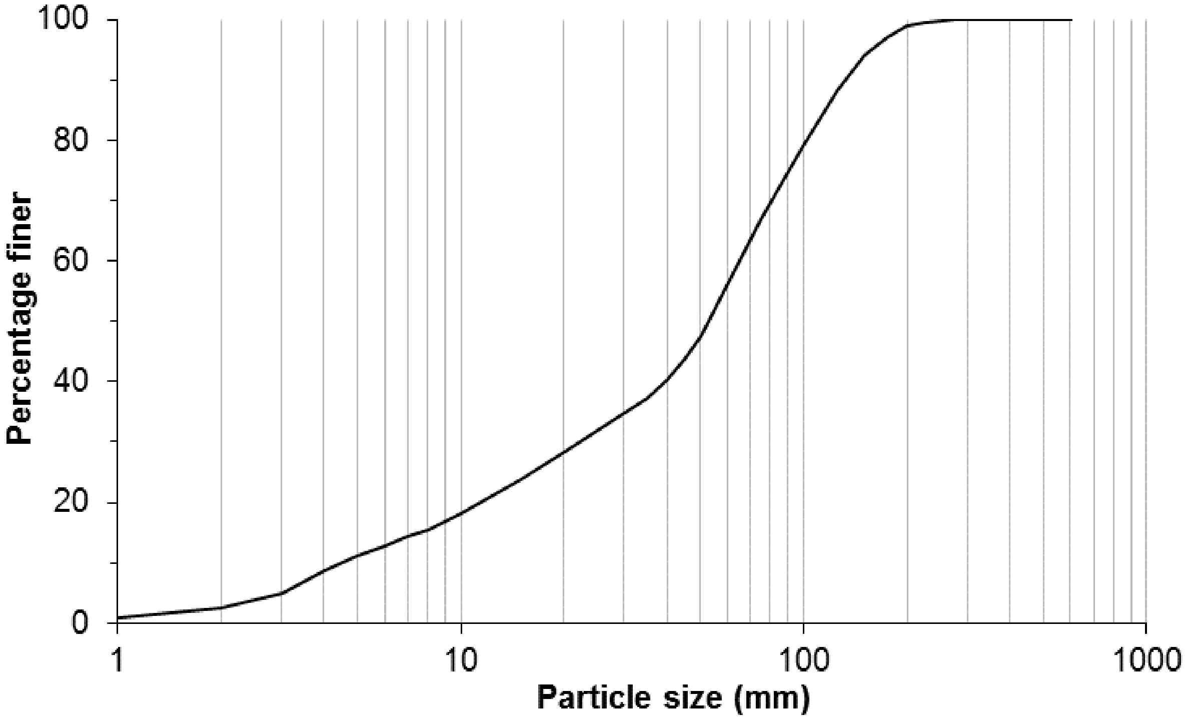


Figure 4PSDs for Auckland City collected by NIWA between 2001-2003. Top: all sites. Bottom: site composite (mean calculated for each particle size class).

Sub-samples of around 1 l were processes for PSD by wet sieving (sieve mesh from 1 cm to 0.2 mm) for coarse sediments. Approximately 1 g of the finest fraction (<200 µm) was taken and added to approximately 20 ml of de-ionised water for further particle size determination using laser diffraction.

Around half of the solids (by weight) in samples from three of the four catchpits were in the 1 mm – 1 cm size range. In the fourth catchpit (Catchpit C), samples were more evenly distributed between the five particle size ranges. Differences between the solids from catchpit C and other catchpits are also evident from the results of the particle size analysis of particles < 200 µm. In samples collected from the first period, only 16% of these solids from Catchpit C were greater >125 µm, compared to 31-52 % of solids from other catchpits. A smaller proportion of solids collected during the second period were in the >125 µm size range (0-31%), except for Catchpit C (32%). Like the findings of Andral et al. (2002) and Kim and Sansalone (2008), the PSD for the fine sediments was typical of PSDs for water samples, however, this was only a small fraction of the total mass of sediments found in the catchpits.

6.14.2.2 Characterisation of catchpit solids by traffic counts (TR2009-123)

In this study, samples of accumulated solids were collected from 30 catchpits in Auckland. Sampling locations, listed in

Table 15, were selected on the basis of vehicle count data expressed as the number of vehicles per day.

Each catchpit was carefully drained to ensure minimal disturbance of deposited solids using the same method as described for TR2009-123. Once drained, a sample was collected from the catchpit using a custom-built long handled auger. By rotating the auger it was possible to penetrate to the base of the catchpit with relatively little disturbance of the settled solids. The auger was then gently lifted to remove a core-sample of the full profile of deposited solids. This procedure was repeated a number of times until sufficient mass of sample (2 to 5 kg) had been collected. Three catchpits were sampled twice and three other samples were split (denoted as a and b, and 1 and 2 respectively in

Table 15) in order to provide information on the variability of results arising as part of the sample collection and processing methods.

Samples were dried, weighed, processed and analysed in order to determine the PSD; the proportion of organic material; the concentrations of Total Petroleum Hydrocarbons (TPHs); copper, lead and zinc in each sample. Only the PSD data are presented here.

The sub-samples were wet sieved through a 1 cm plastic sieve; the two fractions were then assessed for content. It was found that the solids > 1 cm largely consisted of organic debris (pine needles, leaves, twigs) with some litter (e.g., cigarette butts), while the solids < 1 cm consisted largely of mud, sand, grit, glass with some debris and litter. The PSDs of the solid sub-sample fractions less than 1 cm were analysed by wet sieving through 1 mm, 0.5 mm and 0.2 mm sieves.

The PSDs for the 30 catchpits are presented in order of traffic volume in

Table 15 and are plotted in Figure 5. With the exception of sites with a traffic count of 5,000-20,000 vpd, there seems to be no relationship between PSD and traffic counts. The proportion of solids with diameter 1 mm – 1 cm lies in the range 27 to 85 %. Samples with a relatively high proportion of these coarse solids were taken from catchpits 1, 2 (both Glasgow Terrace), 3 (Carlton Gore Rd), 23 (SH 16) and 30 (SH 30). The coarse fraction (1 mm – 1 cm) in samples from these catchpits constitutes more than two thirds of the total dry weight of the sample. The sample collected from catchpit 28 (SE Highway) has the lowest proportion of coarse solids (27 %).

Table 14 PSDs determined for Richardson Road catchpits using sieving (coarse fraction) and laser diffraction (fine fraction). From TR2009-119.

Collection period and catchpit		**Total dry weight (kg)**	**Coarse fraction by dry weight, >200 µm (wet sieving)**					**Fine fractions in size ranges by volume, < 200 µm (laser diffraction)**						
			>10,000	**1,000-10,000**	**500-1,000**	**200-500**	**<200**	**0-3.9**	**3.9-7.8**	**7.8-15.6**	**15.6-31.3**	**31.3-62.5**	**62.5-125**	**125-200**
	A	51.0	5.3	50.0	26.8	5.6	12.2	0.1	0.5	0.8	2.1	8.7	35.7	52.2
	B	29.1	4.6	48.7	25.0	6.0	15.7	0.1	0.7	1.3	3.3	12.3	45.7	36.5
	C	27.0	9.8	32.1	13.2	14.2	30.7	0.4	1.9	2.7	5.7	19.0	54.0	16.2
	D	31.3	5.4	47.4	20.5	11.0	15.7	0.3	1.5	2.1	4.3	11.6	41.4	38.8
1st period	D2 (E)	-	7.4	46.0	22.1	7.2	17.2	0.1	0.9	1.6	3.8	14.8	47.5	31.4
	A	28.2	5.7	56.7	20.4	7.6	9.5	0.1	1.3	4.3	8.7	19.0	42.6	24.1
	A2 (E)		6.8	64.2	16.8	2.1	10.0	0.4	2.2	3.6	7.1	15.5	40.7	30.5
	B	28.2	9.5	51.6	16.2	8.2	14.6	0.3	2.1	4.5	8.4	20.9	49.9	14.0
	C	22.5	12.2	40.4	23.0	12.9	11.5	0.8	3.4	5.1	9.8	20.6	28.3	32.1
2nd period	D	55.9	3.9	60.0	22.4	4.1	9.6	1.1	4.6	6.5	13.6	40.1	34.1	0.0

The (E) samples are duplicates made to assess sample variability

Table 15 PSDs of catchpits sampled in order of increasing traffic (vpd). Subscripts a and b denote repeat samples, 1 and 2 denote split samples. Data from TR2009-123.

Catchpit	**Road Name**	**Location**	**Vehicles per day**	**Proportion of total solids by dry weight (%)**			
				1,000 – 10,000 µm	**500 – 1,000 µm**	**200 - 500 µm**	**< 200 µm**
<1,000 vpd							
1	Glasgow Tce	corner Boyle Cres	113	85	2	4	9
2	Glasgow Tce	corner Boyle Cres	401	77	5	8	10
7	Rangitoto Ave	east of Rakau St	220	50	6	8	37
8a	Rangitoto Ave	east of Rakau St	219	44	5	5	47
8b			219	42	6	7	45
13a	John Davis Rd	opposite Ball Place	873	53	9	14	23
13b			873	51	12	14	23
14	John Davis Rd	corner Ball Place	876	36	14	20	30
1,000-5,000 vpd							
16	Ellis Ave	corner White Swan Rd	1,463	59	14	9	18

Catchpit	Road Name	Location	Vehicles per day	Proportion of total solids by dry weight (%)			
				1,000 – 10,000 µm	500 – 1,000 µm	200 - 500 µm	< 200 µm
15	Ellis Ave	corner White Swan Rd	1,355	61	17	9	12
3	Carlton Gore Rd	corner Seafield View Rd	1,247	73	8	10	9
4	Carlton Gore Rd	opposite Seafield View Rd	2,293	60	7	12	22
11	Carlton Gore Rd	corner Kingdon St	2,135	39	9	7	45
12	Carlton Gore Rd	corner Morgan St	4,514	36	12	23	29
10	Mountain Rd	Auckland Grammar	4,211	46	19	21	15
9	Mountain Rd	opposite Auckland Grammar	4,867	62	15	13	10
5,000-20,000 vpd							
5	Remuera Rd	corner Belmont Terr	7,172	37	23	27	14
6	Remuera Rd	opposite Belmont Terr	9,490	48	17	22	12
17	Richardson Rd	corner May Rd	1,181	40	22	19	19
18	Richardson Rd	opposite May Rd	1,212	53	16	12	19
22(1)	Newton Rd	corner Winchester Rd	16,143	51	24	11	14

Catchpit	Road Name	Location	Vehicles per day	Proportion of total solids by dry weight (%)			
				1,000 – 10,000 µm	500 – 1,000 µm	200 - 500 µm	< 200 µm
22(2)			16,143	50	22	16	12
21	Newton Rd	opposite Winchester Rd	16,500	39	25	23	13
27a	Manukau Rd	opposite Rangiatea Rd	16,742	49	15	16	20
27b			16,742	46	16	16	21
26(1)	Manukau Rd	corner Rangiatea Rd	18,271	44	21	20	15
26(2)			18,271	43	22	21	15
> 20,000 vpd							
29	Fanshawe St	intersection, SH 1 on ramp	20,285	34	12	15	39
28	SE Highway	Carbine Rd intersection	32,503	27	18	23	32
24	SH 16	Carrington Rd to G. North Rd	52,680	46	12	13	30
19	SH 16	G. North Rd to St Lukes Rd	49,669	54	14	23	9
23	SH 16	Newton Rd to St Lukes Rd	58,900	77	6	7	9
20	SH 16	after Western Springs on ramp	56,750	47	27	19	7

Catchpit	Road Name	Location	Vehicles per day	Proportion of total solids by dry weight (%)			
				1,000 – 10,000 µm	500 – 1,000 µm	200 - 500 µm	< 200 µm
30(1)	SH 1	before Greenlane exit	74,155	69	15	8	8
30(2)			74,155	67	15	9	8
25	SH 1	before Greenlane exit	83,550	58	9	23	10

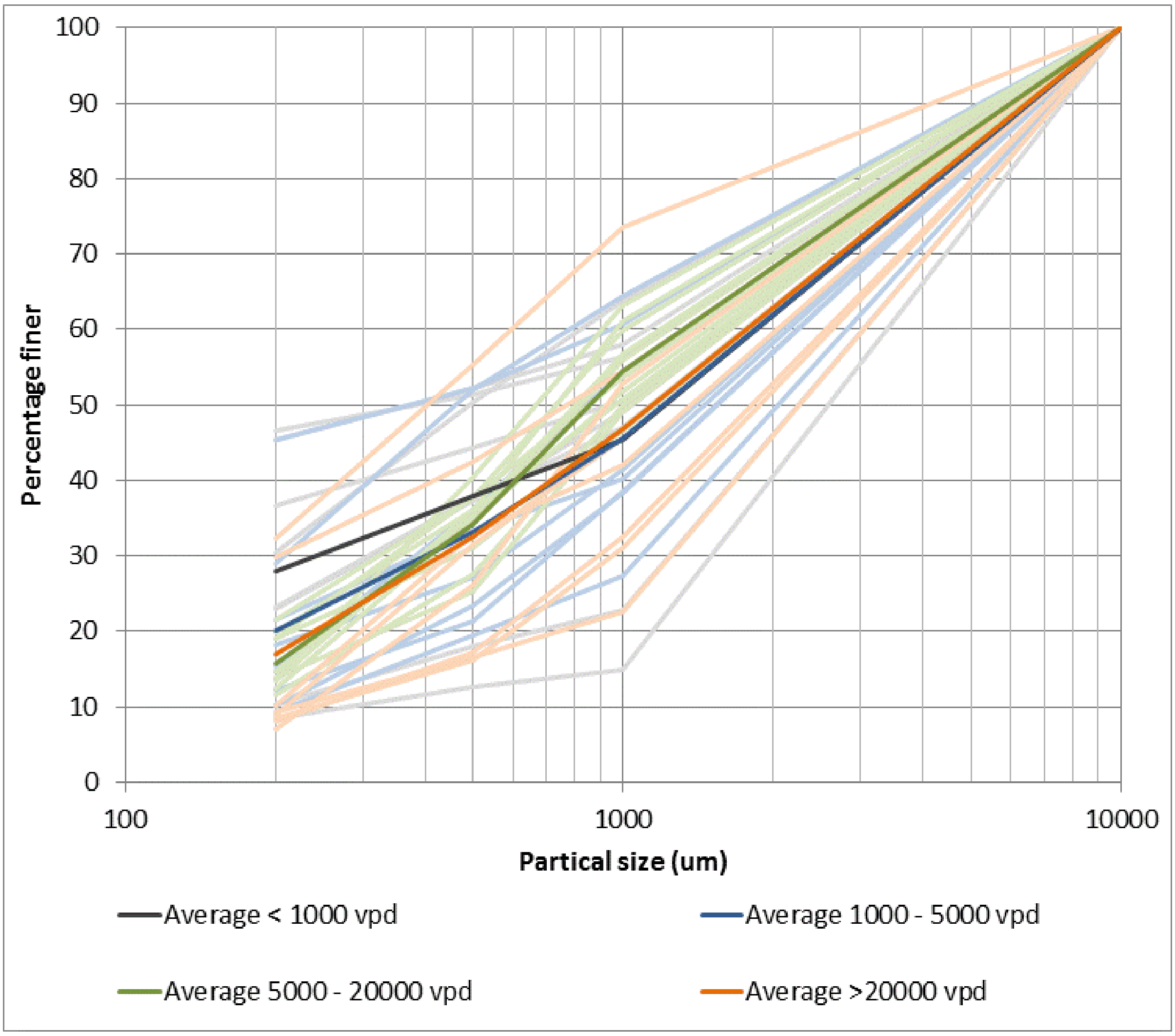


Figure 5PSDs for the fraction between 1 cm and 0.2 mm of solids sampled from 30 catchpits in Auckland by traffic. Line colour denotes traffic counts; grey (<1,000 vpd), blue (1,000-5,000 vpd), green (5,000-20,000 vpd) and orange (>20,000 vpd). Data from TR2009-123.

6.14.2.3 TR2010-002 Contaminants in industrial stormwater catchpits

In the final catchpit study carried out by NIWA, samples were taken from 19 catchpits in the Whau River catchment which were selected by ARC according to their proximity to different industries, namely: service stations (3), automotive workshop (6), paint manufacturers (3), plastics manufacturers (3), metal processors (3) and a timber yard.

Solids from each catchpit were sampled and analysed using the same methods as described above for TR2009-123. The PSDs for the catchpits are given in Table 16 and are plotted in Figure 6.

The PSDs vary widely and is no apparent relationship between the particle size of the solids sampled and industry. The proportion of solids with a particle size of 1 -10 mm lies in the range 10 to 61%. Samples with a relatively high proportion of these coarse solids were taken from catchpits 14 (automotive industry), 15 and 17 (paint manufacturers), 16 (plastic manufacturers) and 13 (timber treatment). The coarse (1 – 10 mm) fraction in samples from these catchpits constitutes more than half of the total dry weight of the sample. Samples collected from catchpits 4 and 19 (service stations), 3 (paint manufacturers) and 10 (plastic manufacturers) had the lowest proportion of coarse solids (all less than 20%).

Table 16 PSDs of catchpits sampled by industry type from TR 2010-002.

Catchpit	**Proportion of total solids by dry weight (%)**			
	1,000 – 10,000 µm	**500 – 1,000 µm**	**200 - 500 µm**	**< 200 µm**
Service station				
4	12	7	11	70
8	39	17	13	32
19	10	15	13	62
Automotive industries				
5	25	5	8	62
7	30	17	11	43
9	20	24	25	32
12	47	18	17	18
14	61	23	7	10
18	41	15	22	22
Paint manufacturers				
3	13	5	8	74
15	64	19	9	7
17	51	13	22	14
Plastic manufactures				
6	37	10	8	44
10	16	15	15	53

16	54	29	10	6
	36	18	11	35
Metal Processors				
1	36	26	17	20
2	26	49	18	8
11	26	18	28	28
Timber yard				
13	54	26	14	5

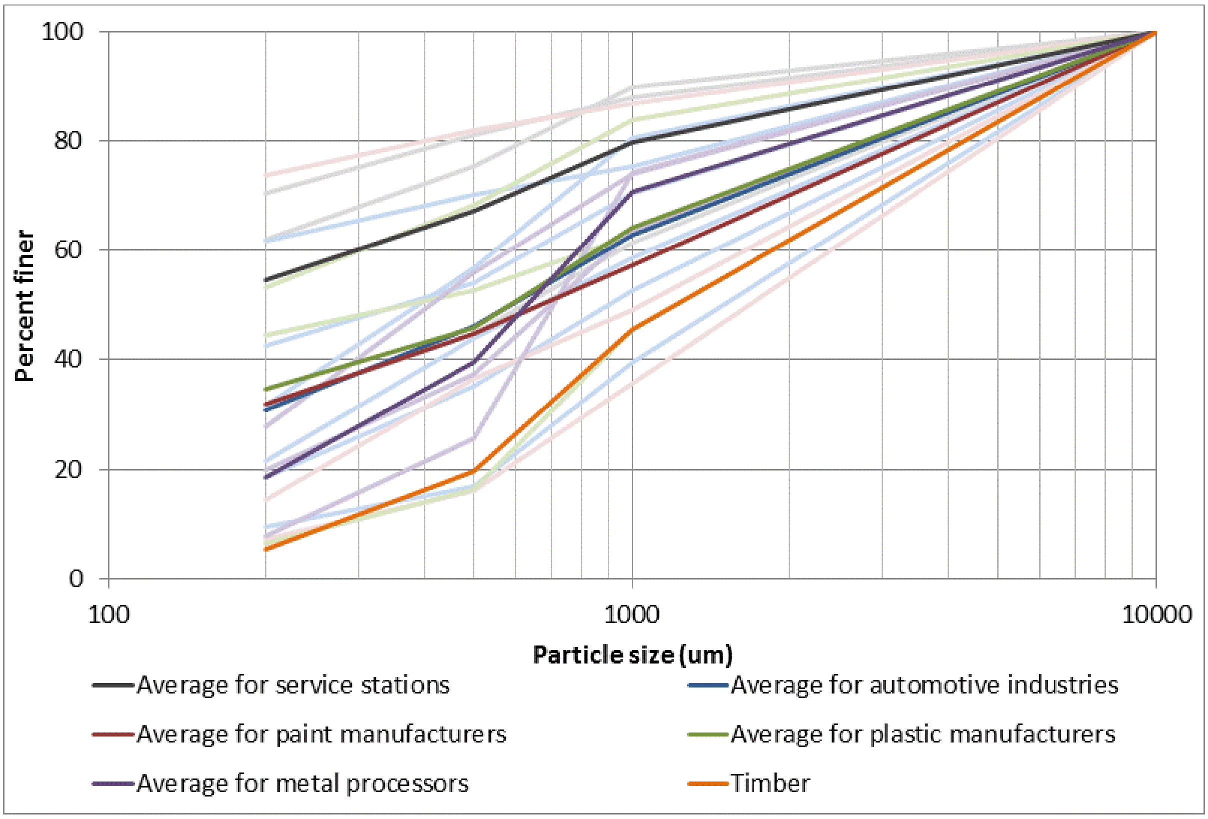


Figure 6PSDs for the fraction between 1 cm and 0.2 mm of solids sampled from 19 catchpits in Auckland by industry. Line colour denotes industry; grey (Service statins), blue (automotive industries), red (paint manufacturers), green (plastic manufacturers), purple (metal processors) and orange (timber).

6.14.3 Comparison of proprietary filters

In this study (Moores et al., 2012) undertaken for the New Zealand Transport Agency (NZTA) and Auckland Council, the performance of three commercially available proprietary filters were assessed under field conditions by comparing influent and effluent quality. The filters were all located on Auckland's North Shore in Albany (Westfield shopping centre), Silverdale (SH 17) and Esmonde Road. The sites were instrumented to measure and record water levels for the estimation of discharge (or flow) and to collect influent and effluent water samples during storm events. Samples were collected during 15 storm events at each site between September 2010 and March 2012. A sub-set of samples was analysed for concentrations of organic solids and for particle size distribution (PSD) in order to relate filter removal efficiency particle size. The PSD data for influent (i.e., pre-treatment water samples) only are presented here.

All samples were made using automatic water samplers. At the Albany and Silverdale sites, the sampler intakes were located on the upstream face of the weirs (i.e., immediately below the level of the weir invert to ensure samples were collected from freely flowing, well-mixed waters). At Esmonde road, the sampler intake was at the invert of the pipe downstream of the weir. The samplers were programmed to collect samples on a flow-proportional basis.

Samples from each site were returned to the NIWA laboratory in Auckland usually within 24 hours of the first samples being collected. PSD was determined by first sieving through 500µm and 250µm meshes to retain larger particles. These were collected and weighed. A sub-sample of at least 30mL of the <250 µm fraction was analysed using the light obscuration particle size analyser in NIWA's Water Quality laboratory in Hamilton. The influent PSDs are plotted in Figure 7 and are summarised in

Table 17. The PSD of samples collected at the Esmonde Rd and Albany sites is similar (median grain size in the 62.5-125 µm size band), while that of samples collected at the Silverdale site is slightly finer (median in the 31.2-62.5 µm size band).

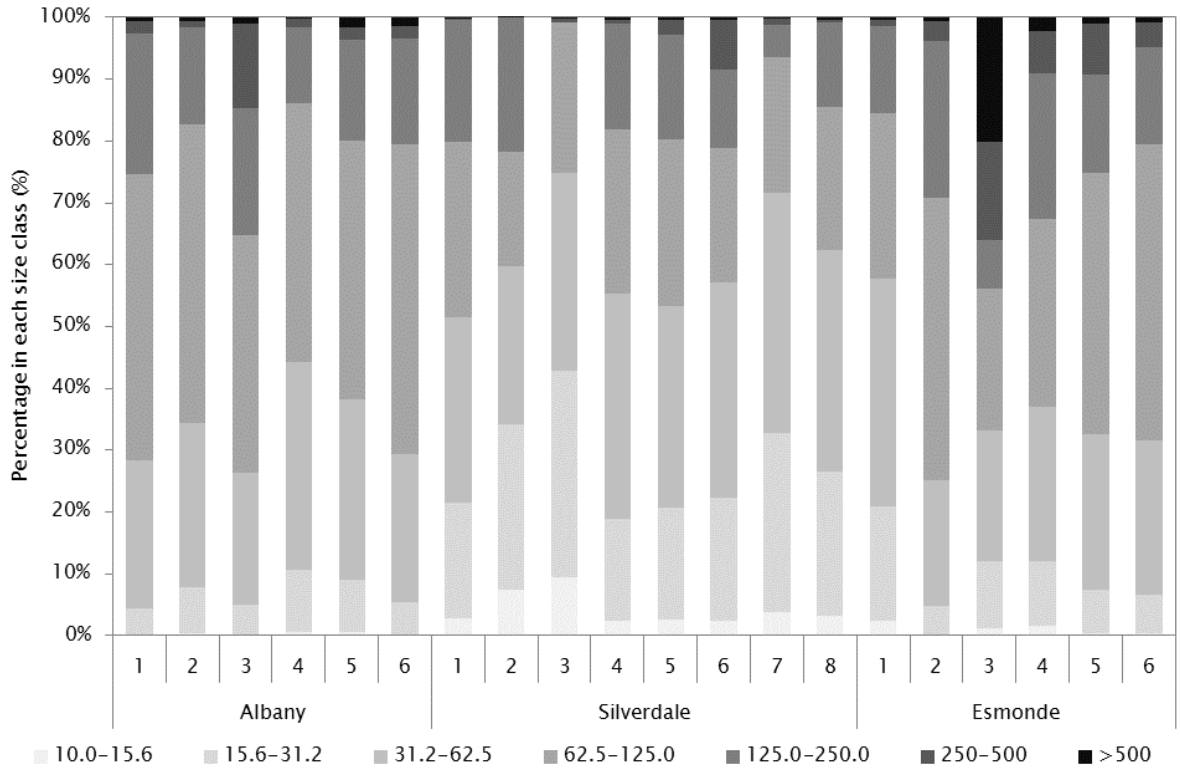


Figure 7PSDs of water samples collected upstream of proprietary filters. Adapted from Moores et al. (2012).

Table 17 Influent PSDs averaged for each filter monitoring site. Calculated from data presented in Moores et al. (2012).

Size band (µm)	**Proportion of solids in each size band (%)**		
	Albany	**Silverdale**	**Esmonde Road**
>500	0.4	4.3	1.0
250-500	6.7	23.1	9.6
125-500	26.4	33.2	25.5
62.5-125	44.5	23.9	35.9
31.2-62.5	17.5	13.4	17.1
15.6-31.2	3.7	1.7	6.5
10-15.6	0.9	0.3	4.2

6.15 Synthesis of PSD data

Table 18 provides a summary of the PSDs from the literature presented above, while Figure 8 plots the PSD for studies where the data were reported in a suitable form. It can be seen that the methodology used to determine PSD and the way in which PSD is reported varies between studies making comparison difficult. Kayhanian et al. (2012) reviewed particle sizes reported in the literature, including some of the studies cited here, which showed that sediments < 50 µm can account for a sizable portion of the total sediment mass. However, others have stated a concern that sampling methods may be biased towards fine particles. Reviews can also be found in Kim and Sansalone (2008), Clark et al. (2009) and Fan (2003); each showing a wide range of sediment sizes which can be attributed to the physical characteristics of sampling sites including land use and soil type. They state that the median particle size reported in the literature for stormwater solids ranges from 8 µm to more than 1200 µm. The former was reported for residential runoff discharging to a detention pond, whereas the latter was reported for runoff from a stretch of highway which has periodic grit applications for skid control following snowfall. These papers also point out that at a particular site, the PSD can vary from event to event, largely as a result of differences between rainfall intensity and antecedent dry periods. It should be noted that as catchments become more impervious, the contribution of sediments from soils will be less. This means that the sediment properties for highly urbanised catchments are more likely to reflect land use rather than soil type. There is also variability due to the choice of sampling and analytical methods and the sediment size bands analysed.

The finest solids presented here were those calculated by the ARC (TP10, first edition, 1992) from the NURP settling velocities reported by Driscoll et al. (1986). However, the NURP samples pre-date the 1993 threshold for reliable use of automatic samplers recommended by Bent et al. (2001). Moreover, while stormwater particles can have a range of shapes and densities (see TR2009-035), the calculations to determine particle size from settling velocity were made under the assumptions of spherical particles with a uniform specific gravity of 2.68 (i.e., equivalent to quartz) which could lead to an under-estimation of particle size.

Those studies which have sampled the entire range of particle sizes of stormwater-borne solids (e.g. using a combination of bed-load sampling and water sampling) or have taken samples close to the source location have shown that much of the original particle mass of stormwater solids are greater than 250 µm in size. Andral et al. (1999), Lin (2003) and various papers by John Sansalone and his colleagues (e.g., Sansalone et al., 1998; Sansalone et al., 1996, Cristina et al., 2002; Kim and Sansalone, 2008) have found a greater proportion of coarse sediments than is generally reported for stormwater. They point out that while coarser sediments readily settle out of suspension, their presence in stormwater treatment devices implies that they must be transported as bed load with stormwater by mechanisms such as rolling, sliding and saltation and therefore must be considered stormwater-borne solids. ASCE (2010) go as far to say that sampling only the water column has led to the misconception that most particulate contaminants found in stormwater are suspended.

To illustrate further using NIWA data from Auckland, the Richardson Road study presents two sets of PSD from the same sediment samples; one for sediments >200 µm which was determined by sieving and one finer sediments (<200 µm) determined by laser diffraction. While the coarse fraction has grain sizes much larger than is commonly reported in the literature for stormwater sediments, the fine fraction is within the size range for stormwater samples found in Auckland (i.e., suspended sediments), albeit at the coarser end.

Table 18: Summary of stormwater solid PSDs reported in selected literature.

Study	Analytical method	Particle size range
Driscoll et al. (1986)	Settling columns	2-82 µm (determined from fall velocity by Beca Carter Hollings and Ferner, 1992 for ARC in TP4)
Leersnyder 1993	Sieving (mesh between 1000 and 20 µm)	79 % of solids in 20 to 63 µm range; 79 % for Pacific Steel and 49.8% for Hayman Park. Only 0.7 % of particles were >1000 µm at Pacific Steel. Hayman Park had 6.7 % of particles >1000 µm.
Sansalone et al. (1998)	Sieving (mesh between 9.25 mm and 20 µm) Light obscuration counter (particles < 20 µm)	555 µm mean median (d_{50}) grain-size over 13 events
Andral et al. (1999)	Sieving (mesh between 1 mm and 50 µm) Laser diffraction counter for fine particles. Fall velocity determined using pipette procedure	Different size ranges for settled and suspended solids. 90% by weight of settled solids >100 µm. 75 % by weight and volume for suspended sediments in runoff > less than 50 µm.
Cristina et al. (2002)	Sieving (mesh sizes not reported) PSD reported as percentage of the particle total surface area by particle size band	98% of total surface area associated with particles > 75 µm
Furumai et al. (2002)	Sieving (mesh for stormwater particles - 20-250 µm, mesh for street dust up to 800 µm)	Variable across events with median grain size between <20 and >106 µm. Coarse sediments are associated with high TSS loads.
German and Svensson (2003)	Sieving (mesh between 250 µm and 75 µm) of street dust collected pre and post street-sweeping	Fraction finer than 250 µm pre-sweeping 26 % post-sweeping 40 % swept particles 20 %
Lin (2003)	Settling and laser diffraction counter	1-250 µm, 90% of solids able to settle within one hour

Study	Analytical method	Particle size range
Fan (2004)	Review of reported sediment sizes in stormwater reaching sanitary sewers.	16 to 62 µm
CRCCH (2004)	Input to MUSIC model, based on reported values from Australia	1-500 µm
Zanders (2005)	Sieving (mesh between 2000 µm and 32 µm) of street dust collected by vacuum over a 2-week period	Initial sample had 28 % particles < 250 µm Subsequent samples had 52 % of particles < 250 µm
Kim and Sansalone (2008)	Settling and laser diffraction counter	Majority of solids in coarse fraction over 75µm. Median grain size for 8 events ranged from 43 µm to 300 µm.
Kim and Sansalone (2008)	Review of reported particle sizes in stormwater and street dust	Particles in water samples generally < 75 µm Sediments in street dust between 20 and 20,000 µm
Clark et al. (2009)	Review of reported particle sizes in stormwater	Median particle size ranges from 8 µm to more than 1200 µm
Kayhanian et al. (2012)	Settling and laser diffraction counter, 38 µm used as cut-off between coarse and fine sediments Samples taken from highway surface sediments, highway runoff and settled sediments from dry detention ponds.	Proportion of sediments <38 µm varied, averages are: Surface sediments – 0.7% Runoff sediments – 67.4% Pond sediments – 32.3%
NIWA – Metrowater stormwater monitoring (Reed and Timperley, 2004; Timperley et al., 2004 a and b)	Light diffraction counter	Most particles in the range 1-275 µm, median particle size ranges between 30-75 µm depending on site
NIWA – Richardson Rd catchpits (TR2009-123)	Sieving for coarse sediments (1 cm to 200 µm mesh) and laser obscuration counter for fines (<200 µm)	Around half of solids are in the 1 mm to 1 cm size class.

Study	Analytical method	Particle size range
NIWA – catchpits by traffic count (TR2009-119)	Sieving for coarse sediments (1 cm to 200 µm mesh))	Proportion of particles in the 1 mm – 1 cm size range varies between 27 to 85 %
NIWA – catchpits by industry (TR2010-02)	Sieving for coarse sediments (1 cm to 200 µm mesh)	Proportion of particles in the 1 mm – 1 cm size range varies between 10 to 61 %
NIWA – Filter study (Moores et al., 2012)	Sieving for coarse sediments (1 cm to 250 µm mesh) and laser obscuration counter for fines (<200 µm)	Median grain size in the 62.5-125 µm size band for Albany and Esmonde Rd. Median grain size for Silverdale site is in the 31.2-62.5 µm size band.

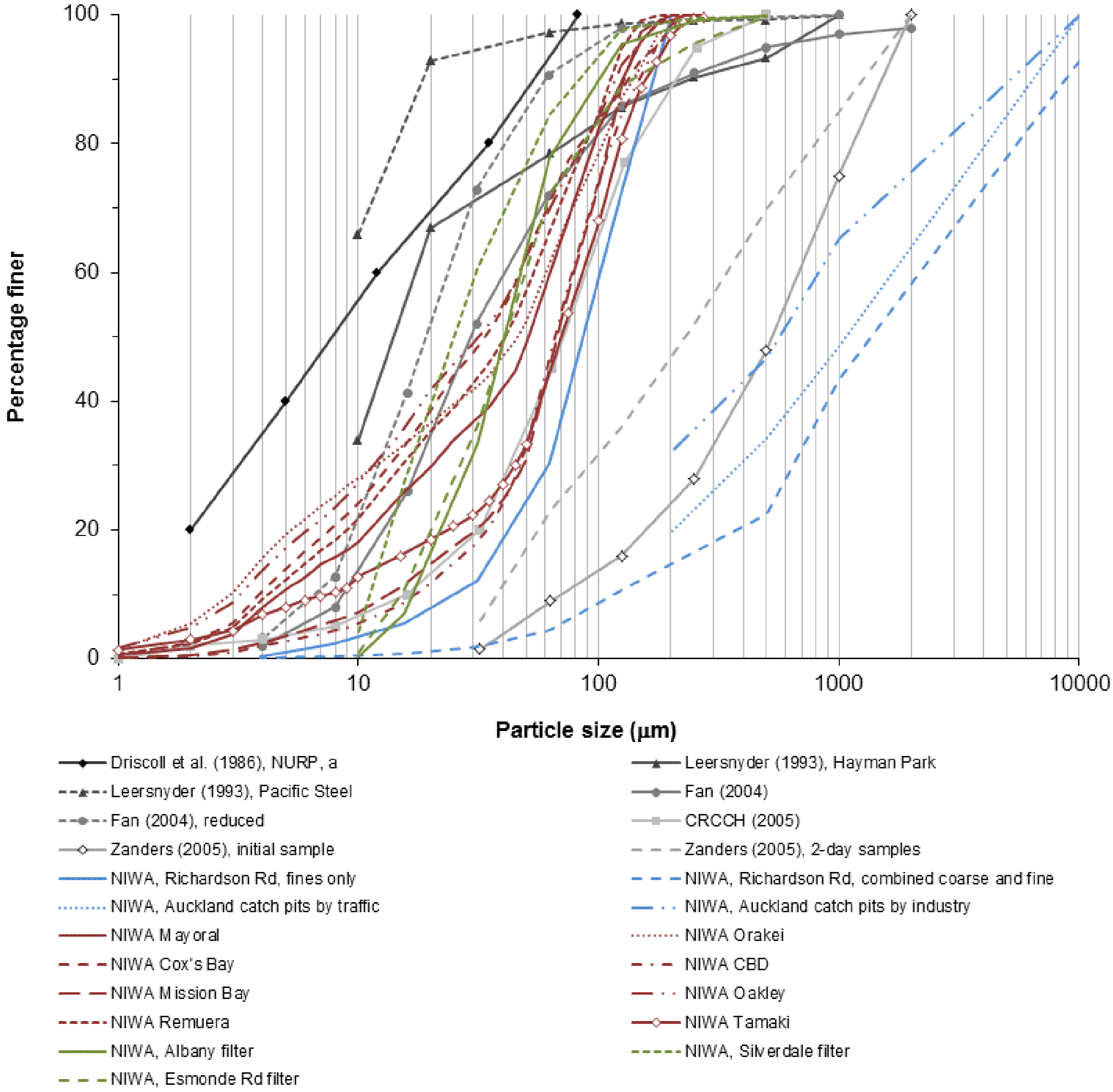


Figure 8PSDs from selected studies showing wide range of particle sizes for stormwater solids.
[a] NURP PSD calculated from fall velocity by Beca Carter Hollings and Ferner (1992; ARC TP4

7.0 Impact of particle size on stormwater treatment

The size and characteristics of stormwater-borne solids and the fractionation of particulate contaminants should play a critical role in the selection, design and performance evaluation of stormwater treatment devices (Kayhanian et al., 2012). While there is a general understanding that finer sediments are associated with greater contaminant content than coarse sediments due to their larger surface area per unit mass (e.g. Timperley et al., 2004 c; Ding et al., 1999); if the stormwater solids at a specific site consist of predominantly coarse grains, these can have a higher total contaminant mass load than fines.

The performance target for stormwater treatment in the Auckland region is for the removal of 75% of TSS on the understanding that TSS is an indicator of stormwater quality and that TSS removal will also result in the removal of particulate contaminants. TP10 defines TSS according to the APHA standard method (SM 2540 D) whereas PDEP has adopted the amendment to this method proposed in the WERF protocol (see Section 5.3.1). In both documents, there are no requirements to remove sediments within a specific target size range in order to maximise stormwater treatment. PDEP requires a critical evaluation of the performance of proprietary devices, such as filters and hydrodynamic separators, against performance claims issued by the supplier. In contrast, there is an underlying assumption in TP 10 that non-proprietary stormwater management devices built to the design specifications will achieve the desired removal target.

Planning and design guidelines to achieve the target removal efficiency are provided in the following ARC publications; TP10, TP108 (ARC, 1999) and TP124 (ARC, 2000). Auckland Council has also issued new guidelines for the construction, operation and maintenance of selected stormwater treatment devices, available to stormwater engineers online (http://www.aucklandcouncil.govt.nz/EN/environmentwaste/stormwater/Pages/stormwaterguideshome.aspx - date of last access 5 April 2013), which complement the design criteria. In addition, there has been a recent review of gross pollutant removal options for the council (Fitzgerald and Bird, 2010) which, amongst others, includes information on catchpit grates and inserts, trash screens, booms and racks. That review adopted the 5 mm lower size limit for gross pollutants in accordance with Allison et al. (1998), which is also the lower limit proposed by the WERF protocol.

7.1 PSD in planning and design

Information on stormwater solids, in addition to other site information such as contaminant sources, slope, catchment area and available space, is required at the stormwater management planning stage to evaluate different treatment options. While there are planning guidelines which relate the choice of stormwater treatment options to generic sediment size ranges (e.g., CSIRO, 1999, 2006 – see Figure 6-1), for the most part stormwater solids are equated to the broad categories of gross pollutants, TSS (as a proxy for solids in the fine, medium and coarse grain size classes) and dissolved solids. TP10, for instance, includes a number of tables which show the suitability of various treatment options in relation to key pollutants (including suspended sediments), downstream environmental impact, and site constraints such as slope, space availability and water table depth. Fitzgerald and Bird (2010) developed a decision matrix which similarly can be used to evaluate treatment options for removal of gross pollutants.

Planning tools such as the Auckland Council Contaminant Loads Model (**CLM**, ARC 2010) and the related NIWA Catchment Contaminant Annual Loads Model (**C-CALM**, Semadeni-Davies et al., 2010) can help decision makers plan catchment wide stormwater treatment options by allowing a comparison of the relative improvements to water quality that could be expected from various treatment options. The Landcare Research developed CostNZ model (Ira et al., 2007) can be used to evaluate options on the basis of lifecycle costs.

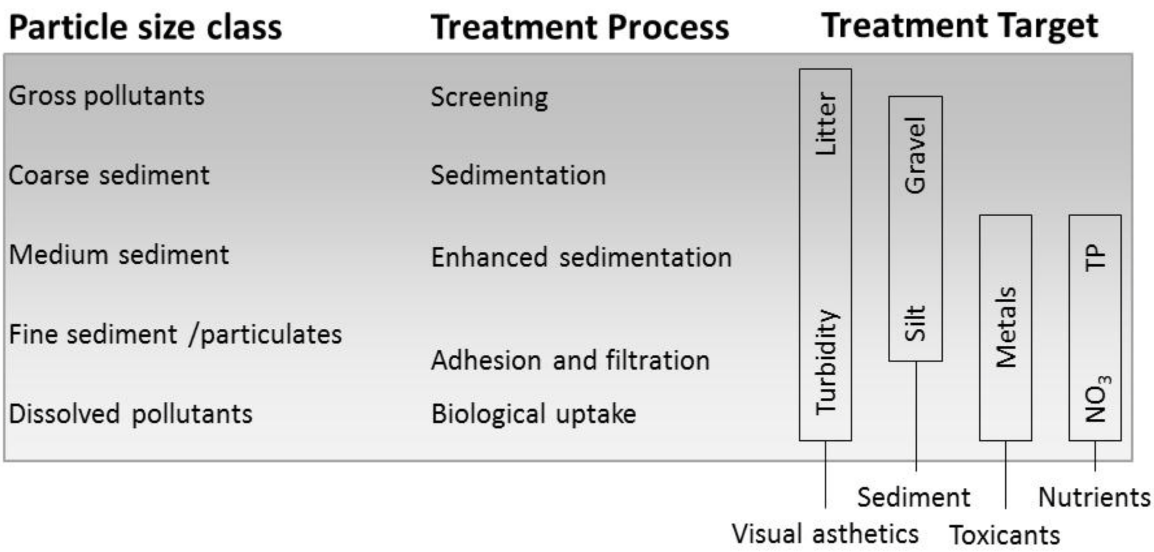


Figure 9CSIRO stormwater treatment options based on particle size class. Adapted from CSIRO (1999; 2006).

Another example of a planning tool is the Multi Criteria Comparator decision support system developed at Middlesex University (Ellis et al., 2006; Scholes et al., 2008) which can be used to choose between treatment options for a particular site on the basis of catchment characteristics, land availability, target contaminants and the desired level of treatment. An assessment of pollutant mechanisms and stormwater treatment options was carried out for TSS as part of the tool development. This assessment ranked settling and filtration as the most effective mechanisms for TSS removal followed by adsorption and microbial-degradation. The other removal mechanism assessed (plant uptake, volatilisation and photolysis) were found to have a negligible impact on TSS. The removal mechanisms were also ranked by their importance to the function of 15 different stormwater treatment options. For instance, settling was ranked as the most important mechanism for detention ponds, but had a low ranking for porous paving. Conversely, the most important mechanism for porous paving was filtration which has a low rank for ponds. The rankings coupled together to allowed Scholes et al. (2008) to score the ability of the treatment options to remove TSS; the top three ranked devices were infiltration basins, constructed wetlands (sub-surface flow) and porous paving.

The Best Management Practices (**BMP**) Database summary of TSS concentrations by treatment device (Geosyntec Consultants, 2012; http://www.bmpdatabase.org/ - date of last access 5 April 2013) can also aid in the choice of treatment options. While percentage removal efficiencies are not reported, comparisons between influent and effluent water quality shows that bio-swales, proprietary devices and wetlands generally have the greatest absolute differences in TSS concentrations.

At the design stage, the chosen stormwater treatment devices should be sized to achieve the appropriate level of treatment relative to the target grain size which is set in accordance to both the

PSD of the solids and the fractionation of associated particulate contaminants. In general, finer sediments have the greatest contaminant concentrations by mass making them the target for treatment (e.g. Timperley 2004 c). However, if the PSD has a large proportion of coarse grained solids, the bulk of the particulate contaminant load may be found on these solids which should instead be targeted.

The WERF protocol suggests that settling is an effective treatment for particles in the fine and coarse size classes, accordingly settling basins should be designed such that the flow distance from inlet to outlet divided by the detention time is equal to the settling rate of the target particle size (e.g., US EPA, 2002). The criteria for sizing ponds in TP10 were devised assuming that stormwater solids in Auckland stormwater have the same settling behaviour as reported for NURP by Driscoll et al. (1986). Likewise, the mesh of sediment trapping screens and choice of filter media should be specific to the target particle size. Both TP10 and TP124 recommend the use of treatment trains to target solids in different size ranges sequentially from coarse to fine in order to maximise sediment and particulate removal and minimise the risk of clogging of devices intended to remove fine particles. Similarly, many devices, such as ponds, wetlands, and sand filters, are designed with settling fore-bays or, in the case of raingardens, surface ponding as a means of pre-treatment to remove coarse settleable solids.

7.2 TSS removal by particle size

Despite the importance of PSD and particulate fractionation to the choice and function of stormwater treatment devices, there are comparatively few studies in the literature which have included an analysis of influent and effluent particle sizes. That is, most studies into solids removal report only TSS. Some examples of studies which have included particle size are summarised below. These typically show that coarser solids are more effectively removed by stormwater treatment devices than fine solids.

7.2.1 Comparison of proprietary media filters, Auckland (Moores et al., 2012)

As part of the study into the in situ performance of commercially available media filters overviewed in Section 6.14.3, Moores et al. (2012) analysed the PSD (using a light obscuration counter) of suspended sediments in the influent and effluent of three filters. It was found that the filters preferentially remove coarser sediments leaving fines in the effluent.

The Silverdale filter treats water from an 859 m^2 section of a major highway (SH 17). The particle size of the solids entering the device can be considered fine with the proportion of medium sand (250–500µm) ranging from 0.5% to 8.1% (mean 2.2%) and the proportion of coarse sand (>500µm) ranging from 0.2% to 0.5% (mean 0.3%). The solids exiting the device had lower proportions of medium (<0.1% to 3.0%, mean 0.5%) and coarse sand (<0.1% to 1.4%, mean 0.3%). The analysis of samples for particles <250 µm in size found that the PSD of influent samples to be coarser than that of effluent samples (Table 19). For the particles <250µm, the median particle size was lower in the effluent than in the influent. This difference was statistically significant based on non-parametric tests.

Table 19 Summary statistics for PSD (<250µm fraction), Silverdale

Statistic	Influent	Effluent
No. samples PSD analysed	7	7
Range of median particle size	35-54	22-49
Mean of median particle size	47	34
Median of median particle size	48	33
Wilcoxon rank-sum test	0.021	
Wilcoxon signed-rank test (for paired data)	0.016	

The Albany filter treats runoff from 4535m^2 of sealed car park with access drives. The particle size of the solids entering the device was dominated by very fine sand (62.5–125µm) and fine sand (125–250 µm). For all samples measured, the mean proportion of very fine – fine sand was 60%, and the range was 48% to 69%. The remainder was typically in the silt size class from 31.2–62.5µm (mean 27%, range 21% to 34%). The proportion of medium sand (250–500µm) ranged from 1.1% to 14% (mean 4.2%) and the proportion of coarse sand (>500µm) ranged from 0.2% to 1.6% (mean 1.0%). The solids exiting the device were also dominated by very fine and fine sand (62.5–250µm). For all samples measured, the mean proportion of very fine – fine sand was 67%, and the range was 61% to 75%. This is a slightly greater proportion than in the influent, due to the slight decrease in the proportion of coarser particles. The proportion of medium sand (250–500µm) in the effluent ranged from 0.3% to 10% (mean 2.5%) and the proportion of coarse sand (>500µm) ranged from 0.1% to 0.9% (mean 0.6%). In most cases, there was little change in the proportion of silt sized particles <31.2µm.

Table 20 Summary statistics for PSD (<250µm fraction) at Albany

Statistic	Influent	Effluent
No. samples PSD analysed	6	6
Range of median particle size	71-81	76-98
Mean of median particle size	76	84
Median of median particle size	76	80
Wilcoxon rank-sum test	0.13	
Wilcoxon signed-rank test (for paired data)	0.063	

The analysis of samples for particles <250 µm found that the PSD of influent and effluent samples to be similar (Table 20). For the particles <250µm in size, the mean and median particle size were slightly higher in the effluent than in the influent. This was not statistically significant based on non-parametric tests.

The Esmonde Road filter was designed to treat roadway runoff from a 9000 m^2 area, but a review of the catchment topography and the stormwater network suggests a catchment area of 9756 m^2. The particle size of the solids entering the device was dominated by very fine sand (62.5–125µm) and coarse silt (31–62.5µm). The mean proportion of very fine sand in all samples analysed was 36% while the range was 23% to 48%. The mean proportion of medium and coarse sand (>250µm) was 11%, although this was skewed by a single sample with 36% in this size class which was collected after road-works on Esmonde Road. All other samples had less than 10% in the size range >250µm, with a range from 1.5% to 9.2%. The solids exiting the device were also dominated by very fine sand (62.5–125µm) and there was generally a slight decrease in the amount of medium and coarse sand. The analysis of samples for particles <250µm in found that the PSD of influent samples to be coarser than that of effluent samples (Table 21). For the particles <250µm in size, the mean and median particle size were higher in the influent than in the effluent. This was statistically significant based on the paired non-parametric test.

Table 21 Summary statistics for PSD (<250µm fraction) at Esmonde Rd

Statistic	Influent	Effluent
No. samples PSD analysed	6	6
Range of median particle size	52-95	38-78
Mean of median particle size	73	57
Median of median particle size	75	53
Wilcoxon rank-sum test	0.093	
Wilcoxon signed-rank test (for paired data)	0.031	

7.2.2 Proto-type Up-Flo media filter

In situ testing of a proto-type Up-Flo filter installed in a catchpit (Khambhammettu et al., 2006; Pitt and Khambhammettu 2006; Pitt et al., 2008) was carried out over a 10 month period. In all, 31 flow events were monitored along with controlled flow experiments to determine removal efficiencies for high, medium and low flow rates. The filter had a carbon/peat/zeolite media mix. The results suggest a removal efficiency for TSS of between 70 and 90% depending on event flow characteristics, the initial sediment concentration and PSD. Particles in the 1-20 µm and 120-250 µm size ranges were reduced by ~50% and respectively. There was a 100% removal of particles > 250 µm.

7.2.3 Surface Wetland (Walker and Hurl, 2002)

Samples of settled sediments were taken using sediment traps at five points with flow distances 70, 330, 630, 1410 and 1890 m from the inlet of a meandering wetland. Sediment and particulate metal removal was assessed for different sediment size fractions. PSD was determined by sieving (2-1000 µm mesh). The mass of settled sediments was greatest at the 330 m sampling site. There was a progressive fining of sediments along the flow path with most sediments at the 1890 m site having a particle size <20 µm.

7.2.4 Wet detention ponds (Pettersson, 1999)

TSS and dissolved and particulate metal concentrations were determined for water samples taken at the inlet and outlet of a small detention pond in order to provide information to develop a fluid dynamic model of flow and stormwater treatment in ponds. The PSD of the suspended sediments was determined using a light obscuration counter which counted the number of particles in 0.5µm steps from <1 to 282µm. It was found that the removal efficiency of the metals was related to their affinity to particles. Lead, which is usually in particular form, had a higher removal rate than zinc which was in dissolved or colloidal form.

7.2.5 Vegetated filter-strip (Han et al., 2005)

Sediment removal was assessed for a 10-m long experimental vegetated filter strip. It was found that it could retain up to 85% of TSS. A model describing the strip's function suggests that the strip was most effective for particles >8 µm, infiltration loss is the main removal mechanism for finer particles. While the saturated hydraulic conductivity and initial soil moisture content had little effect, TSS removal was influenced by the condition of the vegetation, notably density.

7.2.6 Grassed swales (Bäckström, 2002; 2003)

TSS removal was evaluated by comparing the influent and effluent of seven grassed swales in the field and two experimental swales lined with artificial turf in the laboratory in order to determine the factors which affect removal efficiency. Each swale was evaluated following applications of water mixed with sediments collected by a street sweeper. Grab samples from the swale inlets and outlets were taken at two minute intervals during each simulated event.

The sediments collected at the inlets and outlets were separated into three grain size categories 0-75, 75-125 and 125-250 µm. The laboratory swales captured particles in all size classes and particle trapping did not appear to be correlated to size. In contrast, the field measurements showed that trapping is related to sediment size with coarse sediments retained more readily than fine. The factors with the greatest influence on trapping were planting density, swale length, and, for the laboratory swales, water flow velocity.

7.2.7 Street Sweeping (Fan, 2004)

Fan (2004 – summarised in Section **Error! Reference source not found.** and Table 10) collated removal efficiencies reported in the literature for street sweeping and catchpit sumps. It was found that larger particles are removed more readily than fine particles. The removal efficiency of street sweeping for particles greater than > 1000 µm is 70% compared to 15% for particles between 31 and 62 µm. The catchpit removal efficiencies for the same grain size classes are 100 and 10%

respectively. German and Svensson (2002, also cited above) found comparable removal efficiencies for street sweeping.

7.2.8 Porous Paving (Colandini et al., 1995)

Colandini et al. (1995) sampled material clogging the pores of pervious asphalt with and without underlying reservoir structures; these structures consist of several layers of porous media designed to reduce and attenuate peak flows. In all, four sections of paving were sampled. The PSD of the clogging material was determined by a combination of sieving (mesh sizes from 40-2000 µm) and laser particle size analysis (<500 µm). Sediment samples were taken by water-blasting the paving with high pressure water and then collecting the resulting sludge. .

Most of the clogging material for each type of porous paving was in the fine and coarse sand fractions (20-200 µm and 200-2000 µm). The samples from paving with no reservoir had a high proportion to silt clogging material compared to the samples from paving with a reservoir which was clogged by gravel. The median grain size was smaller (146 µm)for the paving with no reservoir compared to a median of 367 µm for the material from paving with a reservoir. The conclusion was drawn that porous paving with a reservoir structure requires more controlled management and regular maintenance to avoid clogging.

7.2.9 Catchpits and catchpit inserts

Pennington and Kennedy (2008) reviewed catchpit sediment removal efficiencies by grain size reported in local and international literature for the ARC. They found that generally catchpits can remove most particles >500 µm while comparatively few (10-20%) particles <100µm are retained. There finding is consistent with Pitt and Field (1998) who state that a well maintained catchpit can retain up to 35-40% of the annual sediment load in stormwater, mostly in the 250 – 2000 µm size range.

Pitt and Field (2004) measured the solids removal effectiveness of 100 catchpits and concluded that solids removal is principally a function of the rate of incoming gutter flow. Removal rates for TSS approach 45% when the inflow is discharging less than 0.005 m^3/s and is negligible for flow rates in excess of 0.139 m^3/s. Fassman and Voyde (2007) evaluated the performance of a full size acrylic test catchpit similar to those found in Auckland at three inflow rates (1, 5 and 20 l/s). They found that at 1 l/s, coarse sediment is more efficiently retained in the catchpit than clay. At 5 and 20 l/s, clay is more efficiently retained than the coarse material. This finding was surprising as it was expected that the coarser sediment would have greater retention efficiencies than the clay. It was stated that at these inflow rates, catchpits can be a net exporter of sediments due to scour of settled sediments in the catchpit sump.

As reported by Pennington and Kennedy (2008), catchpit inserts have been shown to improve sediment removal efficiencies. A number of studies have been carried out in Auckland which report removal efficiency by grain size class. A laboratory evaluation of commercially available mesh filter bags for Auckland City Council (Butler et al., 2004; McQuillan and Menzies, 2004) reported removal efficiencies for TSS of between 78 to 98%. Practically all particles >100 µm were removed, however, the efficiency was only 15 to 20 % for particles <100 µm. The testing was carried out at Auckland University using a full size model of a catchpit with well-defined stormwater sediment characteristics.

A comprehensive field investigation was carried out by the Enviropod NZ Ltd (2001) for North Shore City Council. A total of 294 Enviropods were installed around the city grouped into representative street sub-catchments (Takapuna Beach, Lake Pupuke, and Kaipatiki catchments, Browns Bay, Birkenhead and Milford). The sub-catchments have different traffic and organic loadings. Each area was supplied bags with mesh sizes selected for the local sediment characteristics – thus Takapuna (200 µm mesh) had a coarser mesh than Lake Pupuke (100 µm). At the end of the trial period which varied depending on the site and sediment characteristics, the bags were inspected to determine, amongst other factors, the remaining capacity, degree of clogging and evidence of overflow. Additionally, material collected in the filter bags from Takapuna Beach, Lake Pupuke and Kaipatiki was sampled and analysed for moisture content, metal concentration, sediment PSD and nutrients. The bags were found to be effective at removing coarse sediments as long as they were correctly maintained. The PSD of retained sediments showed that while the bulk of sediments were >2800 µm, the Takapuna and Kaipatiki filter bags had 22.5% and 26% respectively of sediments <63 µm. On the other hand, only 2.6 % of retained sediments at Browns Bay were <63 µm. Unfortunately, the incoming PSD for these catchments is not provided and there are no comparisons available between influent and effluent sediment or contaminant concentrations, hence removal efficiencies cannot be determined. Even so, the conclusion that particulate metals associated with coarser sediments were effectively removed seems reasonable.

8.0 Summary

The key findings of this literature review are summarised below:

Definitions and reported particle size ranges from the international literature:

- The size range of particles found in stormwater differs spatially and temporally – Clark et al. (2009) report median grain sizes from 8 to 1,200 µm, although the upper value was associated with the application of grit to snow for friction control. Differences between sites can be attributed to the physical characteristics of the catchment including land use and soil type. Differences between events are largely due to differences between rainfall intensity and antecedent dry periods.
- The definitions of stormwater solids size classes are many and varied. Divisions between size classes have been made on the basis of standard sieve sizes and the physical behaviour of particles, notably settling. The WERF protocol proposes dividing stormwater solids into four particle size classes based on the ASTM (1992) soil classification:
    - gross (>5000 µm);
    - coarse (75-5000 µm);
    - fine (2-75 µm); and
    - dissolved (<2 µm) solids.
- Sediment grain sizes in the Auckland region are currently classified using a scale similar to the Wentworth (1922) and ISO (2002) scales for soils. The council classification separates coarse from fine solids at 63 µm rather than 75 µm.
- Suspended and settleable solids are found in the WERF fine to coarse solids size classes (2-5,000 µm); however, particles in the coarse size range with a grain-size > 100 µm will generally settle out under quiescent conditions.
- The size boundary between suspended and settleable solids is blurred as settleability depends on a range of factors in addition to particle grain size, notably particle density and shape. Settling is also affected by sediment concentration, flow rates and turbulence – thus, whether a particle in the stormwater drainage system settles or is suspended can vary between flow events. TR2009-035 includes a detailed discussion on particle settling behaviour.
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Influence of sampling and analytical methods on particle size distributions:

- Isokinetic sampling, whereby the inflow speed at the sampler inlet is that same as the ambient flow velocity is the ideal for water sampling. If the velocity into the sampler is less than the stream flow velocity, eddies can form around the sample nozzle which divert particles away from the sampler. If the nozzle inflow velocity is greater than the stream flow velocity, particles can be entrained, pulling them out of the water stream into the nozzle.
- Isokinetic sampling is possible with both grab and automatic water samplers.

- There is particular concern that water samples made with auto-samplers may be biased towards fine particles, though they can generally be considered reliable for particles < 250 µm.
- Samples of stormwater solids which include street dust or bed load or which have been made close to sediment sources generally have a higher fraction of coarse particles than typically found in stormwater samples. While these coarse particles tend to settle, their presence in catchpits and stormwater treatment devices shows that they are nonetheless transported by stormwater.
- Where solids in the range 250-5,000 µm are required, water sampling should be complemented with bed-load sampling for particles.
- Samples of gross solids (> 5000 µm) should be made by collection of accumulated solids, such as in gross pollutant traps or catchpit sumps.
- Further guidelines for taking manual and automatic sampling water from streams were published by the Auckland Council (Hicks, 2011, TR 2011/012) as part of the council's sediment monitoring programme.
- The concentrations of both suspended and settleable solids are determined using standard laboratory methods (e.g. APHA 2450 D and F; USEPA 106.2 and 160.5) which were developed for the analysis of solids in wastewater.
- WERF expresses concern that the standard methods are not suitable to stormwater and have proposed amendments to APHA 2450 D accordingly.
- The concentration of suspended solids is expressed either as TSS or SSC in mg/l. Of the two, Auckland Council advocates analysing for SSC in order to avoid underestimating concentration.
- Depending on the analytical method, settleable solids in water samples are reported as mass to volume (mg/l) or volumetric (ml/l) concentrations.
- Gross pollutants and solids sampled as street dirt or bed-load are reported as mass loads over a particular collection time.
- The most common method of determining PSD is serial sieving and filtration, although this method is generally limited to sediments >20 µm. Several of the studies cited, including those carried out by NIWA, have used light diffraction and obscuration counters to determine the PSD of fine sediments in addition to sieving.
- There is a challenge identified in determining the combined PSD of sediments sampled from stormwater and as bed-load.

Particle size ranges and the influence of sampling and analytical methods, Auckland:

- Of the studies cited for Auckland, samples have been made using grab and automatic water samplers and the collection of solids in catchpits and settled in stormwater ponds.
- Particle sizes reported for Auckland are varied, but are within the size ranges reported internationally. The finest PSDs were reported by Leersnyder (1993) for particles entering stormwater treatment ponds in south Auckland, while the coarsest PSDs were reported by

NIWA for solids collected in catchpits (Moores et al., 2009a and b, Gadd et al., 2010) which included gross solids (i.e., > 5mm).

- Stormwater sampling was undertaken by NIWA for Metrowater during 2002-2003 (Reed and Timperley, 2004; Timperley et al., 2004 a and b) for eight central sites representative of different land uses. Water samples were made using auto-samplers for up to 15 storms for each site and TSS was analysed for PSD. Most solids were found to be in the range 1-275 µm, the median particles size ranged from 30-75 µm depending on the site.
- Solids collected in catchpits (Moores et al., 2009a and b, Gadd et al., 2010) were coarser than the Metrowater stormwater solids with most particles in the 1000 -10,000 µm range. The PSD of the finer catchpit sediments (<200 µm) were comparable to the Metrowater PSDs.
- The filter monitoring programme undertaken by NIWA for NZTA (Moores et al., 2012) showed that PSDs in road runoff samples from the North Shore were similar to those for Auckland Central, with around 90% or more of solids less than 250 µm diameter. The median grain size for each sample analysed was in the 62.5-125 µm size band for Albany and Esmonde Rd. Median grain size for Silverdale site was slightly finer in the 31.2-62.5 µm size band.

Influence of particle size on performance of stormwater treatment:

- There is limited guidance available with respect to the choice and design of treatment devices for the removal of solids of different size classes in stormwater. This is due to the limited number of studies which have investigated PSD; that is, most investigations on the performance of stormwater treatment devices report removal of only TSS.
- Studies cited which present the performance of stormwater treatment devices by particle size show that coarser particles are generally more easily removed than fine particles. The lower limit for effective treatment varies depending on the type of device, its location and the quality of the influent.
- There is progressive fining of settled solids from inlet to outlet in settling facilities such as ponds and wetlands. The removal of solids is largely dependent on the detention time and the settling behaviour of the solids. Ideally, settling basins should be designed so that the path length from the inlet to the outlet divided by the detention time is the same as the settling rate of the target grain size to be removed. According to WERF, 2 µm represents the lower limit of sediments that will normally settle out in a stormwater detention pond.
- Devices which have been evaluated for solids removal by grain size in Auckland include proprietary filters (Moores et al., 2012) and catchpits with and without inserts (Fassman and Voyde, 2007; Butler et al., 2004; McQuillan and Menzies, 2004; Enviropod NZ Ltd, 2001). These studies have all shown preferential removal of coarse particles.
- The median grain size reported for influent and effluent in the filter study dropped from 47 to 34 µm and from 73 to 57 µm for the Silverdale and Esmonde Rd filters. The change at both sites was statistically significant. While there was a slight increase in the median size of particles found in the influent and effluent (from 76 to 84 µm) at the Albany filter, this was not statistically significant.

- The catchpit studies showed that particles >500 µm are mostly retained while comparatively few (10-20%) particles <100µm are removed. Catchpit inserts can improve removal.

9.0 Recommendations

The literature review presented in this report largely concurs with the WERF findings. The WERF protocol was written in response to the concerns that the lack of standardised sampling and analytical techniques has made it difficult to compare water quality between studies and to evaluate the relative performance of treatment options. The protocol presents a literature review which supports the argument for a standard definition of stormwater solids and standard sampling and analytical methods. Furthermore, the protocol succeeds in its aim of producing a set of consistent, reproducible, pragmatic and cost effective methods for sampling and characterising stormwater solids. The recommendations made below build on the recommendations given in the WERF protocol.

9.1 Solid size definition

The WERF protocol puts forward a practical means of separating stormwater solids into size classes based on standard sieve size; the classes are:

- Dissolved (<2 µm);
- Fine (2 – 75 µm);
- Coarse (75-5,000 µm); and
- Gross solids (>5,000 µm).

Under the proposed definition, these classes can be split into sub-classes based on their chemical and physical characteristics such as organic content and settleability. The protocol notes that since settleability depends on other factors such as particle shape and density and even particle concentration, it is not possible to define TSS by particle size. Instead, it is stated that suspended solids (along with settleable solids) can be found in the fine and coarse size classes (i.e., from 2 – 5,000 µm). However, other studies cited here state that particles >100 µm are likely to settle under quiescent conditions.

It is recommended that the council adopt the WERF grain size classification with the exception that the separation between fine and coarse solids be made at 63 µm rather than 75 µm in line with the current council classifications for marine and freshwater sediments. This recommendation will have little effect on either the recommendations for water sampling or analysis of sediment samples set out below.

The maximum size range reported for suspended solids in Auckland is 250-500 µm, and most solids are under the 250 µm limit below which automatic samplers can be considered reliable (Clark et al., 2009). Moreover, the studies cited which have reported removal efficiencies by grain size show that particles above this size are generally removed by stormwater treatment devices.

It is recommended that, for the evaluation of stormwater quality and stormwater treatment in the Auckland region, the sampling and analysis of suspended solids should cover the particle size range 2 – 250 µm. Although coarser particles can be suspended, including them could introduce a sampling bias into the evaluation.

9.2 Sampling stormwater solids

The recommended size range for evaluating TSS given above was set with the reliability of auto-sampling with respect to particle grain size in mind. The WERF protocol recommends a number of sampling guidelines which have been summarised in this document (e.g., Burton and Pitt, 2002, Bent et al., 2001, ASCE 2006 and 2010; see Section 3.1). According to these guidelines, the sampling method chosen should reflect the purpose of the study and the type of solids borne in stormwater. To that end, the WERF protocol recommends the following sampling methods by size class to minimise sampling bias:

- gross solids – trapping device to retain solids;
- coarse solids – bed-load sampling recommended to supplement auto-samples, grab sampling; and
- fine and dissolved solids – auto-sampler, grab sampling.

Of concern is that auto-sampling may not capture coarser solids despite their presence in stormwater as evidenced by their accumulation in catchpits and other collection devices. As stated above, in a comparison of auto-samplers, Clark et al. (2009) found them to be generally reliable for particles up to 250 µm, however, both WERF and ASCE (2010) put the upper boundary at 75 µm. Based on the results of the previous Auckland-based studies cited in this report, auto-samplers deployed in the Auckland region have been found to be capable of sampling suspended solids <250 µm. For studies which require the collection of stormwater solids >250 µm, stormwater sampling can be complemented with bed-load sampling or, for gross solids, trapping.

To minimise sampling bias, isokinetic water sampling techniques should ideally be used to avoid either under- or over-representation of the solid concentration and the size of particle collected. In cases where isokinetic grab or auto-sampling sampling is not feasible or practical, it is important that those collecting and analysing samples are aware of possible bias in both the determination of solid concentration and PSD. Further guidelines on water sampling for sediment monitoring tailored to Auckland conditions can be found in Hicks (2011).

9.3 Analytical methods

9.3.1 Suspended solids concentration

The WERF protocol generally favours reporting SSC over TSS, which is consistent with other literature cited. The Auckland Council sediment monitoring programme also recommends reporting SSC rather than TSS (Hicks, 2011, Curran Cournane et al., in prep). WERF lists a number of concerns about SSC analysis which to some extent have been overcome since 2006. The standard method for determining SSC is ASTM D3977-97.

If TSS is to be analysed, WERF proposes an amendment to APHA standard method SM 2540 D for determining TSiS outlined in Section 5.3 (i.e., total solids in suspension with mixing). The difference between the current standard and that proposed by WERF is that the mixing speed, time period for mixing and the pipette size are prescribed. WERF also proposes a new measure called total solids in suspension with settling. This amendment calls for water samples to be split into two identical samples to enable both TSS and SSC to be determined. The amended method for determining TSS with settlinfg is similar to that for TSiS, but introduces a 5-minute settling period after mixing before the sample aliquot is drawn off to determine settleability. This amendment was proposed as the standard methods (USEPA 160.5 and APHA 2540 F), which have a 1-hour settling period, were developed for waste water where settling is largely quiescent. That is, they take neither the readily settleable nature of solids borne in stormwater or turbulent mixing into account. The amendment also has the advantage that it returns estimates of both SSC and TSS.

It is recommended that Auckland Council either analyses SSC directly for stormwater solids in line with the council's sediment monitoring programme or adopts the WERF amended method for determining TSiS noting that this has already been adopted in PDEP. If possible, both TSS and SSC should be analysed following the WERF amendments so that settleability can be determined as this information, along with PSD, is vital to the choice and design of water treatment devices.

9.3.2 PSD determination

Along with other literature cited here (see Table 4), the WERF protocol notes that that there are many methods that can and have been used to determine the PSD of stormwater solids. Furthermore, there is no one method that can analyse particles across the entire size range found in stormwater. Rather, the method chosen should reflect the purpose of the study and the size range of solids present. The WERF guidance on methods is considered to be appropriate for the Auckland setting.

Wet and dry sieving is the most common method cited for suspended solids and is generally suited to particles >20 µm, though filtering can be used for smaller particles (usually >2 µm). Several of the studies cited, including those undertaken by NIWA, have used light obstruction or scattering sensors to determine the PSD of finer particles.

A concern put forward by ASCE (2006, 2010) is the difficulty in determining the true PSD in studies where both water and sediment/bed load samples have been taken to sample suspended, settleable and gross solids. In the first case, suspended solids are measured as a mass to volume concentration (e.g., mg/l) expressed as either the TSS or SSC. In contrast, sediment samples collected from sediment traps, including drainage infrastructure such as catchpits, and bed-load samplers are presented as a net mass or load accumulated over a certain time period and the contaminant content is expresses as mass to mass concentration (e.g., mg/kg). There are two recommended alternatives:

- Separate presentation of the PSD for settled or trapped solids and suspended solids. This is the most pragmatic option and has been used by most of the studies cited which present PSDs from two sources of solids.
- Use of concurrent sampling methods which collect *all* solids transported in storm water at a specific point (e.g., Kim and Sansalone, 2008). These methods are largely confined to research programmes and are not suitable for operational water quality monitoring.

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