Auckland
Regional Council
TE RAUHĪTANGA TAIAO

Fall Velocities of Stormwater Sediment Particles

Literature Review

March TR 2009/035

Auckland Regional Council
Technical Report No.035 March 2009
ISSN 1179-0504 (Print)
ISSN 1179-0512 (Online)
ISBN 978-1-877528-44-6

Technical Report, first edition.

Reviewed by:		Approved for ARC publication by:	
Name:	Judy-Ann Ansen	Name:	Paul Metcalf
Position:	Team Leader Stormwater Action Team	Position:	Group Manager Environmental Programmes
Organisation:	Auckland Regional Council	Organisation:	Auckland Regional Council
Date:	19 November 2009	Date:	27 November 2009

Recommended Citation:

SEMADENI-DAVIES, A., 2009. Fall Velocities of Stormwater Sediment Particles. Literature Review. Prepared by NIWA Ltd for Auckland Regional Council. Auckland Regional Council Technical Report 2009/035.

Fall Velocities of Stormwater Sediment Particles. Literature Review

Annette Semadeni-Davies, PhD

Prepared for
Auckland Regional Council

NIWA Client Report: **AKL-2008-091**
December 2008

NIWA Projects: ARC09121

National Institute of Water & Atmospheric Research Ltd
41 Market Place, Auckland Central 1010
Private Bag 99940, Auckland
Phone: +64 9 375 2050, Fax: +64 9 375 2051
www.niwa.co.nz

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1 Executive Summary

The Auckland Regional Council (ARC) initially requested a literature review on the fall velocities of particulate matter in stormwater in 2006. This report is an amendment made following a request from the ARC for updated information. The review includes up-to-date research on the subject as well as the studies that provide the basis of the current ARC guidelines for low impact design of stormwater drainage systems (eg, TP 4, 1992; TP 10, 1993, 2003, TP 124, 2000). Topics addressed are:

- the relationship between the particle size distribution (PSD) and fall velocities;
- conditions for flocculation of fine sediments and the relationship between floc properties (eg density and shape) and fall velocity;
- the current state of knowledge about the relationship between sediment size and contaminant fractionation; and
- the PSD and fall velocity of suspended sediments in Auckland stormwater.

Sediment and contaminant sources, and particle entrainment, transport and deposition in sewers or the stormwater network are outside the project brief and are not covered.

The main findings of the literature review are listed below:

- The validity of calculated fall velocities are called into question due to the simplistic assumptions related to particle properties. Fall velocities are very sensitive to density, yet few studies into stormwater sediments have looked at properties other than particle size.
- Flocs which form naturally in stormwater have a variable effect on settling - smaller flocs can aid settling, while flocs larger than 30 µm may not settle in sedimentation facilities. This is because these flocs can have low-density due to the incorporation of liquid in their matrix (ie, high porosity), and a flake-like shape. Flocs are easily broken by turbulence. Case studies of the addition of coagulant aids to sedimentation basins that have been carried out for the ARC are presented.
- There is controversy surrounding both sediment sampling and analytical methods for the determination of fall velocity. The use of automatic water samplers in particular is singled out as a source of error as samplers may have a bias towards sampling fines. Protocols for the use of samplers are given, but there are practical difficulties in setting up samplers to obtain representative samples of suspended sediments. Recent studies which have complemented samples taken with automatic water samplers with other sampling methods which trap sediments have shown that there can be substantial proportions of coarse sediments in stormwater which have hitherto been ignored.
- PSDs and fall velocities reported in the literature vary greatly in time and space. Measurements made at one time and place cannot reliably be transferred to another. Sediment concentration and properties depend on the rainfall dynamics

of a storm event (ie, intensity and duration), sediment source and accumulation rates and antecedent conditions including the length of time between storms.

- The relationship between sediment size and heavy metal partitioning is site and event specific and is related to the physical and chemical properties of both the sediment and the stormwater. For instance, several studies are cited which show that partitioning is sensitive to the pH of the stormwater, low pH leads to higher dissolved metal content and therefore greater metal mobility. The organic content of the sediments can also have an effect on partitioning.

- The fractionation of particulate metals is related to total surface area for a sediment size class rather than particle size per se. While it can be expected that finer sediments can have a greater metal content by unit mass due to the high specific surface are, where the PSD has a significant proportion of coarse particles, particulate metals may be associated with these particles despite a lower metal content by mass. Hence, if coarse sediments are under sampled, then the fractionation of the metals may be biased towards fines.

- Moreover, the relationship between specific surface area and sediment size is dependant on particle shape and texture; larger sediments particles, and, as stated above, flocs, can have high internal porosity which can lead to higher metal loads than would be expected for spheres.

- High dissolved Zn concentrations are common in Auckland, however, the proportion of particulate to dissolved Zn can increase away from the source. This is because the metal is able to adsorb onto particles in the stormwater during sediment transport downstream. Similar findings are presented for Cu. As fines become more prevalent downstream due to settling of coarse sediments, the metal fractionation can also change.

- The most recent studies into sediment size, settling and contamination have favoured granulometric techniques. These place a strong emphasis on representative sampling of sediments in stormwater and determination of sediment physical and chemical properties. Granulometric data can include PSD, metal partitioning and fractionation, the fractal nature of particle size and shape, particle morphology, chemical composition, and settling characteristics (for both primary particles and flocs).

On the basis of the literature review, there are three choices for fall velocities available to the ARC:

1. The status quo – retain the five Nationwide Urban Run-off Program (NURP) settling bands derived in the USA from a number of settling column experiments (Driscoll *et al.*, 1986) which are currently used as the basis of the design criteria in TP 10 as described in TP 4.

2. Pakuranga fall velocities – this approach would see the ARC adopting the Pakuranga fall velocities determined by settling column experiments (ARWB, 1991). The data are local and similar to the results of a later study by Leersnyder (1992), also in South Auckland, and to the NURP values. Hence any adjustments to design criteria would be minimal.

3. Variable sediment fall velocities – this is the preferred option given the criticisms laid out in the literature review. The approach would require a comprehensive sampling program across the Auckland region to cover the range of catchment types, including land use, to give a representative picture of fall velocities Auckland wide. Ideally, fall velocities should be determined directly from settling column experiments rather than calculated from PSD. Metal partitioning and fractionation could be part of the study. A new campaign could also take into account possible biases in sediment sampling and analysis.

2 Introduction

2.1 Background

Urbanisation results in rapid run-off response to rainfall and high peak flows due to the high degree of impervious surfaces. Moreover, this stormwater can have poor water quality. Suspended sediment, which is the focus of this report, is a major concern not only as a contaminant in its own right but also as many other contaminants have an affinity to particles. Thus the physical characteristics of particles in stormwater have profound implications for both the transport and removal of contaminants. Sediments come from a range of sources including particles eroded from the ground surface, which is obviously related to land use and substrate type. Traffic is a major sediment source with particles coming from vehicle wear (eg, tyres and breaks) and wear and tear on roads. The source of sediment is important for determining fall rates as sediments can have different properties (eg, inorganic mineral particles from soil compared to organics from tyres and asphalt) depending on the source location with respect to local geology and land use. The sediment load (product of concentration and flow volume) of a flow event depends on rain intensity, antecedent hydrological conditions, and the time lapse and rate of sediment accumulation between storms.

Urban stormwater can be effectively treated to improve water quality by removing sediments either by settling or trapping in filters. Particulate matter in stormwater ranges from nanometre-sized colloidal organic material to millimetre-sized sand, silt and gravel (size definition, see Table 1) – more than six orders of magnitude (Grant *et al*, 2003, Makepeace 1995). This review is concerned primarily with fall velocities (for suspended sediments (ie, clays to very fine sands: 1 – 125 µm) as sedimentation is an effective removal technique for these sediments though other treatments such as filtering may be required for polishing. Colloids and the dissolved fraction (eg, <1 µm) can flow through the device while coarse sediments (>125 µm) tend to settle rapidly and remain in gutters or are caught in catch pits. With respect to settling, detention basins (ie, ponds and wetlands) are popular structures that are commonly used to treat stormwater. The United States Environmental Protection Agency (US EPA; 1999 a and b) states that, when well-designed and maintained, these devices can remove up to 90 per cent of the total suspended solids (TSS) and with it 40-80 per cent of nutrients and 50-90 per cent of heavy metals. Ideally, the flow distance (from inlet to outlet) of the facility divided by the detention time should be equal to the fall velocity or settling rate to ensure maximum settling. In addition to detention basins, other treatment devices such as swales and rain gardens can be designed with either pre-settling fore-bays or surface ponding during high flows to increase sediment removal. This report also considers the addition of chemicals to aid flocculation, and therefore increase sedimentation.

Table 1
Udden-Wentworth scale (Wentworth, 1922) for particle sizes in microns (µm) typically found in stormwater.

Very coarse sand	Coarse sand	Medium sand	Fine sand	Very fine sand	Silt	Clay	Colloid
1000-2000	500-1000	250-500	125-250	62.5-125	3.9-62.5	1-3.9	<1

The aim then is to design facilities which are adequately sized for effective sediment removal without being unduly large. To do this requires reliable information about the size of particles in stormwater reaching the facilities and their fall velocities. If the velocities used in design calculations are too high, the device will be under-sized and ineffective, while velocities that are too low can lead to over-sizing which introduces unnecessary costs. Stormwater sediments come from a range of sources which are related to land use as well as substrate type; obviously these vary by location. Sediment properties such as grain size, density, shape and roundness are largely dependant on the source. Hence, abraded sediments from road and tyre wear and tear are likely to have different fall velocities than sediments derived from mineral sands soil which are either blown or washed-on to impervious surfaces and from there into the stormwater drainage system. It could be expected that sediments from soils reduce in importance with increased urbanisation and imperviousness. Of concern to this study is the relationship between particle sizes typical of Auckland stormwater sediments and fall velocities.

It should be noted that actual fall velocities in the field often differ significantly to the theoretical values calculated with settling formulae. This is particularly the case with fine particles, owing to the influence of water turbulence caused by wind and aquatic fauna. Stormwater devices that are designed for sedimentation should be able to accommodate stormwater volumes long enough for quiescent settling to occur. Under dynamic flow (ie, water is flowing into or out of the device), the effect of turbulence and potential short-circuiting must be taken into account. Simulating sediment removal on the basis of the fall velocity of particles under both dynamic and quiescent flow conditions was discussed in a report for the US EPA (Driscoll *et al.,* 1986). This report was prepared as part of the Nationwide Urban Run-off Program (NURP, see Section 3.3.1) investigation of stormwater quality and treatment and the methods for determining fall velocity and modelling settling have become standard. The study averaged the fall velocities for some 46 stormwater sediment samples from seven urban catchments. The results are presented in

Table 2, note that the total sediment mass is evenly split into the settlings bands so that each represents 20 per cent of the mass.

The ARC gives guidelines for detention pond design for stormwater treatment in TP 10 (ARC, 2003; 1992) using design-storm calculations set out in TP 014 (ARC, 1999). The design criteria were determined on the basis of TP 4 (ARC, 1992) which gives the technical and scientific background for the determination of the water quality volume that should be treated. Settling behaviour took into account an analysis of sediment and stormwater samples made by the then Auckland Regional Water Board (ARWB, 1991) in a Pakuranga catchment for a single event (

Figure 1). Fall velocity was determined using settling columns in what TP 4 (ARC, 1992) describes as a pilot study. The particle size was then calculated using Stokes' Law (see Section 3.1) assuming the particles have the same density as mineral sand (ie, quartz) and the water temperature was constant at 20°C. The PSD in Pakuranga was found to be bimodal with peaks at 125 μm and 10 μm. However, it was assumed that the larger particles will settle or be trapped in catch pits before reaching stormwater treatment facilities. The similarity between the Pakuranga fall velocities with those cited in Driscoll *et al.* (1986) meant that the five particle settling bands in

Table 2 recommended by the US EPA were adopted in TP 4 (ARC, 1992) rather than using the Pakuranga results directly. Leersnyder (1993; see Section 3.3.2) found similar PSDs and settling characteristics with respect to Pakuranga in Otahuhu and Manukau which has lent weight to the use of the US EPA bands for modelling and design.

Table 2

Pooled fall velocity distribution recommended for pond performance simulation by Driscoll *et al.* (1986) as adopted for setting design criteria by the ARC.

Band	Proportion of total particle mass	Fall velocity	Particle size*	
	(%)	(ft/h)	(m/h)	(μm)
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 in TP 10 (ARC, 1993) for spherical particles, density = 2680 kg/m^3, water temperature = 20°C.

Another design concern is the relationship between sediment particle size and pollutant load as many contaminants have an affinity to particles in stormwater and are found in particulate form. It is generally assumed that the smallest particles provide the greatest surface area to mass ratio (ie, specific surface area, SSA) for bonding, hence they are usually targeted for removal. For instance, a pond which captures all coarse particles but not fines may be of limited value for water quality treatment in an area where contaminants are bound to fines.

Traffic is a major source of stormwater contaminants including metals and PAHs (polycyclic aromatic hydrocarbons), not only due to fuel exhaust but to wear and tear on brakes and tyres and the road itself. The presence of metals in urban run-off can exert both a short-term toxic shock (concentration) and long-term impact due to mass accumulation (load). Metals most commonly associated with traffic are Pb, Zn, Cu, Cd, Cr and Ni (Hvitved-Jacobsen and Yousef, 1991) although there are regional differences. Lead, for example, is no longer found in any significant concentration in

New Zealand stormwater since its removal from petrol, the remaining sources being historical such as traces from lead-based paints and previously contaminated soils. Other sources of metals in stormwater are roofing material (Zn, Cu) and galvanised street fittings (Zn), although metals from these sources are generally in dissolved form at source. In comparison to particulate metals which generally have the highest content by mass in the finest sediment classes, PAH content can increase with particle size, though fractionation of PAHs is complex, and can change with the organic content of the sediments (Grant *et al*, 2003).

2.2 Objectives

The main objective of this report is to revise the particle size distribution (PSD) and fall velocities used by the ARC for Auckland stormwater by providing an up-to-date review of the relevant literature surrounding settling theory and sediment sampling and analytical techniques along with case studies for stormwater. Flocculation and the addition of coagulant aids to improve settling rates are also discussed. The revised values could be used to test the design criteria for settling devices such as ponds and wetlands.

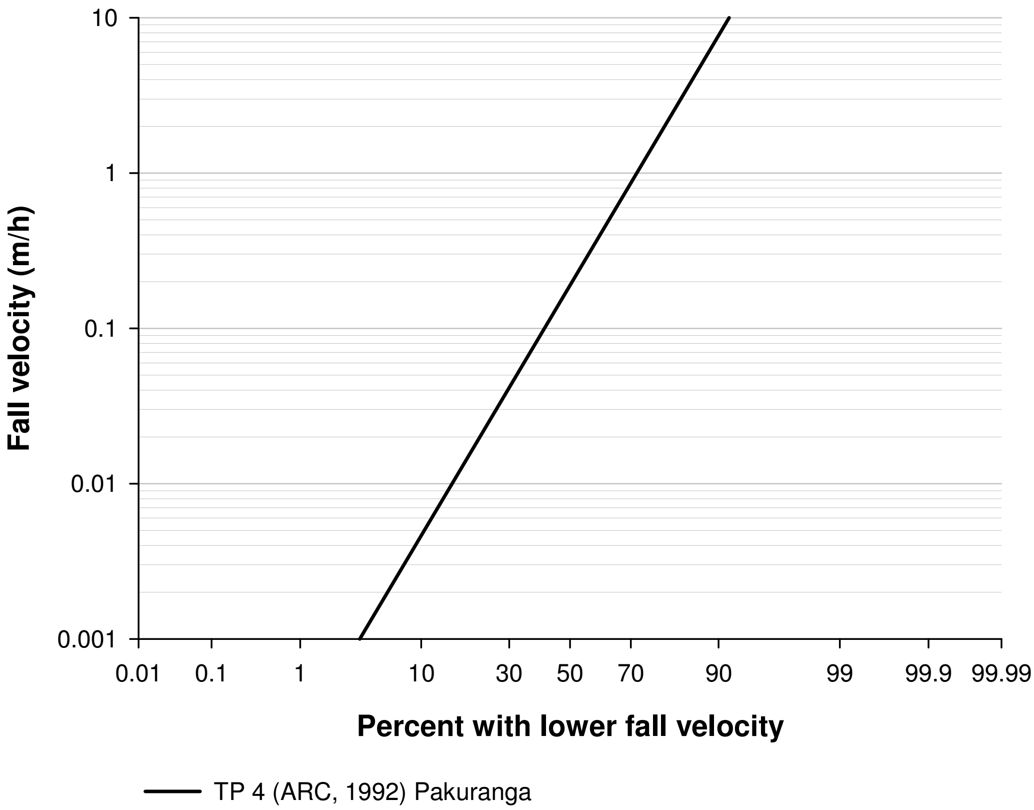
A secondary objective is to examine the relationship between sediment sizes and partitioning and fractionation of contaminants – here illustrated by heavy metals.

In addition to NIWA measurements and reports (eg, Reed and Timperley, 2004; Timperley *et al.*, 2004 a, b and c, Semadeni-Davies *et al.*, 2008), primary sources are TP 4 (ARC, 1992), Leersnyder (1993), Driscoll *et al.* (1986) and Humes (2006).

This work was commissioned in 2006 by the ARC as an independent literature review following concerns raised in Humes (2006). This document is a power-point presentation which questions the validity of the PSD and fall velocities used by the ARC to develop design criteria for the Auckland region and which cites recent literature about stormwater sediments. The two major issues raised by Humes (2006) are;

- sampling methods, particularly pre-1990s, could be biased towards the collection of smaller particles – this bias can lead to average fall velocities determined either with settling columns or by calculation being slower than the actual fall velocity; and
- particle property assumptions which model fall velocity for single, spherical grains with a constant density irrespective of particle size or the presence of flocs.

Figure 1
Probability distribution of fall velocities for particles in stormwater from Pakuranga (after TP 4: ARC, 1992).



3 Literature Review

3.1 Settling theory

The settling behaviour for non-colloidal particles is of great importance for urban stormwater treatment. Settling of suspended particles in stormwater is determined by calculation from the PSD, or by settling experiments, or both. The fall velocity of a particle in a viscous fluid is a function of the size, shape, density of the particle, the number of particles falling (concentration), the cohesion-flocculation properties, the fluid temperature (density and viscosity), the extent (depth) of the fluid, and the fluid turbulence velocity and turbulence (Burton and Pitt, 2002; Raudkivi, 1990).

The simplest case is for a single particle. If the particle is falling in a viscous fluid by its own weight, then a terminal velocity, also known as the fall velocity or free settling velocity or settling rate, is reached when the frictional and buoyant forces exactly balance the gravitational force. For a sphere in a stationary fluid of infinite extent, the fall velocity can be calculated using Stokes' Law (1851):

$$V_s = \frac{2r^2 g(\rho_s - \rho_f)}{9\mu} \qquad \textbf{Equation 1}$$

where V_s is fall velocity, r is the sphere radius (Stokes' radius), ρ_s and ρ_f are particle and fluid density respectively, μ is fluid dynamic viscosity and g is acceleration due to gravity.

Stokes' Law is valid only for laminar flow where fluid particles move in layers or lamina. For such conditions, settling is known as quiescent settling. Whether the conditions are turbulent or laminar can be determined using the dimensionless Reynolds number, Re, of the particle moving though the fluid. This is the ratio between the inertial and viscous forces within the fluid. The Reynolds number can be written as:

$$\mathrm{Re} = \frac{2rV_f \rho_f}{\mu} \qquad \textbf{Equation 2}$$

Where V_f is the fluid velocity and can be equated to the fall velocity, V_s, if the fluid is still.

For the case where a viscous and incompressible fluid is flowing around a sphere, Stokes' Law is valid providing the Reynolds Number has a value less than 1.0. In still water at 20°C, this corresponds to a falling particle of around 100 µm assuming a density of 2680 kg/m^3 - which is equivalent to quartz. For larger particles, the fall velocity can be determined using Rubey's (1933) general formula or Newton's second law of motion. Alternatively, Weber (1972) gives the following expressions depending on the Reynolds number:

$$V_s = \left[2.32(\rho_s - \rho_f)r^{1.6}\rho_f^{-0.4}\mu^{-0.6}\right]^{0.714}$$ **Equation 3**

When the fluid movement around the particle is transitional (1<Re<1000); and

$$V_s = 1.82\sqrt{\frac{(\rho_s - \rho_f)rg}{\rho_f}}$$ **Equation 4**

under turbulent conditions (Re>1000).

Lin (2003) has reviewed equations for fall velocity suitable for particles in stormwater which can be used for a range of conditions such as differing sediment loads, variable grain sizes and flocculation. Ferguson and Church (2004) have proposed a universal settling equation that covers a range of sediment sizes and converges on Stokes' Law for small particles.

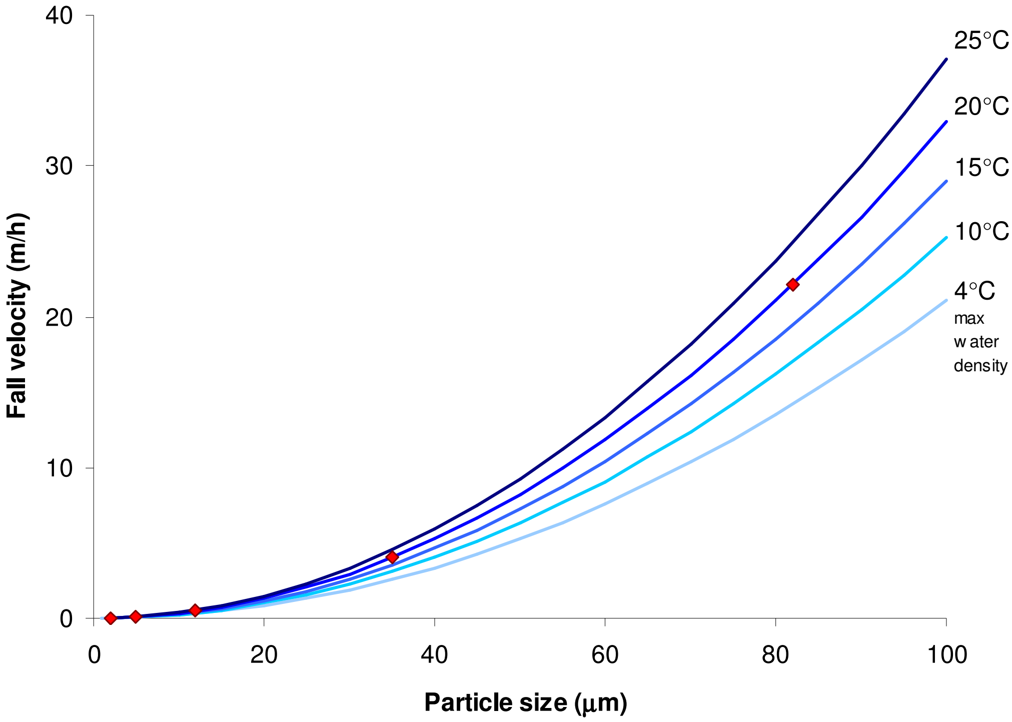
3.1.1 Fluid temperature

Fluid density and viscosity, are key parameters for determining fall velocity and are both dependant on fluid temperature (Table 3). Figure 2 shows the effect of water temperature on fall velocity for particles under 100 µm calculated with Stokes' Law.

Table 3
Water density and dynamic viscosity as a function of temperature.

Temperature (°C)	Density (kg/m³)	Dynamic viscosity (Pa.s)
4	1000	0.00156
10	1000	0.001304
15	999	0.001137
20	998	0.001002
25	997	0.00089
30	996	0.000798

Figure 2
Effect of water temperature on particle fall velocity calculated using Stokes' Law, particle density = 2680 kg/m^3. The median particle sizes in the ARC/NURP settling bands are indicated by red diamonds.



3.1.2 Particle properties

The fall velocity of a particle depends on its density and shape as well as size. Yet comparatively few studies of stormwater sediments have presented such information and it is generally assumed that the particles are spherical with a density equivalent to mineral sands (around 2600 – 2800 kg/m^3). Density is seldom determined in relation to particle size (Cristina *et al*, 2002). Humes (2006) lists these assumptions as key criticism of the methods which calculate fall velocity in relation to particle size.

3.1.2.1 Particle density

It is common practice to equate particle density to that of quartz (2650 kg/m^3), given the variety of sediment sources in urban areas, this assumption is dubious. However, few studies of particles in stormwater have taken particle density into account. Those studies that are available have shown a wide density range with particle size and can be contradictory, particularly if the sediment load consists of both organic and inorganic particles as these particles can have different size ranges depending on their source. Organic particles from leaf litter, for instance, are generally less dense but larger than particles from mineral sands (Lin, 2003), however, organic particles from tyres, which also have a low-density, tend to be in the fine size range (Sansalone and Triboullard, 1999).

Stahre (unpublished, personal communication 2006 and cited in Stahre and Urbonas, 1990) carried out a number of experiments to determine the PSD and fall velocities of sediments in stormwater in Sweden. He found that density seems to vary with particle size, the pH of water and the heavy metal content of the water. However, the nature of the relationship with pH was not clear and no mechanisms for the effect of pH were given. Stahre found that it is helpful to split stormwater particles into two groups, the first with densities between 1000-1160 kg/m^3, and the second greater than 1160 kg/m^3. The former group tends to consist of smaller particles (eg, silts). For the latter group, the average density was around 1300 kg/m^3.

Other authors have stated that density is also a function of sediment type; generally, inorganic particles have a higher density than organics (Karamalegos *et al*, 2005). Butler *et al.* (1996) found that organics in stormwater had a density range of between 1100 and 2500 kg/m^3. Sansalone and Tribouillard (1999) stated that abraded vehicular matter from tyres has a large range in density (1300 – 1700 kg/m^3) and particle diameter (1-104 µm, mean of 20 µm) respectively. However, in general abraded road particles were inorganic and had a density in the range of 2700 – 3010 kg/m^3. The highest densities were associated with the largest particles, in the range of 850 – 1400 µm. They further stated that the low-density particles from tyres were easily entrained by vehicle turbulence and were dry deposited on road shoulders. (Lin (2003) found that organic matter in stormwater consisted of leaves and other plant materials (the density of leaves for instance is given as 1940 kg/m3) as well as matter from tyres and had a density range of between 1400 and 2300 kg/m^3. Unlike Stahre, Lin (2003) found that the particles less than 425 µm had a density of around 2500 kg/m^3. Andral *et al.* (1999) analysed stormwater sediments collected during eight rainfall events (Table 4). They found relatively less variation with particle size, even so, particles less than, which made up the bulk of the sediment mass, had a slightly lower range in density than the coarser sediments. The MUSIC model (CRCCH, 2005) assumes a variable density with particle size, based on Lawrence and Breen (1998), that ranges from 1100 to 2600 kg/m^3 for particles between 1 and 256 µm respectively.

Table 4
Density and PSD of stormwater sediments found by Andral *et al.* (1999).

Particle size range (µm)	**Density range (kg/m^3)**	**Proportion of total sediment mass* (% weight)**
<50	2400 - 2650	77.8
50 – 100	2530 - 2860	8.6
100 - 500	2500 - 2820	9.2
>500	2510 to 2790	4.4

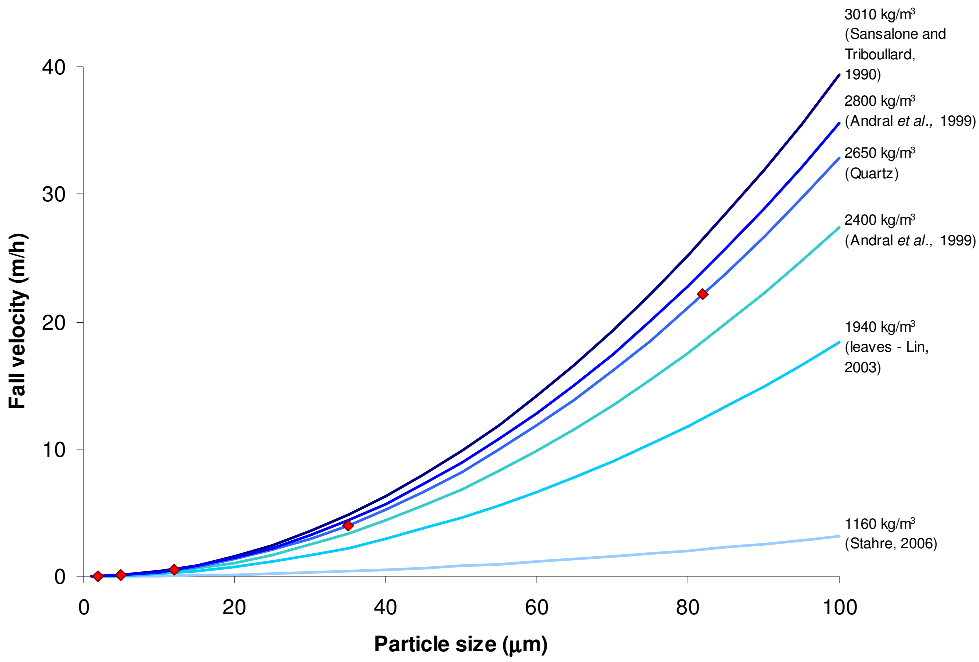
*Results of one rainfall event presented as representative of PSD by Andral *et al.* (1999)

The theoretical effect of density on calculated fall velocity is shown in

Figure 3. The great range in fall velocity highlights the importance of density. The densities given lie within the range of those measured or commonly-assumed in the cited literature.

Figure 3

Effect of particle densities reported in the literature on particle fall velocity determined using Stokes' Law (spherical particles, water temperature = 20°C). The median particle sizes in the ARC settling bands (Table 2) have been calculated assuming a density equivalent to quartz and are indicated by red diamonds.



3.1.2.2 Particle roundness and shape

That sediment roundness/angularity and shape affect fall velocities is well established (see review by Raudkivi, 1990).

Roundness is the curvature variation along the grain surface and increases as the particle becomes smoother. A worn, naturally occurring quartz particle would have a roundness factor of around 3.5 while a smooth, well rounded particle would have a roundness of 6 (Jiménez and Madsen, 2003). Le Roux (2002) found that in the silts and clay size range, particles tend to be more angular than coarser particles, which can be partially explained by the assumption that fines are flaked or chipped from larger particles.

Particle shape is often indicated by the Corey shape factor, SF, defined as:

$$\mathrm{SF} = \frac{c}{\sqrt{ab}}$$ **Equation 5**

where *a*, *b*, and *c* are the lengths of the longest (length), intermediate (breadth or thickness), and shortest (width) axes, respectively. These axes are the mutually perpendicular axes of the particle. The shape factor is zero for a two dimensional plate and one for a sphere. Natural sediment typically has a shape factor of about 0.7.

Williams (1966) tested the effect roundness on fall velocity using column experiments with artificial particles. Three shapes (sphere, cylinders and discs) with different surface textures (smooth, grooved and pitted) and sizes (nominal diameter from 0.32 to 2.0 cm) were tested. It was found that sharp edges reduce the fall velocity by 8-28 per cent compared to well rounded discs and cylinders if all other particle properties were held constant. The types of surface texture caused only a minor reduction in fall velocity compared to smooth particles.

More recently, Göğüş *et al.* (2001) carried out similar settling column experiments to determine the effect of shape on the settling behaviour. Fall velocities for 174 particles with a variety of shapes (cylindrical, cubic, wedge-shaped prism, and box-shaped prism) and dimensions (max length ranging from 1 to 5 cm), and made of five different materials (density range between 1180 and 2160 kg/m^3) were measured. Each of the particles was placed in a settling column and the fall velocity and flow path observed. They note that in addition to the gravitational force on the particle, particle motion depends on the magnitude of forces caused by flow patterns that develop around a freely falling particle. Because of the fluctuating forces, the fall of a particle may be subjected to three classes of motion: sliding, tipping, and rotation. These forms of motion may occur separately or in combination. They report that most of the time, particles fall through a fluid with their maximum projected area perpendicular to the fall direction. In general, the different particle shapes exhibited different flow patterns, for instance, cubes followed a helical flow path around the column centre line and rotated as they fell while wedges quickly orientated point down and thereafter did not deviate from the column centre line.

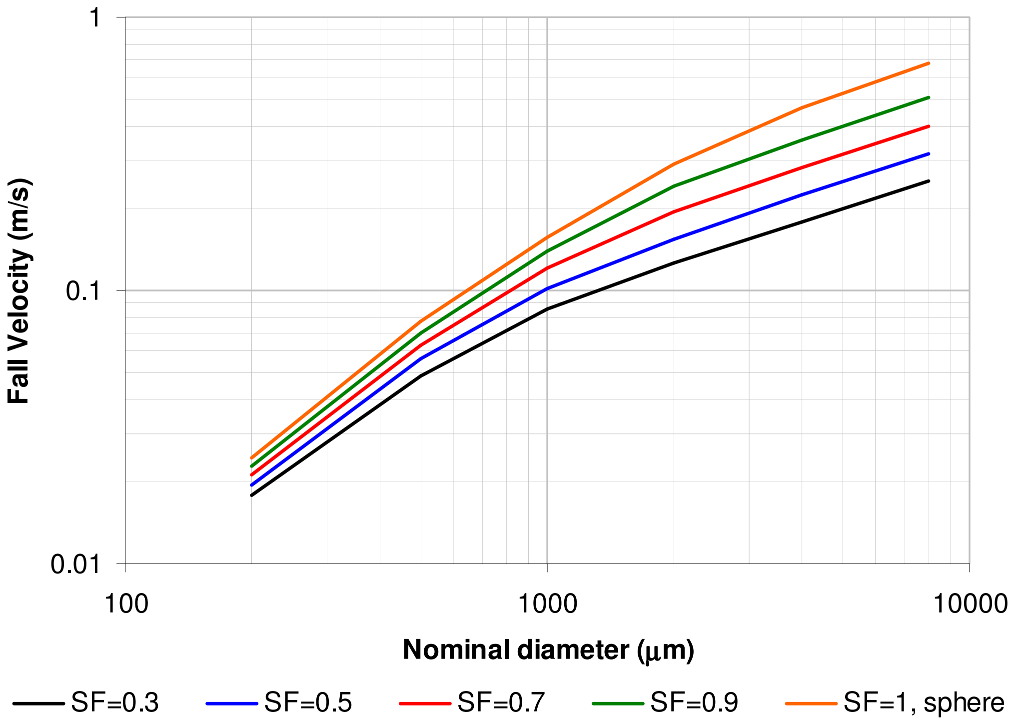
The effect of the shape factor on fall velocity was determined experimentally by the U.S. Inter-Agency Committee on Water Resources (1957) for medium sand to fine gravel. Their results are summarized below for water at 20°C (Figure 4). The nominal diameter is the equivalent diameter of a sphere with the same volume as the particle. For natural, worn grains in the range 200-2000 µm, the sieve diameter is around 0.9 times the nominal diameter. Figure 4 shows that the effect of shape diminishes as particles become smaller – for gravel, a sphere has almost three times the fall velocity as a grain with a SF of 0.3, whereas for medium sand, the difference is around 30 per cent.

Lin (2003) used electron microscope imaging to determine the shape, mineral composition and fractal nature of particles in stormwater and presents a detailed discussion of the effect of shape on settling including means of modifying settling equations for shape (equated to degree of sphere distortion) and roundness. Settling equations that take shape and roundness into account which are valid for the more coarse particle sizes found in stormwater have been presented by Jiménez and

Madsen (2003: 63 to 1000 µm) and Ferguson and Church (2004: >30 µm). However, as stormwater particles are generally smaller than the sediments shown in Figure 4, the effect of shape is likely to have only a minimal effect on fall velocity.

Perhaps of more interest to urban stormwater treatment is that particle shape and roundness also have an effect on SSA which has implications for the fractionation of contaminants bound to sediments – the effect of surface area is discussed in Section 3.5.

Figure 4
Relationship between shape and fall velocity constructed using experimental data from the Inter-Agency committee for Water Resources (1957, cited in Raudkivi, 1990).



3.1.3 Particle concentration

When the particle concentration is high, particles interact with each other and the fall velocity becomes a function of the volumetric concentration of the particles in suspension (Burt 1986). Particle concentration has two impacts on settling depending on whether the particles are cohesive or non-cohesive. Non-cohesive materials are coarse-grained materials composed of particles greater than 62 µm. Particle interaction between non-cohesive particles is solely mechanical and is restricted to momentum exchanges occurring from fluid drag, random collisions, and the interlocking support from adjacent grains. Cohesive materials are those particles in the fine silt and clay size range which can form aggregates or flocs due to the possibility of electro-chemical bonds between individual particles.

3.1.3.1 Non-cohesive particles

Raudkivi (1990) states that while the settling behaviour of single particles is already complex, in most applications, fall velocity must be determined for a cloud of particles. He observes that a few evenly spaced particles will settle faster than individual grains however, if the particles are irregularly spaced, the fall velocity can decrease. When non-cohesive particles are released into a water column, they disperse to form a heterogeneous cloud where some particles are close together while others are separated. When the particle concentration is high, particles interact with each other and the fall velocity becomes a function of the volumetric concentration of the particles in suspension (Burt 1986). The overall effect is an increase in fall velocity compared to single particles.

Raudkivi (1998) gives the following empirical relationship between the fall velocity of a group of identical sediment particles and particle concentration:

$$V_a = V_s(1 - C_s)^{\beta}$$ **Equation 6**

Where V_a is the apparent fall velocity of the grouped sediments, V_s is the fall velocity of a single particle, c is the volumetric concentration of the particles and β is a function of the Reynolds number and particle shape. The β coefficient can estimated from the non-dimensional grain size:

$$D_* = \left(\frac{(\rho_s - \rho_f)\rho_f g (2r)^3}{\upsilon^2} \right)^{1/3}$$ **Equation 7**

Whereby *β=4.65 for D_* < 40, β=2.35 for D_* > 8000 and $\beta=7.47\, D_*^{-0.129}$ for 40 < D_* < 8000.* For sizes typically found in stormwater (<200 μm) and with low concentrations (eg, in the order of 0.001), the difference between V_a and V_s will be minor.

The effect of concentration on a mixture of sediments with different particles sizes is more complex. Raudkivi (1998) states that the apparent fall velocity of a sediment mix can be estimated as:

$$V_a = \frac{\sum_i p_i V_{si}}{\sum_i p_i}$$ **Equation 8**

Where p_i and V_{si} are the weight and fall velocity of the grains in the size range *i*. This fall velocity may be very different from the fall velocity for the median grain size.

Aliseda *et al.* (2002) carried out particle velocity experiments with water droplets in a wind tunnel. In these experiments, the fluid is air and the particles are the droplets. They found that the enhancement of the fall velocity depends on the particle loading, that is, the velocity increases with the volume fraction of particles in the flow. They found that distribution of particles is heterogeneous and that particles tend to cluster. In the presence of gravity, heavy particles have a vertical velocity with respect to the surrounding fluid causing turbulence. Along its trajectory, every particle interacts with different vortices and the crossing trajectories effect causes the particle to be preferentially swept to the downward side of the eddies. Thus, the mean effect of the turbulence caused by surrounding particles on a particle is a net force that accelerates it downwards.

That the fall velocity is increased with the sediment load has implications for contaminant removal in settling basins and suggests that facilities receiving high sediments loads may have greater removal efficiencies than those receiving low sediment loads. Moreover, several authors have found that the proportion of larger particles (fine sands and upwards, >62 μm), which have more rapid fall velocities, increases with sediment concentration (eg, Grizzard *et al*, 1986; Furumai *et al*, 2002). Given that turbulence increases with particle size, the net effect of high concentrations of these particles would be to increase the fall velocity of other nearby particles creating a higher apparent fall velocity.

3.1.3.2 Coagulation and flocculation

Burton and Pitt (2002) state that simple particle size information may not be sufficient when flocs are also present as flocs do not have the same settling properties as primary particles of the same size. They suggest that particle size analyses should include identification of the particles by microscopic examination to assess the extent of flocculation. The discussion below addresses mechanisms for coagulation and flocculation (C/F)[1], and the differences between the fall velocities of naturally formed flocs and flocs formed after the addition of chemicals to initiate C/F.

Lin (2003) presents a thorough review of literature surrounding coagulation and flocculation. C/F is a two-step serial process. Coagulation refers to the destabilization of a colloidal suspension resulting in the formation of charged cohesive particles by physical and chemical processes. The aggregation of these particles into a larger settleable structure or floc is known as flocculation. In general terms, coagulation results in compact particles whereas flocs are open networks of loosely bound particles. C/F processes are complex and depend on a number of factors such as fluid pH, coagulant/flocculant type and concentration (if present); particle chemical and physical properties such as composition, PSD, concentration, surface area and surface charge; and interfacial reactions and collisions between suspended particles (Gregory, 1993).

Mechanisms for coagulation include: double layer compression by different electrolytes; charge neutralization; enmeshment in a precipitate; and adsorption. Following coagulation, flocculation occurs as the resultant cohesive particles collide with each other to form larger fragile aggregates. The form a floc takes is a complex function of particle mineralogy and the electro-chemical nature of the suspending medium (in this case, stormwater). The size depends on the particle collision frequency and the strength of the cohesive forces (ie, van der Waals interaction). Floc shape is also of importance; flakes are likely to have lower fall velocities than clumps of the same mass and density.

In a natural system, suspended particle collisions which lead to flocculation occur in water due to velocity variations caused by three different processes, namely, Brownian

[1] Coagulation and flocculation have tended to be used interchangeably in everyday parlance, however, here they are considered separate but related processes.

diffusion, local fluid shear, and differential settling. Brownian flocculation, which is due to particle diffusion, is only significant for particles less than 1-μm. Fluid shear or orthokinetic flocculation means that particle contacts are caused by differences in fluid velocity. Differential settling is when particles with different fall velocities collide - this mechanism is significant for suspensions with larger particles (>50-μm). Brownian motion, local shear and differential settling are as significant as gravitational forces for cohesive flocs. Brownian motion for cohesive particles becomes important when the sediment concentration exceeds approximately 10 g/L (Kranck, 1986).

There is very little literature on natural C/F in stormwater. Lin (2003) compared stormwater and natural river water as well as wastewater. He found that stormwater, which typically has rapid, unsteady, turbulent wet weather flows within shallow channels, has fewer flocs than natural waters. The residence time of stormwater can be as little as a few hours, so steady state floc development seen in rivers, has not occurred by the time flow reaches either treatment devices or receiving waters. None-the-less, there is scope for C/F within treatment devices and flocs have been observed.

Krishnappen *et al.* (1999) and Krishnappen and Marsalek (2002 a and b) are arguably the most comprehensive and relevant papers to appear in recent years which look at natural C/F in stormwater. They investigated C/F processes operating in the Kingston pond facility in Canada both *in situ* and under laboratory conditions. The pond serves a drainage area of 4.5 km^2 and consists of a wet basin (0.5 ha, depth 1.2 m) with a dry basin of similar size to contain heavy flows. The site has been the subject of a range of studies into stormwater treatment, particularly with respect to winter conditions including the effects on water quality and pond performance of cold temperatures, ice coverage, freezing of the inlet and outlet, and high concentrations of de-icing salts in inflow (eg, Marsalek *et al*, 2003, Marsalek and Marsalek, 1997). The results of floc studies were used to modify a flocculation model developed for quiescent flow to the dynamic flow conditions found in ponds.

Krishnappen *et al.* (1999) investigated the seasonal differences in floc sizes and settling rates at the pond. They used a submersible laser particle size analyzer that enabled them to examine the particulate characteristics *in situ* without disturbance by sampling. Readings were taken at 17 sites in the pond to give a pond wide average PSD for primary particles and flocs. The analyser consists of a 2 mW laser, a receiving lens, a detector plant, an electronic interface and a microcomputer. The analyser senses the diffracted light of a laser beam passing through the water in order to calculate the PSD in the water volume. The particle size is defined as the diameter of an equivalent spherical particle (ie, the nominal diameter) – they justify this potential source of error for field studies where there is a likelihood of irregularly shaped particles because the analyser takes a large number of sweeps of light energy distributions which will smooth out errors.

Krishnappen *et al.* (1999) found that fine particles in the pond tend to form flocs, but these can easily break-up in turbulent flow fields. They showed that besides flow conditions, the formation of flocs and the associated flocculent settling are strongly affected by particle concentrations and properties (including size and composition); water temperature, chemistry, and microbiology; and electrochemical forces. The primary particle and floc diameters were least during autumn and winter, especially under ice during winter (Table 5). Wind is included in the table as wind drives some of the currents seen in the pond, these currents determine the level of turbulence and therefore the conditions for flocculation. The PSD of primary particles is heavily skewed, but summer had the greatest spread and largest particle sizes. For winter and autumn, around 80 per cent of particles were 3.5 µm or less, for summer 50 per cent of the particles were in this size range. At the other end of the spectrum, about 5 per cent of particles in autumn and winter were greater than 30 µm, the corresponding size was 212 µm for summer. Around 40 per cent of flocs were less than 3.5 µm irrespective of season, however, summer had the largest flocs and the greatest spread (up to 5 per cent of flocs were greater than 164 µm compared to 40 µm in autumn and winter). The summer floc sizes were larger due to microbiological activity. This activity produces polymeric substances which act as flocculants to initiate aggregation and depends on warmer water temperatures and higher nutrient loads.

Table 5
Summary of results of PSD analysis for primary particles and flocs (constructed from results presented in Krishnappen *et al*, 1999).

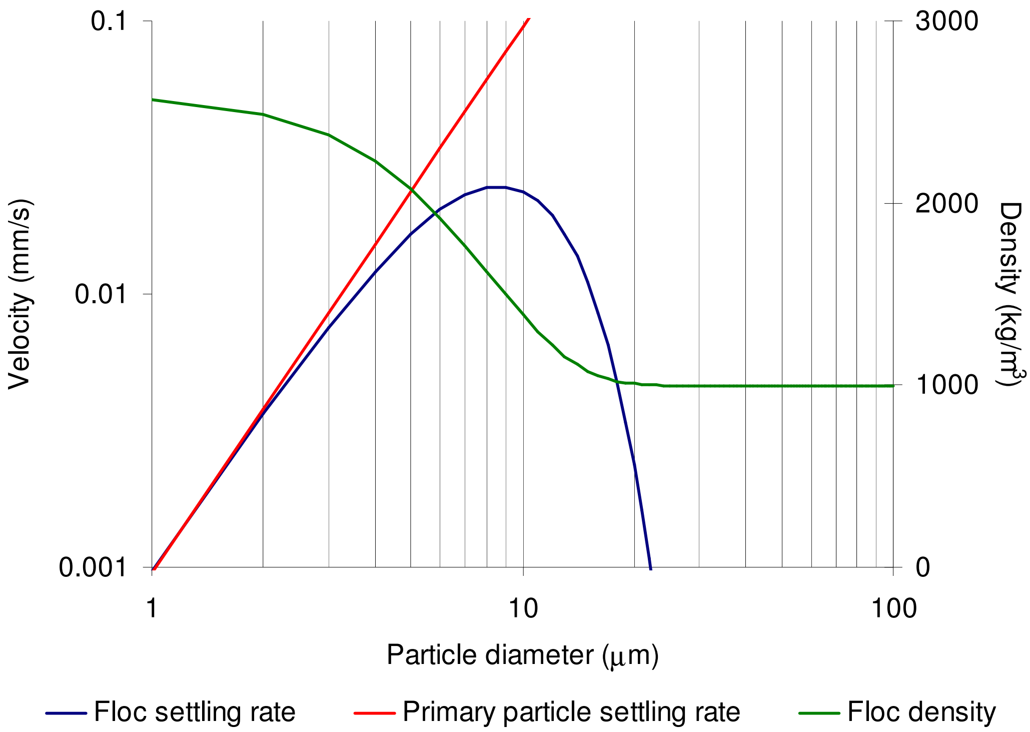
Date	Water temperature (°C)	Wind speed (m/s)	Inflow/outflow (l/s)	TSS (mg/l)	Median diameter (µm)	
					Primary particles	Flocs
Nov 1996 (Autumn)	4.0	2.1	29/35	13.4	3.58	8.11
Feb 1997 (Winter)	2.4	1.8	Not available	14.5	3.90	6.62
Sept 1997 (Summer)	16.7	1.0	19/24	28.2	6.16	17.49

Krishnappen *et al.* (1999) applied the floc density relationship determined from floc diameter and primary particle density by Lau and Krishnappen (1997) to sediments in the Kingston pond in order to calculate fall velocity. Floc porosity increases with floc size which causes a lowering of density as pore spaces are filled with water which has a lower density than the primary particles. Fall velocity was calculated for laminar flow conditions with a water temperature of 25°C according to Stokes' Law (

Figure 5). They state that for flocs greater than 9 µm, the effects of lowering floc density outweigh the effects of increasing floc diameter and fall velocity diminishes quickly as floc size increases. The calculated fall velocities for particles between 5-15 µm are faster than smaller, but denser flocs (which resemble primary particles) and larger flocs with low densities. This suggests that large flocs can have extremely slow fall velocities, indeed, Watt and Marsalek (1994) reported seeing flocs in the order of 100-250 µm which remained in suspension at the Kingston pond. Randall *et al.* (1982) too found that suspended solids in stormwater behave liked a mixture of discrete and flocculent particles. The discrete, larger particles settled rapidly, while the flocs were very slow to settle. Krishnappen *et al.* (1999) state that natural flocs are likely to be less dense (ie, liquid is incorporated into the floc which has high porosity) than those formed with chemical aids (see discussion below) which have rapid fall velocities. The seasonal differences in floc size could have an effect on fall velocities, but it is noted that turbulence in the pond easily breaks flocs.

Figure 5

Floc density and Stokes' fall velocity for flocs and primary particles of different sizes, water temperature is 25°C (constructed after Krishnappen *et al*, 1999).



On the basis of their earlier field findings summarised above, Krishnappen and Marsalek (2002, a) investigated the transport characteristics of fine sediment sampled from the pond bottom in a rotating circular flume using the same laser particle size analyser. This data was used by Krishnappen and Marsalek (2002 b) to test a modification of the settling and flocculation model developed by Krishnappan (1990) for still water (ie, quiescent) to dynamic flow conditions. Both the deposition and erosion characteristics of the fine sediments were examined in the flume experiments (Krishnappen *et al*, 2002a). It was found that sediments from the pond exhibit cohesive behaviour and form flocs when subjected to a flow field. At low bed-shear stress (ie, low turbulence), particle collisions are neither frequent nor intense enough to cause sediments to flocculate. Increasing bed-shear stress leads to increased turbulence and more frequent and intense collisions between particles which promotes flocculation. But further turbulence causes flocs to break as the intensity of collisions increases. To illustrate, at a shear stress of 0.121 N/m^2, the maximum floc size was 55 µm; floc diameter dropped to a maximum of 45 µm when shear stress was raised to 0.213 N/m^2 indicating breakage. The optimal bed-shear stress to form and maintain flocs is around 0.14 to 0.16 N/m^2 for the sediments found in the pond.

The modified flocculation model presented by Krishnappen *et al.* (2002 b) was able to simulate floc development and changes in fall velocities well and could offer an alternative method of simulating pond sedimentation other than the continuous-flow stirred tank reactor method recommended by the US EPA (Driscoll *et al*, 1986). However, full scale simulation of flocculation and settling has not yet been carried out and there are no plans to do so in the near future as it would require complex computational fluid dynamics (CFD) modelling of the pond (Jiri Marsalek, personal communication, 2006).

Coagulants and flocculants

The other articles found which looked at C/F in stormwater discussed the effect of chemical aids. Chemicals to facilitate the C/F process are commonly used in water supply and wastewater treatment plants to initiate settling. These coagulants and flocculants (also called coagulant aids) are formulated to assist destabilisation and aggregation. Two of the most commonly used coagulants are alum (aluminium sulphate, $Al2(SO_4)_3.18H_2O$) and ferric chloride ($FeCl_3.6H_2O$). When these coagulants are dissolved in water, they generate highly charged cationic ions for destabilizing dispersed colloidal particles. These particles are generally negatively charged, this means they repel each other and remain in a stable colloidal suspension without contact. The positively charged coagulant interferes with the repulsive stabilization by charge neutralization and allows the particles to come into close contact. Once in contact, the particles are able to adhere to each other to form cohesive aggregates. Flocculants facilitate the agglomeration of the coagulated particles to form larger flocs and thereby hasten gravitational settling. Some coagulants serve a dual purpose of both coagulation and flocculation in that they create large flocs that readily settle.

While there is much literature on C/F for drinking water and wastewater treatment there are comparatively few studies specifically for stormwater treatment. The potential use of coagulants to aid settling in ponds was simulated using a CFD model by de Cock *et al.* (1999). Ding *et al.* (1999) and Lin (2003) both used jar tests to determine the effectiveness of various coagulants with different doses as an aid to quiescent settling, both reports discuss the experimental set-up of jar tests in detail. Briefly, in a jar test, different doses of coagulant and flocculant are added to the different jars containing the water-sediment sample. An agitator is used to mix the additives with the water and to promote C/F by allowing particles to collide. A settling period then follows and samples of water are drawn off to be analysed for particle size distribution and concentration.

De Cock *et al.* (1999) added a flocculation simulation routine to a CFD model to simulate the effect of coagulation and flocculation on an end-of-pipe detention pond (total volume around 11,000 m^3) which treats storm and wastewater from a combined sewer overflow (CSO). Steady state flow conditions (the design flow was 0.364 m^3/s) were assumed with a constant incoming sediment and chemical oxygen demand (COD) concentration (164 and 225 mg/l respectively). The model was run assuming no addition of coagulant (ie, settling only) and with a constant dose of ferric chloride (30 mg/l). The model suggests that the conditions for floc growth, which requires agitation or turbulence for mixing, is at odds with the requirements for the design ideal of quiescent settling during detention. Without some form of mixing, the model shows that the addition of coagulant has very little effect on fall velocities. This means that two zones in a sedimentation pond are needed to allow C/F processes to occur and subsequent settling. That is, a pre-basin with a stirrer or baffles to increase turbulence could be used to promote floc growth followed by a larger, still pond for quiescent settling. Another alternative could be to add the coagulant into the combined sewer to allow mixing in the pipes before the water reaches the detention pond.

Ding *et al.* (1999) investigated the validity of jar tests and made recommendations for modification of standard methods for the US EPA. Ding *et al.* (1999) suggest that turbidity should also be monitored when evaluating the efficiency of C/F for stormwater treatment. They looked at run-off from a carpark and CSO as well as synthetic mixes with controlled sediment concentrations with controlled levels of inorganic and organic materials. The coagulants were alum and ferric chloride (doses 10-120 mg/l). Additionally, five types of flocculants were tested (doses 0.3-1.5 mg/l). The particle size and concentrations ranged from 100-500 μm and 3000-10000 mg/l respectively. Pre-treatment stormwater had 14 per cent of the particles below 10 μm and 81 per cent of particles between 10-100 μm. They suggest that alum is better for stormwater and ferric chloride for wastewater. Alum was found to remove all particles greater than 2 μm from the stormwater. Alum concentrations of 60 mg/L without flocculant and 40 mg/L with 1 mg/L of flocculant yielded better turbidity reduction efficiency than settling alone for stormwater. The required doses are greater for CSO; 190 mg/L of ferric chloride alone or 40 mg/L as Fe^{+++} with 6 mg/L of flocculant.

Lin (2003) compared C/F in stormwater, wastewater and river water using jar tests, again with alum and ferric chloride as coagulants, and two sets of flocculants (cationic polyacrylamide flocculants 1 and 2 and anionic polyacrylamide flocculants 1 and 2) at different doses (0-50 mg/l for the coagulants and 0-12.5 mg/l for the flocculants). Settling column experiments were carried out to determine the fall velocities of the flocs. Flocs were examined under an electron microscope to determine their physical characteristics. It was found that flocs formed large flake aggregates and have a fractal structure whereby aggregates of particles are self-similar as floc size increases. Moreover, floc properties such as density and fall velocity are a function of the fractal dimension. The jar and settling column tests results were similar to Ding *et al.* (1999) and showed that the addition of either alum or high charge density polyacrylamide caused particles in stormwater to destabilise, coagulate and flocculate allowing them to settle out of solution after a short time period. Again, like Ding *et al.* (1999), ferric chloride was found to be more effective for wastewater. Lin (2003) used the results of the jar and column tests, along with observations of particle properties, to develop a modified fractal model to simulate and predict the particle size distribution during the sedimentation and coagulation process in urban rainfall run-off treatment system.

Coagulant aid studies in Auckland

In addition to the stormwater examples given above, the use of coagulants and flocculants to decrease sediment loads from earthworks has been investigated in two studies undertaken for the ARC. The first was carried out by Mike Larcombe (TP 227: ARC, 2004) while the second was undertaken by NIWA (Moores and Pattinson, 2008).

Field trials for TP 227 (ARC, 2004) were carried out during the construction of the Northern Motorway extension between Albany and Puhoi (ALPURT) and a residential development at Greenhithe to test the effect of liquid and solid dosing on water treatment in sedimentation ponds. There is no information in TP 227 about PSD or fall velocities. Two liquid coagulants (alum and polyaluminium chloride, PAC) along with three types of solid flocculant were trialled (two anionic polyacrylamide blends, Percol AN1 and Percol AN2, and a cationic polyacrylamide blend, CN1). The solid flocculants were in the form of floc blocks, commercially prepared solid blocks of flocculant which dissolve slowly in flowing water, the advantage of floc blocks is that they allow more even mixing of the flocculants in run-off without the use of special tanks or electricity for dispersal and mixing. The dosing and delivery methods for the flocculants and coagulants is given in detail in TP 227.

The ALPURT liquid coagulant trials showed that both alum and PAC can significantly improve sediment removal in ponds. Alum was added to a single pond from a catchment with limestone soil and lead to a suspended solids removal of 92 per cent compared with removal of about 10 per cent for a similar storm at the same catchment with the same retention pond but with no alum treatment. PAC was added to ponds at several sites with clay soil that naturally produce more acidic run-off (ie, PAC is less acidic than alum and is more suitable for acidic run-off), each was adjacent to a second, control pond to allow comparison. PAC resulted in similar improvements (77 to 98 per cent) compared to the untreated ponds (4 – 12 per cent).

The floc blocks were trialled as part of the ALPURT construction project and later at the Greenhithe site. Bench mark tests using sediment laden run-off from the site showed that of the flocculants, AN2 was the most efficient for sediment removal, thus this flocculant was trialled at the site. Floc blocks, held in netting, were placed in a special flume to divert some of the inflow from the inlet channel into an end-of-pipe sedimentation pond. Initially, the divert quickly became choked and floc blocks were buried with sediment which meant that water into the flume was subsequently taken from the pond fore-bay rather than direct from the inflow channel. While effective, a number of problems were identified, particularly in regard to providing optimal doses with variable stormwater volumes and sediment loads. For instance, if the floc blocks are allowed to remain in the flume, they can become soft forming a viscous solution that can flow downstream.

The floc block trial at Greenhithe was carried out to further test the flocculant AN2 and to design a better, more robust dosing system. Rather than being placed in a flume, floc blocks were suspended in cages that could be lowered and raised into and out of the flume as needs be. However, this arrangement too had its problems, the main one being degradation of the floc blocks following wetting and drying. The blocks broke down which meant that unreacted chunks could be carried with sediments downstream leading to a possible environmental hazard. Again, without a fore-bay, the flume system became clogged, thus, the dosing system needed regular maintenance.

The NIWA study for the ARC (Moores and Pattinson, (2008) was undertaken with a specially constructed dual pond system with two parallel ponds receiving run-off from a construction site that was evenly split between the ponds (

Figure 6a and b). Like the Mike Lacombe trial study, the ponds are intended to treat run-off from the ALPURT extension of the Northern Motorway. The inflow to the treated pond was automatically dosed with PAC during rain events in accordance with ARC flocculation guidelines set out in TP 227. Automatic water samplers were set up at the inflow before the splitter and at the outflow of each pond. A total of seven flow events were sampled. Water sampling was time-weighted with the sampling interval determined on the basis of forecasted rainfall (and therefore expected run-off). TSS concentration and PSD was determined for the samples, the latter using a Galai particle size analyser. Dissolved alumininium leaving the treated pond (ie, from the PAC dosing) was also analysed. In addition to sampling, flows into and out of the ponds were monitored in order to determine loads and event mean concentrations.

The study showed that dosing with PAC is an effective method for improving the sediment removal efficiency of sediment retention ponds. The total sediment load discharged from the untreated pond (8.75 tonnes) over the settling events monitored was three times that of the treated

pond (2.95 tonnes). The treated pond had an estimated sediment removal efficiency of at least 68 per cent, whereas the untreated pond removed around 30 per cent.

Figure 6a

Dual sedimentation ponds were constructed to compare fall velocities with and without flocculant dosing (Figure 6a). Note that the left pond has been dosed and appears clearer than the undosed pond, this can also be seen in the colour of the water samples from the two ponds (Figure 6b below; photos from Moores and Pattinson, 2008).

Figure 6b

The effectiveness of treatment did not appear to correspond with the preferential removal of particles of a particular size. There was little difference between the PSD of samples collected at the treated and untreated pond outlets during five of the events sampled. This suggests that the treatment is effective for the range of particle sizes which characterise the majority of sediments at the study site (0 – 31.3 μm). Addition of PAC did result in an elevated concentration of dissolved Al from the treated pond. The concentration was greater than ANZECC (2000) water quality guidelines for nine samples from the untreated pond and 13 samples from the treated pond, however, the median concentration was for both ponds was less than ANZECC guidelines.

3.2 Sampling and analyzing particles in stormwater

3.2.1 Sampling stormwater

There has been increasing concern, voiced in Humes (2006), that there is an apparent bias towards smaller particle sizes being collected in stormwater samples taken with automatic samplers. Burton and Pitt (2002) state that these (or any pumped samplers) may not provide a true picture of sediment loadings or PSD in stormwater. To illustrate, settled sediments collected from ponds (eg, Liebans, 2001) can have high proportions of sand despite the low proportion of these coarse sediments in stormwater samples. The standard is that the suction tube intake is placed mid-stream and mid-channel. Clay and silt-sized particles are generally well-mixed with depth, however, the maximum sediment loading is often near the channel bottom and larger and denser sediment are found disproportionately at lower levels due to gravitational forces. This means that larger particles may not be sampled despite their presence in the water column.

Furthermore, automatic samplers may disproportionately collect smaller particles if the intake velocities vary significantly from the water velocity. The ideal is for isokinetic sampling where the sampler intake points directly into the flowing water (ie, the tube is running parallel to the flow streamline) and the velocity in the intake is the same as the flowing water in order to get a representative sample with larger particles included (Burton and Pitt, 2002). Most intakes have a velocity less than stream velocity which means they are unable to entrain larger particles with greater fall velocities such as sands.

URS Greiner Woodward Clyde (1999) cite a study carried out by the US Geological Survey (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 (ie, 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 per cent 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 BMPs 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.

Furthermore, Lin (2003) gives the criticisms that:

- the suction tube intake end is rarely orientated towards the flow to be sampled;
- the 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;
- there is no assurance that the intake location is representative of the channel flow or the size distribution of particles with respect to the entire channel cross-section; and
- there is no assurance that tube can capture a representative sample with all particles sizes present.

However, Bent *et al*, (2001) states that further research is needed to determine the relationship between data collected by automatic and isokinetic sampling methods in highway and urban drainage systems. They go on to list the following criteria for 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.
- 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.
- 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.

Bent *et al*, (2001) state that 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 (ie, the US EPA NURP samples, Driscoll *et al.,* 1986; ARWB, 1991; and Leersnyder, 1993). Indeed, later studies cited below which use different sampling techniques tend to have a greater range of sediment sizes and a greater representation of coarse particles.

Sansalone *et al.* (1996), Sansalone and Buchberger (1997) and Sansalone *et al.* (1998) found that the particle sizes of stormwater particulates investigated at a freeway site in Cincinnati, Ohio were much larger than typically found elsewhere. In their samples, particles several hundred microns in size were common. They stressed the need to carefully collect stormwater samples for particle size analyses considering the difficulty of representing large particles in samples collected with automatic samplers.

Lin (2003) collected stormwater in a grit chamber and settling basin. 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. Lin (2003) found that the grain size of settleable solids was coarser than found in other studies and that most sediments in the sedimentation basin were in the fine sand to sand range; over 50 per cent of particles had a size greater than 250 μm.

Burton and Pitt (2000) have made a number of recommendations on the use of automatic samplers. For instance, multiple intake sampling can be used where there is a vertical gradient of particle sizes. Bed load samplers can be used to supplement automatic water samplers in order to obtain more accurate PSDs. Alternatively, conventional water samplers may be used to represent all of the sediment in flowing water (floating material, suspended sediment, and bed load), if the water is very turbulent and capable of mixing the sediment of interest. The American Society for Testing and Materials (ASTM, 1995) refers to these locations as "total-load" stations, allowing the collection of all sediment greater than about 2 mm in diameter. These are generally located at outfalls or other free-falling locations.

3.2.2 Analytical methods

Hydrologically, the distribution of fall velocities is of more importance than the PSD as it determines the rate of sedimentation directly (Oden, 1924: Skinner, 2000) though the two are related and are often used interchangeably where one is calculated from the other. As was shown above, the relationship between the two variables is difficult to define and depends on fluid temperature and flow conditions as well as particle properties and concentrations. Where there is a choice of experimental data, water managers should use fall velocities in preference to particle sizes to dimension water treatment devices. In the following discussion, the main methods of determining particle sizes and fall velocities experimentally are addressed.

3.2.2.1 Particle size distribution (PSD)

In order to understand what is meant by the PSD, it is first necessary to define what is meant by particle size. There are five main definitions:

1. **Nominal diameter** – the diameter of a sphere that has the same volume as the particle. This diameter can be calculated from particle weight and density.
2. **Sieve diameter** – the length of the side of the smallest square opening through which the given particle will pass – this is equivalent to the sieve mesh (or filter). Raudkivi (1990) gives the rule-of-thumb that the sieve diameter is roughly 0.9 times the nominal diameter for naturally worn sediments between 0.2 and 20 mm.
3. **Sedimentation diameter** – the diameter of a sphere that has the same density and fall velocity as the given particle in the same fluid under the same conditions. It is based on the aerodynamic drag force caused by the difference in velocity of the particle and the surrounding fluid. Sedimentation diameter is also known as the Stokes' diameter and is the particle size that should be used to determine fall velocity with Stokes' Law.
4. **Fall diameter** – the diameter of a sphere that has a density of 2650 kg/m^3 (ie, equivalent to quartz sand) and has the same fall velocity as the given particle in quiescent distilled water at a temperature of 24 °C. For quartz, the fall diameter is related to the shape factor and the nominal diameter.

5. **Geometric average diameter** – is the average diameter of a particle and is equal to the cube root of product of the width, breadth and length of the particle – $(abc)^{1/3}$ using the same nomenclature as Equation 5.

Skinner (2000) gives further examples of sediment size definitions that are not based on spheres. Each of the size definitions above has different implications for the interpretation of PSD, for instance, if samples are sieved (or filtered), particle size is equated to the sieve diameter. However, if the PSD is calculated from fall velocities (eg, from a column experiment, see Section 3.2.2.2 below), the particle size is equated to the sedimentation diameter or fall diameter - this approach can be problematic if particles are irregularly shaped, flocs are present or if particle density changes with sediment size. Indeed, there is often a mismatch between the measured PSD and PSD calculated from fall velocities (*ibid*).

The measurement of particle sizes was covered in detail by Grant *et al.*, (2003) in a comprehensive review of particle contamination in highway run-off prepared for the California Department of Transportation. They note that a fundamental limitation of characterizing particle size distributions in roadway run-off is that no single approach can characterize the entire range of particle sizes present. This limitation arises because:

- no single instrument can sense the more than six orders of magnitude in the range of particle sizes present in stormwater, from nanometre-sized colloidal organic material to millimetre-sized sand and silt; and
- the physical properties of particles (eg, density, shape, roundness, etc.) are highly variable and subject to systematic biases (eg, the physical properties of large and small particles can be different).

They state that relative to road run-off (or indeed stormwater) applications, the ideal particle size analyser would:

- provide the abundance of particles in a given size range;
- cover a wide size range;
- require little in the way of assumptions about the physical properties of the particles or the dispersion medium;
- have a direct and tractable relationship between particle size and instrument response; and
- be robust and field-ready for online monitoring.

Grant *et al.* (2003) found that there is a wide variety of instruments commercially available for particle size analyses using one or more physical properties. Some of the physical phenomena exploited include electrical properties (where particles are vacuumed through a small aperture with an electric current across the opening, the resistance of the particle is then related to particle size), transport properties in the case of sedimentation and hydrodynamic chromatography, and optical properties as represented by a wide variety of light scattering phenomena.

Skinner (2000) breaks particle sizing instruments into six categories:

- Sieves (and filters)– routinely used in stacks to mechanically divide samples into size-range fractions.
- Microscopes – manually or automatically gauge 2D particle images (see Lin, 2003, for examples of electron microscope images and analysis thereof).
- Sensing zone instruments – gauge particles by their interaction with acoustic beams, light beams, or electric fields. The Galai sensor used to determine PSD by NIWA falls into this category and is further detailed below.
- Elutriators – include (a) cyclone separators that size particles as they spin in a fluid vortex and (b) laminar flow deposition instruments in which low-speed currents carry particles horizontally as they settle. Points at which the particles cross a reference plane are calibrated according to particle size.
- Gravity-driven sedimentometers – includes settling columns (discussed below) where PSD can be determined *in situ* by light scattering (eg, optical backscattor sensors) or by drawing off sub-samples which are then analysed for TSS concentration. Another variant is to catch particles on submerged weighing pans where sediment size is equated to pressure on the pan.
- Centrifugers – sense the distribution of particles through their interaction with light rays or X-rays.

Of the instruments available, some detect and enumerate one particle at a time (eg single particle counters) while others analyze the sum of measured signals (eg, light scattering) to obtain an ensemble average. Readers are referred to Grant *et al.* (2003) and Skinner (2000) for comparisons of the techniques and instruments used to size particles and a discussion of their accuracy and where and how they should be used. Suffice to say that they both conclude that there is no ideal instrument available for determining PSD.

PSD at NIWA is often determined using a Galai CIS-100 time-of-transition stream-scanning laser system. 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 quickly counts large numbers of particles, providing good statistics on size and shape populations.

Wet and dry sieving is by far the most common method of determining the PSD for stormwater sediments. 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. The liquid run-off 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 run-off sample must be evaporated to obtain the sediment. Some of the fine particles can clump together and act as a larger particle 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 mesh size is around 20 μm, particles passing through the sieve stack can be mixed with water and filtered (eg, with membrane filters) to determine the loads of finer sediments.

Wet and dry sieving were used variously to determine PSD by the case studies reported in Section 3.3 below. Indeed, particle sizes reported in the literature usually refer to the sieve diameter though this is not often explicitly stated. The obvious problems are that flocs are destroyed and that long, thin particles can be miss-classed with respect to their settling behaviour. Moreover, sieving gives discrete steps in particle size rather than a continuous distribution. The advantages of sieving is that the method is easy to carry out and the sieved sediment samples can be further analysed for contaminants to give a measure of contaminant partitioning and fractionation (eg, dissolved vs. particulate; load by particle size).

Aside from the choice of PSD analytical method, Bent *et al.* (2001) add the further concern where sub-samples are taken from a water sample. They state that if a sample contains a substantial percentage of sand-size material, stirring, shaking, or otherwise agitating the sample before obtaining a sub-sample will rarely produce an sub-sample representative of the sediment concentration and PSD of the original sample due to the rapid settling of sand compared to silts and clays. Sub-samples obtained by pipette might be withdrawn from the lower part of the sample where the sand concentration tends to be enriched immediately after agitation, or from a higher part of the sample where the sand concentration is rapidly depleted. Additionally, the physical characteristics of a pipette used to withdraw an sub-sample can introduce bias in the sub-sample (Skinner, 2000).

3.2.2.2 Settling columns

The primary method for determining fall velocities of suspended sediments is the use of settling column experiments to determine gravitational settling. The use of settling columns was pioneered by Oden (1924) who stated that fall velocity, not sediment size, is the key issue for sedimentation. He noted that particles of differing sizes have differing fall velocities and that over time, particles are depleted from a water sample as settling progresses in proportion to their size. Oden (1924) noted that trying to equate the sedimentation diameter with sieve diameter can lead to misconceptions due to the reality of irregularly shaped particles and stated that sediment size should be used as an image to aid conceptualisation rather than a physical parameter. His view has been reiterated many times since 1924 (eg, Wong *et al*, 1991; Skinner, 2000). Sediment sizes back calculated with, for example, Stokes' Law, from fall velocity, normally assume that the particles are spherical and the size is equated to the sedimentation diameter (or fall diameter if particle density is assumed to be 2650 kg/m^3 and water temperature is held at 24°C). However, as was shown in the discussion of settling theory above, there are settling models which take differences in fluid and particle properties and sediment concentration into account.

Oden (1924) gives four conditions on the applicability of settling columns to determine fall velocities:

- complete dispersion of particles and prevention of C/F by use of dispersants;
- particles uniformly distributed in the solution at the start of the experiment;
- particle concentration should be dilute to ensure that particles do not interact with each other in their fall, and that the density of the suspension does not vary significantly from the density of the pure liquid; and
- the water temperature should be constant throughout the column and during the entire experiment.

Settling column tests can be split into two types (Lin, 2003):

- homogeneous suspension method – the sediment is 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 sediment sample is distributed in a thin uniform layer at the surface of the fluid at the start of measurement, the mass fraction of particles decanted over time is a function of the fall velocities.

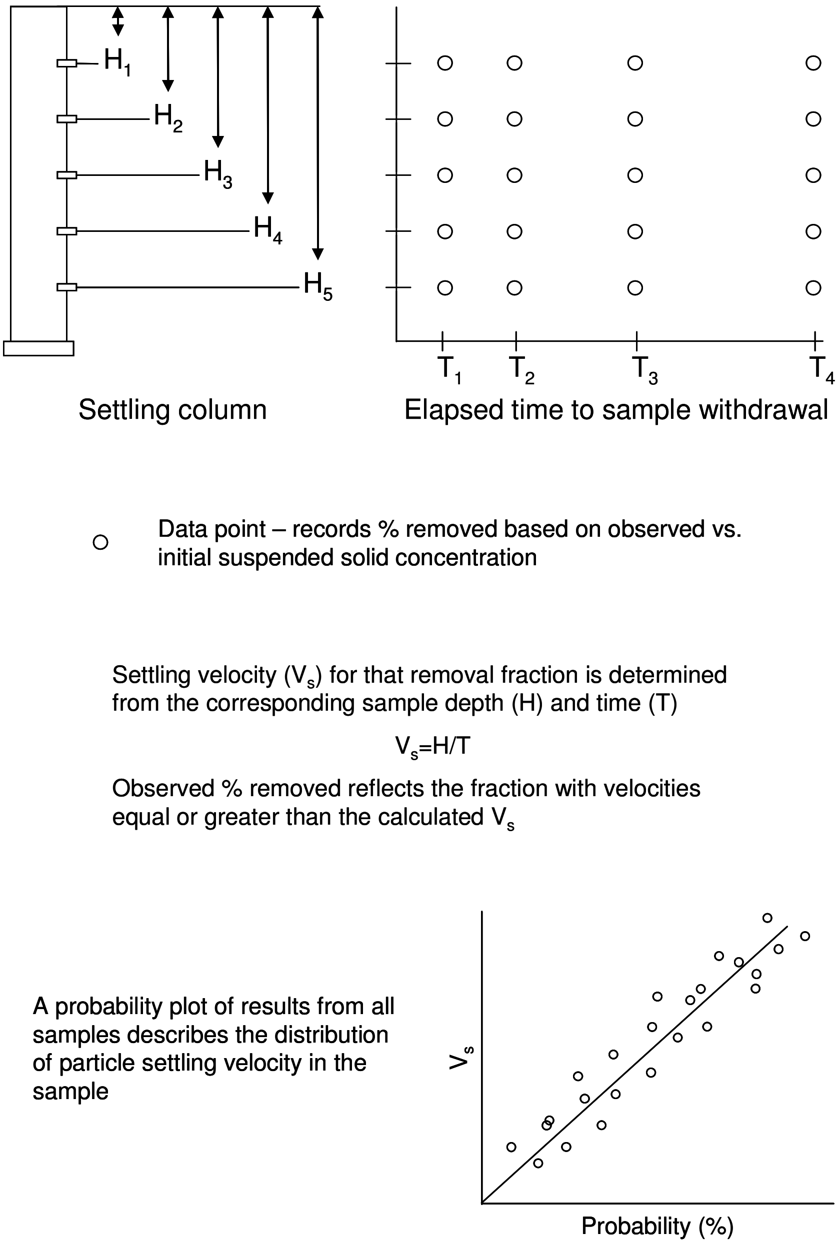
Of the two methods, the first is most common and is known as the pipet procedure. Pisano (1996) states that the settling column typically is made of clear plexiglas (acrylic) with ports for sub-sample withdrawals along the column length. The column is usually between 1.8 and 3.7 m high with a diameter of 15 to 30 cm. Column depth is usually equivalent to that of a clarifier or settling basin. Various methods have been used to pre-mix the sample before the column test begins. Fall velocity is determined either by analysing the concentration of suspended solids in sub-samples taken from the ports at specific times or, as is becoming increasingly common, by use of light scattering or x-rays where the sensors are located within the water column. The sub-samples are dried, and the sediment weights are plotted to form a cumulative distribution curve of percent-less-than (PLT) values versus particle-fall diameter. Driscoll *et al.* (1986) gives a protocol for the pipet procedure to determine fall velocities for stormwater sediments which is summarised in Figure 7. This method formed the basis of the NURP study.

There are a many of criticisms of column experiments both in terms of assumptions and methodology.

In terms of methodology, the time taken waiting for settling (four-hour minimum) and labour intensity of analysing sub-samples for sediment concentration and PSD (see Skinner, 2000) are the main considerations. Another concern is that taps or pipettes used to draw-off samples can give a bias towards smaller particles as the suction velocity may be less than the fall velocity of larger particles. This criticism is similar to that in Section 3.2.3.1 for non-isokinetic stormwater sampling with automatic samplers. Furthermore, if pipettes are used, they can cause localised mixing of suspended sediments and turbulence. Drawing-off sub-samples also reduces the volume of the column and is destructive in that the original sample is altered in both its concentration and PSD. However, use of light scattering, as was carried out by NIWA, removes these objections but brings further problems (see Section 3.3.3.2).

The main theoretical criticism of the use of settling columns is that only quiescent settling can be determined. That is, columns cannot reproduce field conditions characterised by flow circulation (driven by incoming flow) or wind-driven waves and currents (Marsalek *et al*, 2005). Such flow patterns in a stormwater device can both increase settling by driving particles downwards or can cause resuspension. Flow is also a major determinant of flocculation and floc break-up.

Figure 7
Determination of fall velocity using a settling column, pipet procedure (redrawn from Driscoll *et al*, 1986).



Take condition 1: that there should be no coagulation or flocculation. In the discussion of natural flocculation in Section 3.1.3.2 above; Krishnappen *et al.* (1999) and Krishnappen and Marsalek (2002 a) showed that fall velocities in a stormwater pond could be dependant on floc properties, especially during summer when floc sizes are greatest. Moreover, the level of turbulence caused by flow is crucial to whether flocculation occurs and whether flocs can remain in suspension or are broken down. Defenders of condition 1. (cited in Skinner, 2000) state that flocs are easily broken by turbulence and have a minimal impact on sedimentation, which is at odds with the observations for stormwater given by Watt and Marsalek (1994); Randall *et al.* (1982)

and Krishnappen *et al.* (1999). Detractors of condition 1. also point out that the presence of a dispersant in the column, its chemical make-up and concentration, has a great impact on the PSD, especially for particles less than 8 μm.

The second condition that the suspension is evenly distributed necessitates the use of paddles, pumps or other means of agitating the suspension. This means that there can still be eddies in the suspension (ie, local turbulence) at the beginning of the experiment. Thus, when to start timing can be an issue if there are larger particles present, but is of little consequence for small particles (Skinner, 2000).

The requirement that the concentration of the sediments in suspension be dilute (condition 3.) to avoid the particles interfering with the fall of other particles is problematic in the pipet procedure as analysis of PSD by sieving requires that drawn-off sample has enough sediment to allow accurate measurement.

The requirement for constant temperature (condition 4) is difficult to achieve over extended time periods. There are two possible impacts: temperature gradients lead to convection circulation which can cause sediment transport; and changes in temperature will also change liquid density and viscosity, both of which influence fall velocity (see Section 3.1.1). Skinner (2000) cites several papers which suggest a lower size limit on analysis with gravitational settling of about 2 μm when water is used as the suspending fluid.

Skinner (2000) mentions a further assumption that the column walls do not influence the fall velocity due to the effects of inertia. This means that the column should be large enough to avoid interference – Skinner (2000) recommends that the diameter be at least 5.5 cm, however, the effect of walls is largely unexamined.

3.3 PSD and fall velocities – case studies

The PSD and sediment settling properties of sediments in stormwater are site specific and related to local geology/soils and land use as well as rainfall patterns. Even within a single stormwater catchment assuming homogenous land cover and rainfall depths, there can be differences in PSD between the head- and receiving waters. While the PSD reaching the stormwater system, including the reticulated network and stream, may be similar throughout the catchment (eg, due to wash-off from impervious surfaces and soil), settling, resuspension and erosion of sediments within the system can change not only the PSD but also the partitioning and fractionation of associated contaminants. Of course, it stands to reason that the PSD would be even more variable with heterogeneous land cover.

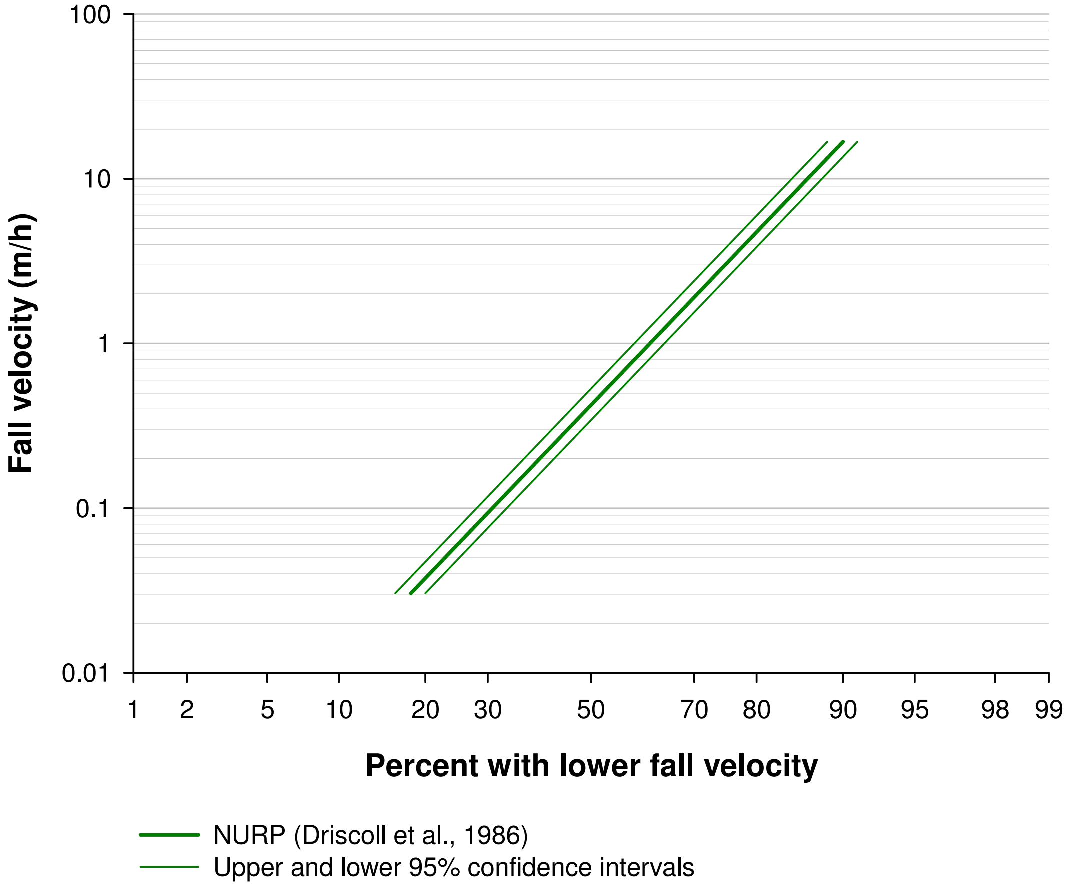
Particle diameters of suspended solids in stormwater vary over six orders of magnitude (Grant *et al*, 2003; Makepeace, 1995) and fall velocities vary over four orders of magnitude (Burton and Pitt, 2002). The case studies below represent those publications cited by Humes (2006) with the addition of Zanders (2005) and NIWA research both of which present data from New Zealand. They can be described as traditional stormwater treatment studies which are concerned primarily with suspended sediments. Other recent studies of note are Andral *et al.* (1999), Lin (2003) and various papers by Sansalone on granulometry (eg, Sansalone and Hird, 1999, Sansalone and Buchberger 1996, Cristina *et al*, 2002). Their results are discussed Sections 3.5. Suffice to say that the granulometric studies found a greater proportion of coarse sediments usually not associated with suspended sediments than other researchers which led them to query sampling practices as noted above. They point out that while coarser sediments readily settle, their presence in stormwater treatment devices implies that they must be transported with stormwater with mechanisms such as saltation. Earlier influential publications such as Whipple and Hunter (1981) and Grizzard *et al.* (1986) are not covered as they pre-date TP 4 (ARC, 1992) and TP 10 (ARC, 1993). It should be noted, however, that Grizzard *et al.* (1986) found a relationship between particulate concentrations and PSD that has been supported by Furumai *et al.* (2002). High particulate concentrations were found to be associated with relatively high quantities of larger particulates, in contrast to waters having low particulate concentrations. The high particulate concentration water would therefore have increased particulate removals in detention ponds, especially as higher sediment loads have greater fall velocities.

3.3.1 US EPA (Driscoll *et al*, 1986 and Fan, 2004)

The Nationwide Urban Run-off 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. They provide protocol for carrying out settling column experiments (see Section 3.2.2.2) and a summary of settling behaviour determined using column experiments for 46 stormwater samples from seven catchments (Figure 8, presented in tabular form earlier in

Table 2). All samples were taken using automatic water samplers which, obviously, pre-date the 1993 threshold for reliable water sampling recommended by Bent *et al*, (2001, cited in Section 3.2.1). 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 fall velocities in any sample of stormwater and local data collection is recommended.

Figure 8
Probability distribution of fall velocities for particles in stormwater summarised from NURP data (converted in to SI units, after Driscoll *et al*, 1986).



The ARC design criteria for sedimentation devices (TP 4, 1992 and TP 10, 1992) adopted these bands stating that the settling behaviour for Auckland stormwater (ie, two rainfall events from a catchment in Pakuranga) was similar to the data given in Driscoll *et al.* (1986). The bands and calculated PSD determined by the ARC are given in

Table 2.

More recent reports from the US EPA have also looked at particle size distributions in urban run-off. One cited throughout Humes (2006) is a reference guide for sediment control in sanitary sewers which includes sediments from stormwater entering combined sewers (Fan, 2004). This report was not intended for modelling sediment removal in treatment devices but rather to predict sediment sources and transport through sewer networks. This report has amalgamated PSDs (calculated and measured) and fall 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, CSO, stormwater, street solids, sediment scraping, pipe slime) collected across North America and Germany over the last two decades.

Figure 9 and

Table 6 summarise the results of the Fan (2004) review of PSDs, most particles 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 catch pits. Fan (2004) cites the NURP results to state that regular street sweeping (eg, monthly) can reduce TSS by 15 to 20 per cent. It is also noted that Ashley and Crabtree (1992) found larger particles have the highest removal rates. Liebans (2001) found that street sweeping is effective for removing sands but leaves fine sediments often associated with the highest metal concentrations. Further sediment reductions are made by Fan (2004) for catch pits. Pitt and Field (2004, cited in Fan, 2004) measured the solids removal effectiveness of 100 catch pits and concluded that solids removal is principally a function of the rate of incoming gutter flow. Removal rates for TSS approach 45 per cent 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.

Calculated fall velocities for the PSDs are summarised in Figure 10 and Figure 11. The velocity calculations assume the sediment consists of worn angular particles in water with a temperature of 10 °C. The report notes that fall velocities determined from most settling column tests of stormwater have excluded bed-load materials, and are thus generally within the lower end of this range. This comment is echoed by the concerns raised in Humes (2006). However, the review also notes that larger urban sediments may not be present in samples due to the effect of street sweeping and catch pits which remove particles before they enter the pipe network.

Figure 9

Particle size distribution for sediments found in stormwater including CSO according to Fan (2004: US EPA) for sediments. The reduced curve shows the combined effects of street sweeping and catch basins on sediment sizes.

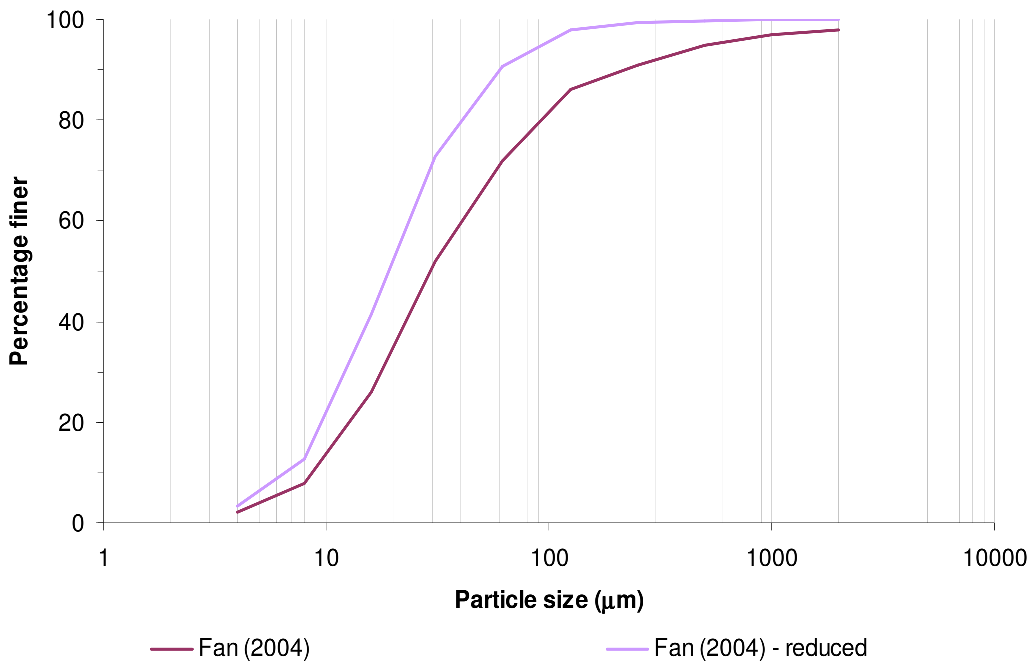


Table 6
Potential reductions of sediments in urban stormwater due to street sweeping and catch pits.

Particle size (µm)	Initial proportion mass in category (%)	Effectiveness of street sweeping (% reduction)	Effectiveness of catch pits (% reduction)	Proportion of mass after sweeping and catch pits (%)
>2000	1	80	100	0.0
>1000	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
TOTAL	98	-	-	-

Figure 10
Calculated fall velocity by particle size (Fan, 2004).

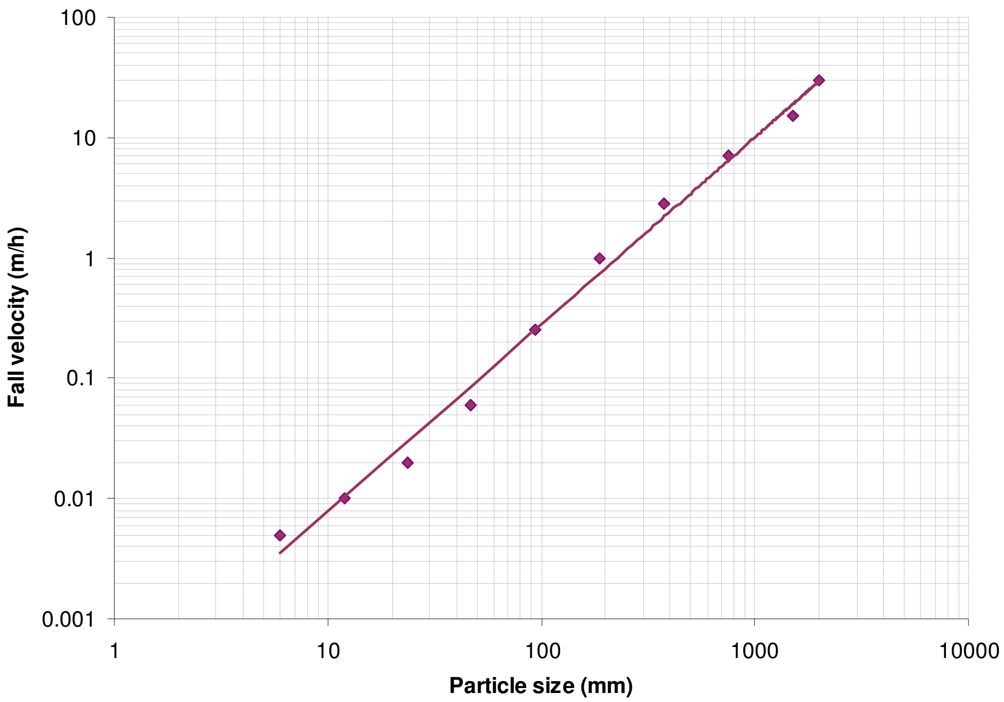
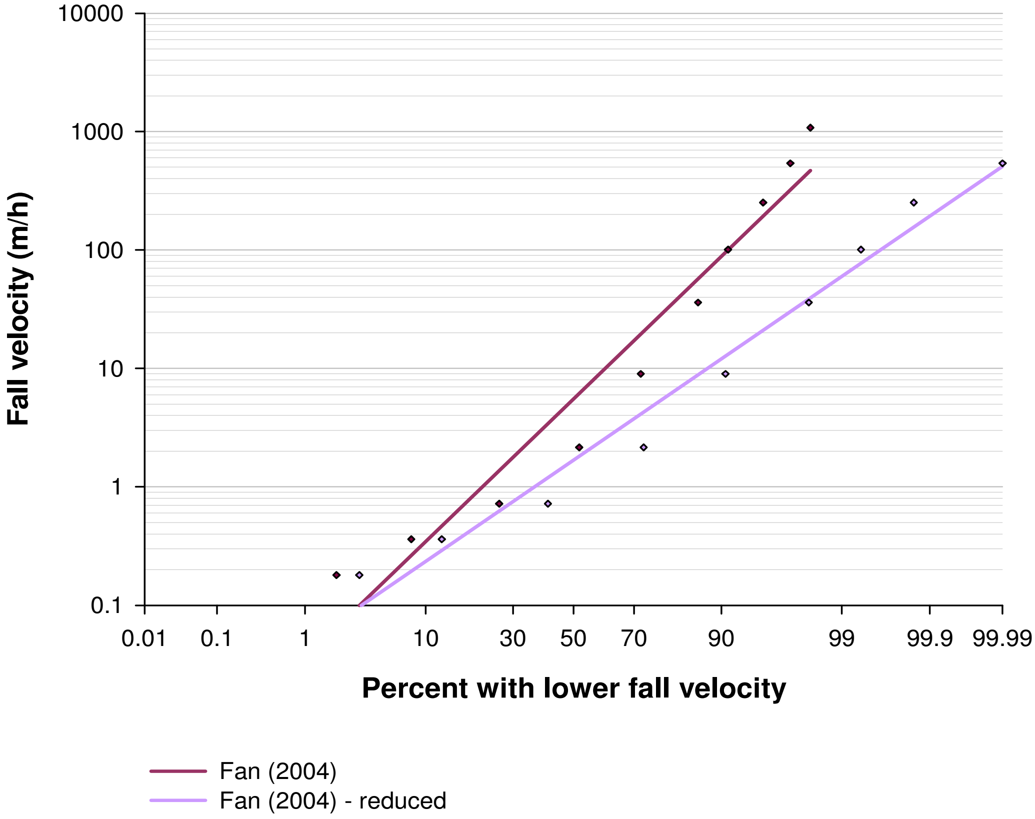


Figure 11
Probability distribution of fall velocities for particles in stormwater (Fan, 2004).



3.3.2 Leersnyder (1993)

The MSc thesis work carried out by Leersnyder (1993) under the auspices of the ARC has been used to support the use of NURP particle fall velocity bands by the ARC. The results have close agreement with those found earlier in Pakuranga (ARWB, 1991) cited above which were used in TP 4 (1992) to determine water quality volumes in Auckland. 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 through a stack of stainless steel sieves with mesh sizes of 1000, 500, 250, 125, 63 and 20 µm respectively. Of the sediments trapped by the sieve, the majority had particle sizes in the 20 to 63 μm range; 79 per cent for Pacific Steel and 49.8 per cent for Hayman Park.

Sediments collected in the sieves were rinsed into beakers with de-ionised water. The beakers were then dried and re-weighed to determine TSS. Note that the results found by Leersnyder (1993) lump silts into a single group due to the chosen methodology. The combined PSD of the sieved particles and those less than 20 μm (plotted at 10 μm) are given in Figure 12. Of note is that the particles in the Pacific Steel stormwater samples tend to be finer than those from Hayman Park.

Settling properties plotted in Figure 13 were determined for bulk sediment samples from the inlets of each pond using column tests. The columns were 2 m high with a diameter of 225 mm, sampling taps were placed at intervals of 300 mm. The bulk sediment samples were thoroughly mixed and a sub-sample poured into each of the columns. Samples were taken at time intervals of 15 minutes, 30 minutes, 1 hour, 2 hours, 4 hours, 8 hours, 16 hours and 32 hours and the TSS removal determined. For the Hayman Park pond, which is more representative of urban stormwater, 50 per cent of particles had settled after 6 hours, 65 per cent after 16 hours and 70 per cent after 32 hours.

Fall velocity was determined from the columns using the technique described by Driscoll *et al.* (1986) for the US EPA. It was found that fall velocities for Hayman Park were similar to those in Pakuranga, while, in keeping with the PSDs above, Pacific Steel had slower settling. Both Hayman Park and Pacific Steel a greater proportion of particles with fall velocities slower than those in the NURP study, which suggests that the particles are finer or have a lower density or both.

Figure 12

Particle size distribution according to Leersnyder (1993) for Hayman Park (Manukau – commercial) and Pacific Steel (Otahuhu – industrial).

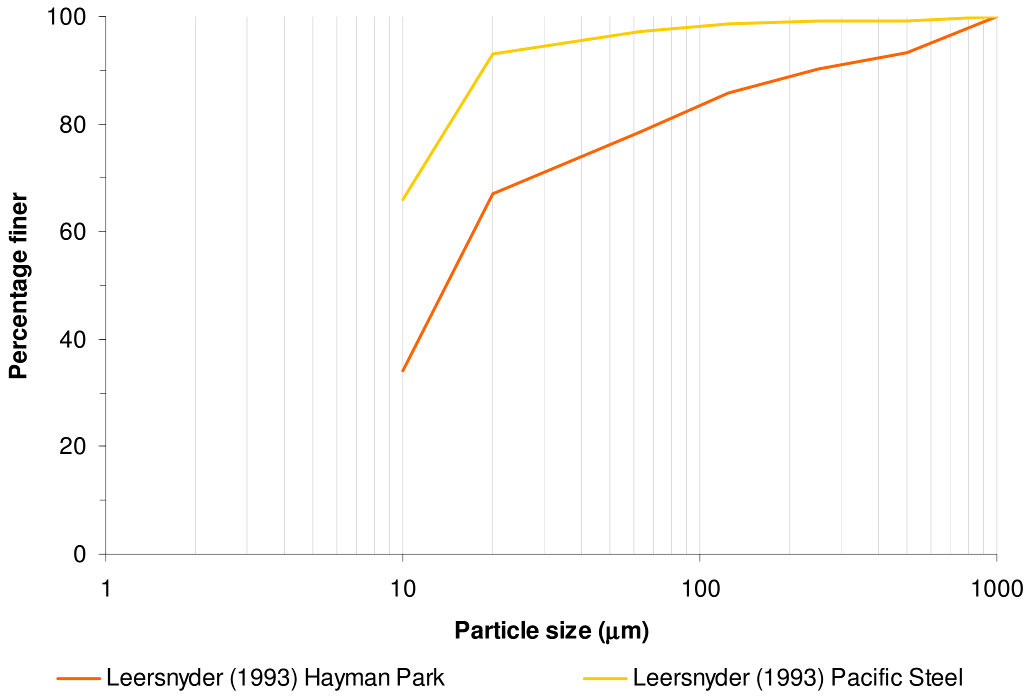
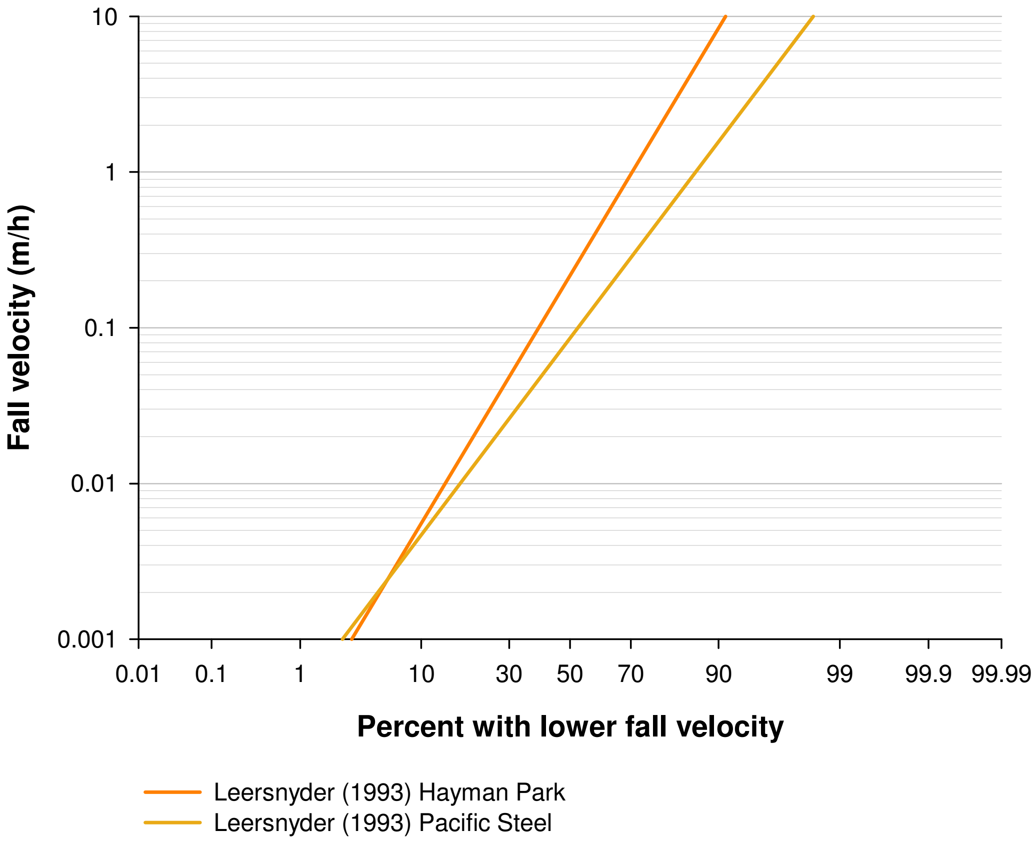


Figure 13
Probability distribution of fall velocities for according to Leersnyder (1993) for Hayman Park (Manukau – commercial) and Pacific Steel (Otahuhu – industrial) stormwater samples.



3.3.3 NIWA research for Auckland stormwater (2004)

3.3.3.1 PSD

NIWA has collected extensive data on sediment sizes as part of stormwater monitoring programme commissioned by Metrowater and Auckland City (discussed here with permission from Metrowater: Reed and Timperley, 2004; Timperley *et al.,* 2004 a and b; summarised in Griffiths and Timperley, 2005). The data has been compiled from dozens of samples for between seven and 15 events per site (Table 7). The average distributions for samples collected from eight of the sites are given in Figure 14a and b. With the exception of samples from Oakley Creek, samples were taken from the reticulated stormwater network, which, in the case of Cox's Bay was a combined network. Automatic samplers were used, thus the samples were subject to the potential bias towards fines discussed above (though the samplers post date the 1993 threshold). It must be added that the catchments are all in Auckland City, other areas are likely to have different sediment sizes and characteristics due to differences in local geology. North Shore City, which has clayey soils, has finer sediments, while sediments from the volcanic soils in south Auckland (Manukau, Papakura, Franklin) are likely to be more coarse. It should be noted that as catchments become more impervious, the contribution of wash-on from soils will be less. This would mean that the sediment properties for highly urbanised catchments would be more likely to reflect land use rather than soil type.

Particle sizes for the sediments in Auckland stormwater was determined at NIWA Hamilton using a Galai WCIS-100 particle size analyser. 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. As expected, repeat analyses of the same samples gave similar results.

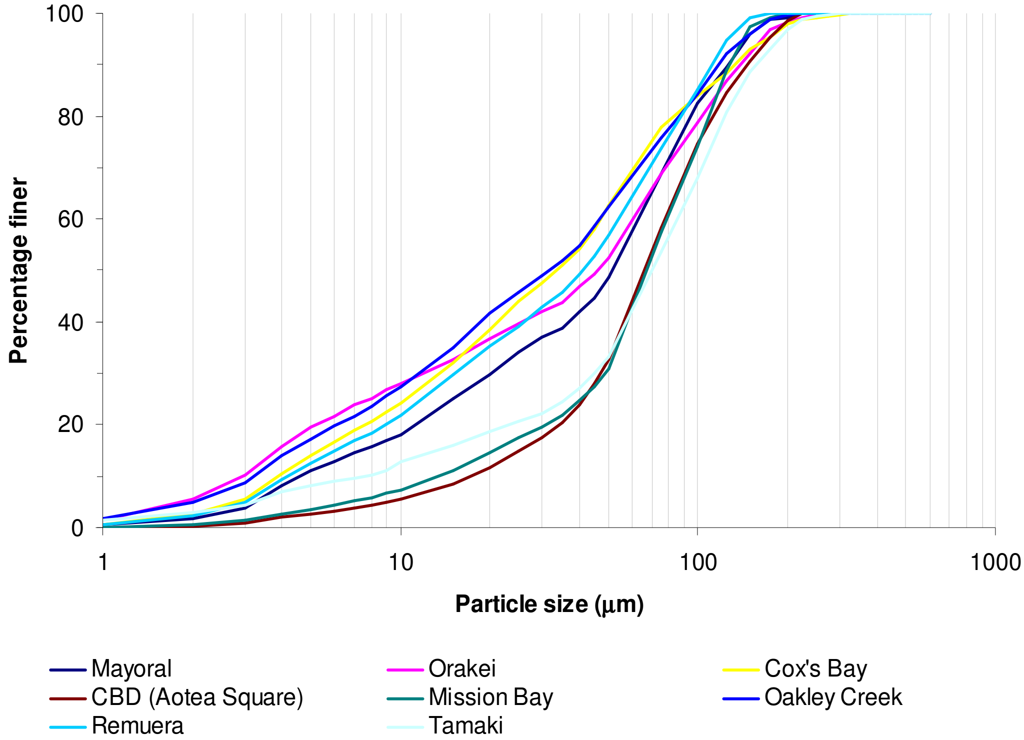
Table 7
Sample summary for Auckland catchments analysed for stormwater particle sizes by NIWA.

	CBD	**Mission Bay**	**Orakei**	**Mayoral**	**Tamaki**	**Cox's Bay**	**Remuera**	**Oakley Creek**
Land use	Mixed	Mixed	Residential	Commercial	Industrial	Mixed	Residential	Mixed
Number of events	15	15	14	16	16	9	7	8
Number of samples	160	153	164	134	134	143	95	182

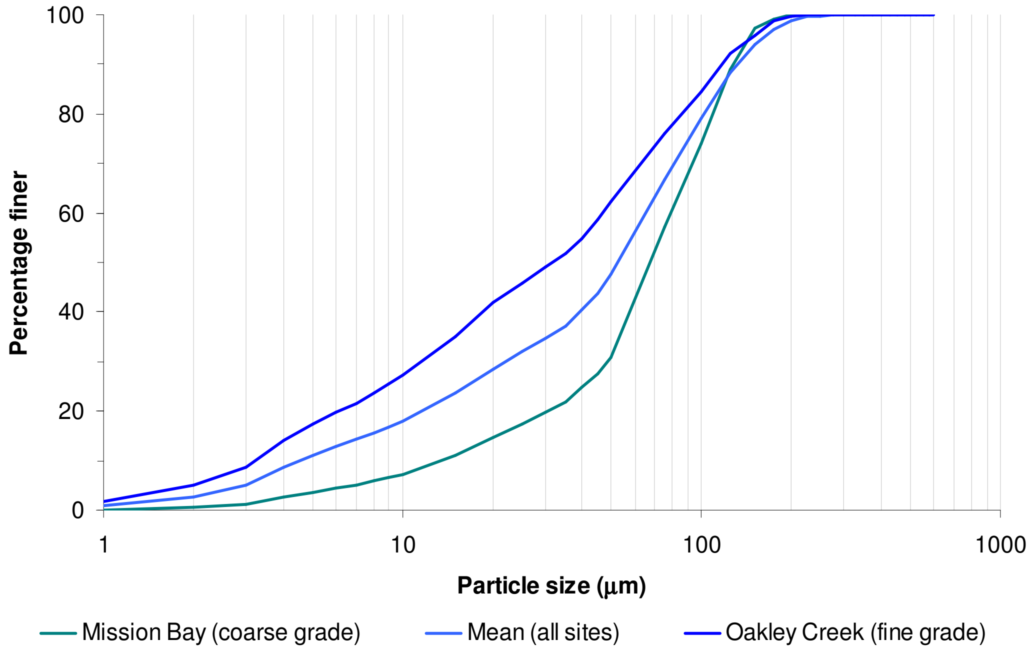
Figure 14

PSDs for Auckland City: a. selected sites; b. coarse, mean and fine grade PSDs (NIWA research).

a. Selected sites.



b. Coarse, medium (mean average) and fine sediments.



There is a considerable range of particle size distributions for different events at each site and between sites. There seems to be two 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 per cent (by volume) of the particles were less than 50 µm compared with 65 per cent in Oakley Creek water. Similarly only 10 per cent was less than 20 µm at the stormwater sites compared with 40 per cent in Oakley Creek.

Suspended sediment in the Auckland City stormwater system (after catch pits) is generally less than 300 µm in size. The results obtained by the ARWB (1991, cited in Humes, 2006) for Pakuranga are close to the mean PSD in Figure 14b for particles between 20-100 µm though there is a higher proportion of coarse sediments in Pakuranga and particles can be greater than 1 mm in size. The difference is most likely due to local geology. The mean PSD in Figure 14b is skewed towards fine particles (32 per cent of particles are smaller than 25 µm), but there are also a sizable proportion of sediments, 31 per cent, in the range 50-100 µm (ie, fine sands). Unfortunately, the Pakuranga PSD does not go below 20 µm, so a comparison of fines is not possible.

3.3.3.2 Settling column experiments

In a variation of the pipet method described in Section 3.2.2.2, the change in sediment concentration can be analysed to determine the fall velocity as was demonstrated in a report prepared by NIWA for the ARC (Semadeni-Davies *et al.,* 2008). The NIWA study used a variation of the McLaughlin (1959) method of estimating the change in the mean or apparent fall velocity (V_a, see Section 3.1.3.1) over time of a fine-particle suspension by measuring time-series of suspended solid concentration (SSC) profiles. The general principle underpinning this work is that temporal changes in the time-averaged vertical SSC profile result from particle settling. By measuring: (1) the rate of change in the suspended mass (by integration of the concentration depth profile); and (2) the SSC at fixed depths, the apparent fall velocity for the suspension can be determined at any depth in the water column for any point of time. McLaughlin (1959) obtained these data by simultaneously collecting water samples at several depths of a suspension quiescently settling in a settling column. The NIWA method instead used optical backscatter sensors (OBS) set at four levels in the column to increase the amount of concentration data collected in the expectation of improving the estimation of fall velocity. Sub-samples were also taken at the same level throughout the experiment for calibration of the OBS sensors and to determine the PSD (using the Galai sensor). However, as the relationship between OBS measurements and SCC is dependant on the PSD, which changed over time due to settling, calibration of the OBS was problematic.

Three settling column experiments carried out in 2005 were analysed using stream bed sediment samples collected with stormwater, two replicates using sediments from highly urbanised Oakley Creek (OK1 and OK2) and one using sediments from the largely rural Mangemangeroa Stream ME2. The settling column was purpose-built and was 2-m high with a 20-cm diameter. The sensors were placed at depths of 10 cm, 25 cm, 65 cm) and 1.35 m with respect to the initial water level. The OBS were controlled using DASY-LAB software to take readings at 5 Hz for 115 s every 120 s (first four hours) then subsequently for 115 s every 300 s. Water samples were extracted after 4, 8, 16 and 32 minutes and 1, 2, 4, 6, 12, 25, 45 and 69 hours, the OK1 replicate also had samples taken after 30 hours.

The main conclusions of the report were:

- Reliable estimates of fall velocity were obtained for the OK1 and OK2 samples. Fall velocities could not be determined for the ME2 sample using the OBS results.
- Use of the OBS data did not achieve the expected improvements in fall velocity estimates for a mixture of sediment sizes because the relationship between the OBS signal and SSC changed as larger sediments settled out. The fall velocities calculated using the sampled SSC are more reliable despite the fact that there are less data available for the analysis.
- The method works best during the early stages of settling when the mass of sediment in the water column above each sensor decreases rapidly. Later in the settling experiments, after eight to 12 hours, mass changes slowly.
- The PSDs determined by the Galai scanner conformed to expectations. At the upper levels of the column, the PSD decreased monotonically as larger sediments settled out. At the lower levels, PSD initially increased as larger sediment from above settled into the zone. Thereafter PSD decreased due to settling. The PSD data obtained with the Galai sensor showed that after 12 hours, there was also little difference in median and mean grain size for the different depths in the column and the grain size remained stable over time.
- Taking the above two points together, the columns had fairly homogenous sediment sizes and concentration after 12 hours. As a result it became increasingly difficult to accurately estimate the rate of change of mass over time as required by the McLaughlin method. Hence, fall velocities equivalent to very fine sediments (<2.5 μm) could not be estimated after a certain cutoff time (between eight and 25 hours).
- The settling column experiments are representative of ideal quiescent settling and the results imply that it is unlikely these facilities will be able to remove sediments remaining in detained stormwater after 12 hours, indeed, the 24-hour design detention time required by TP 10 (ARC, 2003) may not be adequate for settling of fines.

3.3.4 Zanders (2005)

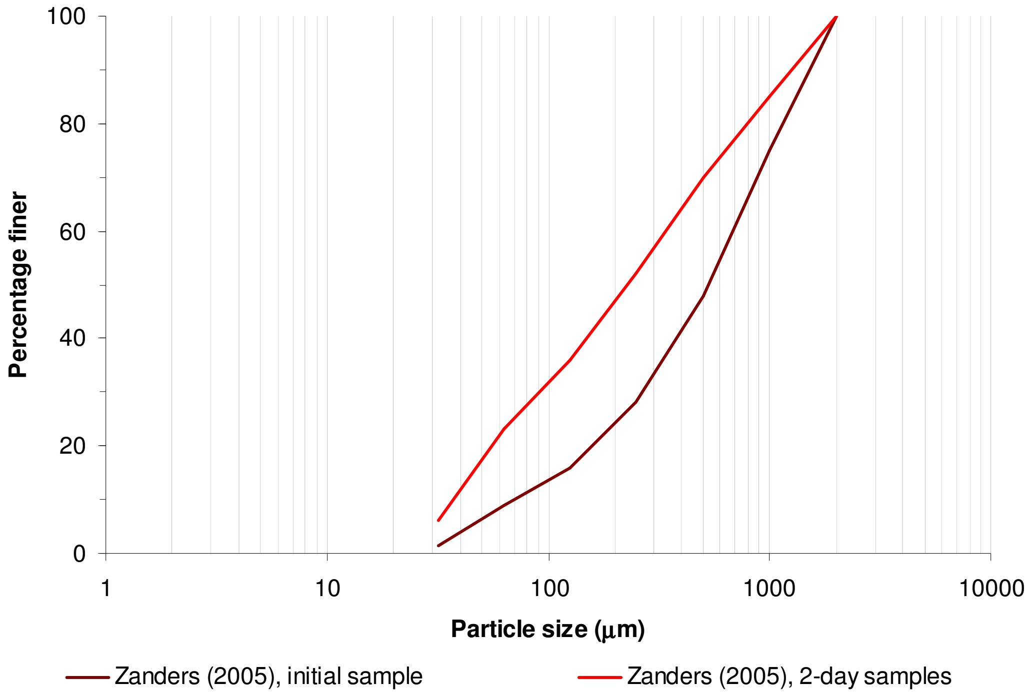
Zanders (2005) is one of the few internationally-published studies of urban sediment data from New Zealand. She investigated particles vacuumed from a length of gutter running next to a major intersection in Hamilton (Cobham Dr/Normandy Ave; 25000 vehicles per day). The site is subject to monthly street sweeping. Samples were taken at two-day intervals over a two-week dry period. The focus was on street dirt (ie, sediments available for transport) rather than suspended sediments in stormwater and the objective to assess the potential for pollutant removal using road-side vegetated strips. That is, the ability of vegetation to trap sediments.

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; 1000; 500; 250; 125; 63; 32 μm respectively). The density was generally less than 2200 kg/m^3. The two-day samples were found to contain predominantly fine particles (52 per cent as <250 μm), however, the sediments were comparatively large compared with studies of particles in stormwater – this is most likely to be an artefact of the sampling method.

Zanders (2005) notes that the initial sample had a greater proportion of large particles and fewer fines, this is not surprising as the potential for particles to be entrained by run-off is dependant on both particle mass and rainfall intensity. The upper size limit of particles that can be suspended in stormwater is around 500 μm with larger particles carried as bed load (Lloyd and Wong, 1999). Moreover, smaller, lighter particles are more likely to be removed by wind. Hence, over time, gutter sediments will be enriched with coarse particles while fines will be blown away or re-suspended and transported to the stormwater system. The initial sample is thus an indicator of the sediment pool available to run-off. The PSDs for the mean of the two-day samples and the initial sample are given in Figure 15. Fall velocities were not determined.

Figure 15

Particle size distribution according to Zanders (2005) for street dirt from a gutter in Hamilton sampled every second day over a two-week period.

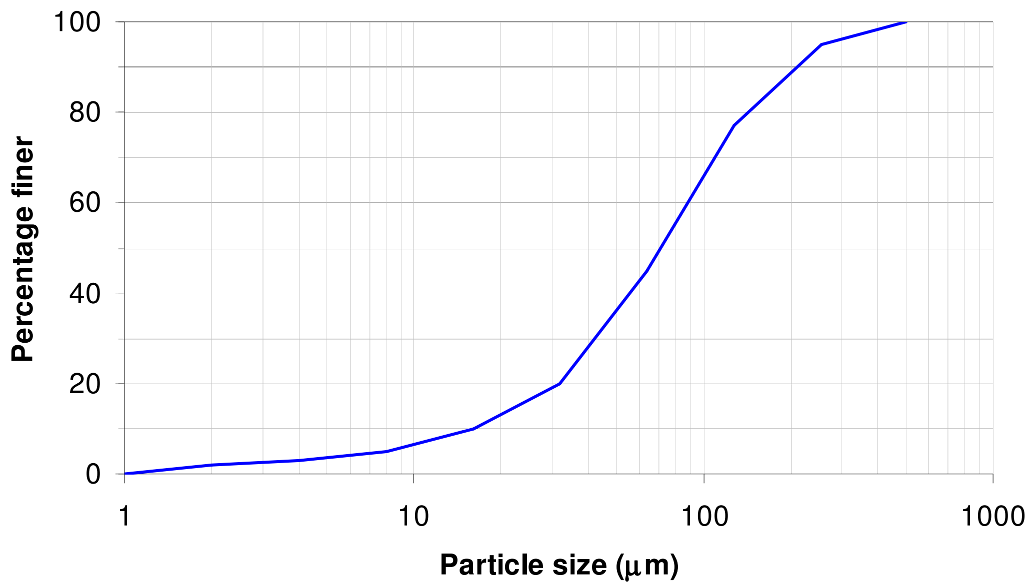


3.3.5 Cooperative Research Centre for Catchment Hydrology (2005)

The Humes (2006) presentation refers to a number of studies carried out by the Cooperative Research Centre for Catchment Hydrology (CRCCH) in Australia, the results of which have been used to guide parameter selection for the k-C* first order decay routine for sediment and pollutant removal in the MUSIC model (CRCCH, 2005).

The PSD used in MUSIC (Figure 16) has 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 run-off 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 per cent impervious, approximately 100 x 15 m in size and is not subject to street sweeping. Grab samples of run-off 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).

Figure 16
Particle size distribution used in the MUSIC model (CRCCH, 2005).



The proportion of suspended solids with a particle size less than 118 μm varied between 74 and 100 per cent. 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, 1998) 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 found that particles in stormwater run-off from roads and highways in Australia were relatively finely graded.

Under the assumption that smaller particles are likely to have a lower density (eg, abraded tyre sediments compared to mineral sands), the MUSIC model has adopted a variable particle density according to the findings of Lawrence and Breen (1998) in order to calculate fall velocities. They recommend a density range from 1100 kg/m^3 at 2 µm to 2600 kg/m^3 at 500 µm be used when determining fall velocity (Figure 17) from particle size. Note that water temperature is not given in the MUSIC documentation, but back calculation with Stokes' Law suggests 20°C. There is also a reference curve assuming a constant density of 2680 kg/m^3 (ie, quartz). The probability distribution of fall velocities derived from the PSD is given in Figure 18.

Figure 17

Effect of variable density on fall velocities after CRCCH (2005) and Lawrence and Breen (1998). A reference curve where particle density = 2680 kg/m^3 is given for comparison.

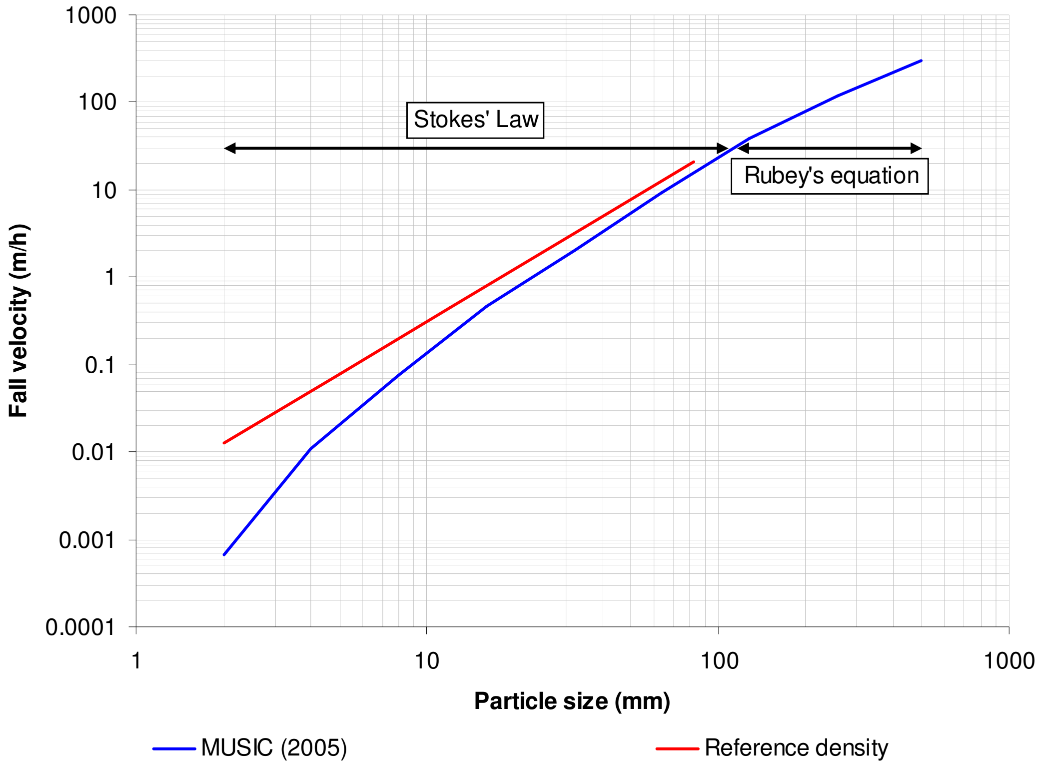
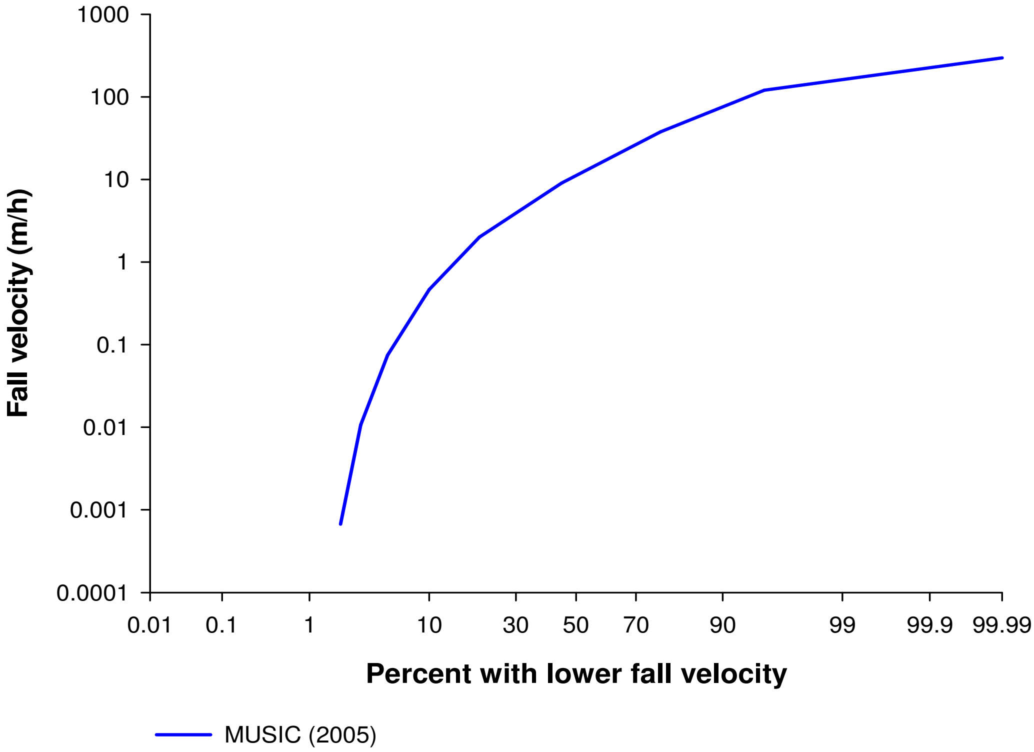


Figure 18

Probability distribution of fall velocities after CRCCH (2005).



3.4 Heavy metal contamination

The quality of stormwater is generally related to the chemistry of urban sediments. The density and the size distribution of particles affect the transport of the solids and associated pollutants (Characklis and Wiesner, 1997). Larger particles in stormwater tend to settle out, whereas smaller particles remain suspended in stormwater run-off and travel greater distances. In addition, smaller particles have a greater SSA, allowing more adsorption of dissolved constituents onto the surface of the particles and therefore a greater contaminant content per unit mass. Thus, terms of water treatment, knowing the contaminant content per mass sediment is the key to relating sediment removal to contaminant removal. The discussion below focuses on the relationship between metals and sediments.

3.4.1 Partitioning

Metals in stormwater are partitioned between dissolved and particulate phases. The particulate phase comprises metals attached to settleable solids, that is, sediments larger than around 0.45 µm. In the general case, Johansson *et al.* (2001) reviewed a number of studies which model the particulate fraction of various dissolved substances found in lakes according to statistical relationships between partitioning ratios and water chemistry and sediment variables such as pH and organic content.

For practical purposes, the ratio of particulate to dissolved concentrations with respect to the sediment concentration can be used to derive a partition coefficient K such that:

$$K = \frac{C_p / SCC}{C_d} \qquad \textbf{Equation 9}$$

where SSC is the suspended solid concentration, C_d is the dissolved concentration and C_p is the particulate concentration. Physically, K represents the chemical equilibrium of numerous processes such as sorption onto particulate matter, precipitation and dissolution. K is not constant and varies with the factors given above.

Sansalone *et al.* (1995) investigated the hypothesis that heavy metal concentrations are significantly correlated to suspended solids in highway run-off. This suggests that metals in stormwater and highway run-off have an affinity to sediments present and are usually found in the particulate form. Run-off data from eight highway sites in the United States and Europe were analyzed to test this hypothesis. Results indicate a strong positive correlation between heavy metals and suspended solids. The partitioning of metals into particulate and dissolved forms is influenced by pavement residence time, the pH of rainwater, the physical characteristics of the sediments and the solubility of the metals.

Timperley *et al.* (2004 c) discuss the processes involved in metal partitioning for Zn. This metal is a problem for Auckland due to the prevalence of galvanized roofs which means that the Zn is often found in its dissolved form. Between rainfall events chemical reactions occur in the Zn on the roof surface. These reactions involve water, atmospheric gases (mainly carbon dioxide, sulphur dioxide and nitric oxides), chloride from sea salt, and Zn. These gases dissolve in the water to produce a range of acids which then react with the Zn to produce salts including zinc carbonate, zinc chloride, zinc nitrate and zinc sulphate. The zinc salts accumulate on the roof surface so that when it rains, the salts dissolve into the rainwater and wash off the roof. The dissolution is quite fast leading to a first-flush in roof run-off. Generally, Zn in roof run-off is in the dissolved state. The main source of particulate Zn in stormwater is vehicle tyre rubber. This contains about 0.7 per cent of Zn as zinc oxide. Tyre wear leaves deposits of fine rubber particles containing this Zn on the road surface. In exactly the same way as described above for Zn metal on roofs, this zinc oxide reacts with atmospheric gases and moisture to produce Zn salts on the road surface. However, these reactions may not go to completion before the next rainfall event. Thus, when it rains the Zn is present in the run-off in dissolved forms as well as in the tyre particles.

Wind-blown dust, mostly mineral particles from soil, is always present on roads and additional mineral particles are generated by abrasion of the road surface. The soil particles and to a lesser extent the particles of road gravel, are coated with iron and manganese oxides. Iron and manganese oxides are efficient sponges for dissolved metals although the rates at which dissolved metals adsorb to these coats are not particularly fast. However, it is fast enough so that by the time stormwater has passed through the catch pits into the stormwater network, quite a lot of the dissolved metals have adsorbed onto the mineral particles. Of the three main metal contaminants in stormwater, the strength of the adsorption is Pb > Cu > Zn, although the difference between lead and copper is small (*ibid*).

Characklis and Weisner (1997), found the concentration of particulate Zn increased with organic carbon in stormwater sediments sampled for four catchments in Houston, Texas. Lin (2003) found that Cr, Cu, Zn, As, Cd and Pb in urban rainfall-run-off are primarily in particulate form, but As and Cd also have a strong affinity with the dissolved fraction. Dempsey *et al.* (1993) found that the pH of stormwater was a major consideration for metal mobility and that there is desorption of metals originally bound to particles in suspension over time. The rate of desorption is strongly related to pH with higher concentrations of dissolved metals occurring with decreasing (acidic) pH. However, if the pH remains above 7 (neutral – alkaline) particulate metals are fairly stable and can be treated in stormwater devices which remove sediments.

Sansalone *et al.* (1996) and Sansalone and Buchberger (1997) too found that metal mobility increases in acidic stormwater. They looked at the partitioning of metals and solids generated by traffic by collecting lateral pavement sheet flow from a 300 m area of Interstate 75, Cincinnati during five rainfall run-off events in 1995. They found that metals partition into dissolved and particulate-bound fractions as a function of pH, pavement residence time, and solids concentration. Results indicate that Zn, Cd and Cu are mainly in dissolved form while Pb, Fe and Al are mainly particulate. The dissolved metals exhibit a strong first flush pattern; the fraction of dissolved metals increased with decreasing rainfall, pH and increasing average pavement residence time.

3.4.2 Fractionation

The international literature is divided as to whether the fine or coarse particle fractions have the greatest metal load. The controversy about fractionation centres on sediment sampling methods and the relationship between sediment size, specific surface area (SSA) and total surface area (SA). More recent granulometry-based research has called for collection of coarser settleable solids, which can make up a sizable proportion of the total sediment load, as well as suspended and colloidal solids in stormwater. This is the stance taken to the ARC by Humes (2006). They also show that the theoretical relationship between the SSA of spheres with different diameters may not reflect the true SSA of stormwater particles with irregular shapes and textures and internal pores.

The following discussion illustrates the concern over equating bonding to the SSA rather than the SA for a particle size class. Assuming a spherical shape; sediments with a diameter of 1 μm will have a surface area of around 3 μm^2 per particle but a SSA of 25,000 $\mu m^2/g$ compared to sediments with a diameter of 10 μm (314 μm^2 per particle or 2500 $\mu m^2/g$). Thus, the smaller the particles, the greater the potential for metals to bond to them. However, fractionation also depends on the PSD which describes the proportion of the total mass of sediments in each size class. The PSD therefore also determines the SA for each particle size class. The metal load for a particle size class is the product of the particulate metal content and the sediment mass held in that size fraction. Therefore, similar particulate metal loads can result from high metal content and moderate sediment mass, and moderate metal content and high sediment mass. A large proportion of coarse sediments could mean that the highest metal loads are associated with sands rather than silts and clays despite the greater SSA and metal content per unit mass of fines.

Characklis and Wiesner (1997) found that particles with a diameter below 2.5 µm did not account for a large portion of the total mass; but the high SSA meant that the SA was enough to give particles in this size range a greater metal load relative to the other size fractions. This result is typical of stormwater sediment studies based on samples made with automatic water samplers or grab samples. To illustrate, Ding *et al.* (1999) collated data from a number of studies of suspended sediments collected with stormwater sampling (Table 8) and found that fractionation changes depending on the metal and that the highest metal loads are generally associated with finer particle sizes.

Table 8
Metal distribution vs. particle size (collated from literature by Ding *et al*, 1999).

Particle size (µm)	Metal distribution (%)							
	Cd	Co	Cr	Cu	Mn	Ni	Pb	Zn
<10	46	60	71	63	71	63	73	60
10 - 100	36	31	24	30	21	29	23	35
>100	18	9	5	7	8	8	4	5

In Australia, Lloyd and Wong (1999) analysed stormwater quality from water samples taken from a busy Melbourne street during two flow events (see sampling details given in Section 3.3.5). The relationship between metal content and sediment size was illustrated by comparing literature values of Zn fractionation from Australia, and the USA and Europe (

Table 9). They conclude that even though the Zn content is highest for the smallest size fraction, the pollutant load is well distributed across the particle size range for the USA and Europe. However, in Australia, where the sediments are more finely graded, the greatest Zn loads are associated with the particles less than 40 µm. They postulate that for Australian urban catchments, sedimentation basins should be up to four times larger than those found in Europe or the USA to achieve the same removal of particulate Zn.

Also in Australia, Walker and Hurl (2002) investigated removal efficiencies for particulate metals in wetlands. They used sediment traps placed in a wetland basin along the inlet to outlet flow path to determine the transport and deposition of particulate metals (Zn, Cu, Pb, Cr and As) through the wetland. They found that Zn, Pb and Cu particulate concentrations decreased by 57, 71 and 48 per cent respectively between the first and last sediment traps, though Cr remained constant and As increased. The differential removal is explained by the fractionation of each metal (and therefore fall velocities of the associated particles) and their chemical behaviour particularly with respect to the organic matter in the wetland.

Table 9
The mass of Zn related to the size distribution of particles (collated by Lloyd and Wong, 1999).

Particle size fraction and mean Zn concentration	Australia		USA and Europe	
	% of solids in fraction	Zn mass (mg)	% of solids in fraction	Zn mass (mg)
<40 µm ~ 900 mg/kg	40	360	10	135
40-250 µm ~ 300 mg/kg	50	150	50	150
>250 µm ~ 450 mg/kg	10	45	40	180

In contrast, Lin (2003) cites several studies which conclude that the relationship between metal content and sediment size fraction is at best weak. NIWA has found this for particulate metals in Auckland stormwater (see Section 3.4.3). Dempsey *et al.* (1993) found high Cu, Pb and Zn concentrations for sediments with a particle diameter between 74 µm and 250 µm. Particles less than 74 µm had a lower metal content, they found this result surprising and speculated that the result may be an artefact of the analysis.

Sansalone *et al.* (1998) presented a granulometry-based analysis where the total spectrum of particles in stormwater were collected. They found higher contaminant loads associated with coarse sediments largely due to the greater proportion of these sediments with respect to fines leading to a greater SA for bonding. Their findings are discussed with respect in more detail in Section 3.5.1. Lin (2003) found a similar relationship. He used a combination of sampling methods to trap all sediments carried in stormwater for two sites over a eight storm events (see Section 3.5.4).

3.4.3 Metal partitioning and fractionation in Auckland

NIWA has carried out a number of programmes in recent years which look at the sources, transport and toxicity of metals in Auckland stormwater. For instance, metal partitioning and fractionation has been discussed by Timperley *et al.* (2004 c) for Auckland City. Detailed analysis of metal partitioning was made for stormwater sampled from the reticulated network serving Richardson Rd. Dissolved Zn was 51 per cent of the total Zn load. The dissolved Cu load was 75 per cent of the total copper load. Dissolved lead concentrations in natural waters are usually very low and this was also the case for stormwater. The load of dissolved Pb was only 2 per cent of the total lead load. With respect to the particulate fractionation, they start by exploring the theoretical relationship between sediment size, SSA and metal adsorption. The relationship of metal content and particle size was then tested using bed sediment samples from different catchments around the city with rather surprising results:

- There seems to be only a weak relationship between sediment size and Zn content at source, however, the form of this relationship changes as the sediment moves through the urban stormwater system from streams to estuaries. Data are presented from catchments throughout the city, however, many of the sediments were separated into only two size classes (<63 µm and 63-500 µm).
- With respect to samples taken down the length of Oakley Creek, the proportion of particulate Zn seems to drop initially near the headwaters and then rise again

down-stream. The drop could be due to a combination of settling and resolution while the subsequent rise may indicate that dissolved metals have re-adsorbed to the suspended particles. However, not enough data is cited to draw any real conclusions.

The metal fractionation of bed sediments collected by NIWA from Oakley Creek in 2004 (discussed with respect to settling columns in Section 3.3.3.2) have been analysed for the ARC by Semadeni-Davies *et al.* (2008). Like the findings above, the analysis suggested only a weak relationship between metal content and sediment size at the site near the head waters. Lead has a slightly greater affinity to larger particles than copper or zinc which had greater proportions associated with fines. The implication of a weak relationship between metal content and grain size at this site for contaminant removal at the site is that particulate heavy metals will have similar removal properties as sediment.

Bibby and Webster-Brown (2005) compared the concentration and partitioning of Cu, Zn, Mn, Fe and Pb in urban and rural streams in the Auckland region. Sediments from the different catchments were characterised by their size and physical properties into four groups: fine inorganic grains which make up a sediment matrix (<2 μm); angular crystals set in the matrix (1-20 μm), agglomerates (1-50 μm) and diatoms or other organic materials (5-50 μm). The type of sediment found in the different catchments was related to catchment size and geology rather than land use. Little difference was observed between the ability of the non-urban Waikato and Kaipara River sediments and urban catchment sediments to adsorb trace metals. However, the trace metal concentrations in the water column of the non-urban streams were significantly lower than in urban streams irrespective of flow or sediment class. Furthermore, they found no clear relationship between Zn, Cu and Pb particulate content of the sediments and the sediment concentration which they suggest indicates that the metal content of the sediment is related to land use. Within the urbanised catchments, the ratio of dissolved to particulate metal concentrations varied between sites. For instance, the East Tamaki site, which has higher (more alkaline) pH compared to other sites, had higher binding rates and therefore particulate metal contents.

In a further study, Bibbey and Webster-Brown (2006) demonstrated the complexity of physically-based modelling of portioning. They used simulation as a tool to understanding binding of trace metals in Auckland urban streams compared to rural catchments in the region (Bibbey and Webster-Brown, 2005, cited above). The model estimated the relative proportions of dissolved, adsorbed and precipitated phases of Zn, Cu and Pb. Under the simplifying assumption that Fe-oxide in the partlcle was the only adsorbing surface they showed good agreement between observed and modelled adsorption for Pb, indicating the importance of Fe-oxide surfaces for Pb adsorption. However, the model did not predict Zn or Cu adsorption as well. The total organic carbon content of the sediment and presence of dissolved ligands and organic matter in the water column appeared to play an important role in Cu adsorption. For Zn, the presence of adsorbing surfaces other than Fe appeared to influence adsorption. They also found that pH has a great influence on binding. On the basis of earlier work (Bibbey and Webster-Brown, 2005, cited above), they postulated that changes inflow rate which change the composition of urban sediments could also change the partitioning of metals. Similarly, seasonal changes in pH and organic content could be a factor in partitioning.

3.5 Granulometry

Granulometry is the characterisation of sediments in terms of particle properties and proportion of weight of particles of different sizes. Granulometry thus represents collective information for urban particles, this can include PSD, metal partitioning and fractionation, fractal nature of particle size and shape, morphology, chemical composition, and settling characteristics (for both primary particles and flocs). In recent years, granulometry has been used to finger-print particles in stormwater; the work by John Sansalone and his colleagues is heavily cited by Humes (2006). Lin (2003), who completed his doctorate under the supervision of Sansalone, states that the partitioning, transport and transformation of particulate-bound contaminants are determined by their granulometry, that is the physical and geochemical properties of particulate carriers. Lin (2003) further states that previous research emphasized in the transport of colloidal and suspended particles in urban rainfall-run-off from an environmental perspective, while the settleable materials transported by urban rainfall-run-off were ignored. However, these sediments may be a major granulometric fraction which may contain most of the sorbed or transported constituents such as heavy metals, organics or inorganics.

Granulometric studies of urban sediments therefore differ from the others presented above in that the entire spectrum of sediment sizes is included in the analysis and other considerations apart from PSD and fall velocity are taken into account. Sediments are not only collected from stormwater (ie, suspended and colloidal particles), but also from gutters, catch pits and grit chambers.

3.5.1 Sansalone *et al.* (1998)

Sansalone *et al.* (1998) looked at sediments from the same section of interstate in Cincinnati as Sansalone *et al.* (1996) and Sansalone and Buchberger (1997) cited above (Section 3.4). The study had three main objectives:

1. to characterise the mass delivery of sediments during the first-flush;
2. to determine the PSD and 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 the SA.

Lateral flow from the road was sampled during 13 separate storms in 1995-97. Samples collected over the course of each storm were analyzed for PSD and the event mean concentrations of suspended solids (TSS and total dissolved solids, TDS). Particles greater than 25 μm were sieved while those finer were counted and sized using a light obscuration particle counter. SSA was determined using the EGME method which is fully described in the paper.

Storm events were divided into low and high run-off volume events. In the former, TDS and TSS were released continuously over the course of the storm, presumably because of large vehicle to run-off volume ratios. In the latter, TDS and TSS were released primarily at the beginning of the hydrograph. The authors refer to these two different cases as "mass limited" and "flow limited" events. The effect of antecedent dry period was also noted.

The PSDs were similar across storm events. Perhaps the most interesting results were for the analysis of SSA as a function of particle size. The SSA are 1000 times larger than what would be estimated if the particles were spheres which has great implications for contaminant bonding. The authors state that the difference between the SSA calculated for spheres of equivalent diameter and determined for the particles can be explained by the presence of folds, pores, notches, pits and roughness – all of which are visible when particles are viewed under a microscope.

Although SSA does, as would be expected, increase with decreasing particle diameter and particles in the size range 2 to 8 µm had the greatest count, coarse, readily settleable particles in the 425 to 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 and 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.

3.5.2 Andral *et al.* (1999)

Andral *et al.* (1999) analyzed 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 catchment area for drinking water. 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 run-off were collected with a water sampler, settled and filtered. The first method was used to reveal the particle size of solid matter carried in run-off and the second to calculate the load of TSS in run-off during the rainfall event.

Both TSS and settled sediments were analyzed for PSD, density and mineral content; TSS was also analysed for heavy metals (Cd, Cr, Cu, Ni, Pb and Zn). The results from this study with respect to particle density were discussed in Section 3.1.2.1. PSD was determined using dry sieving and filtering for coarse particles above 50 µm in diameter and using a laser counter for fine particles. The fall velocity was found using a settling column (pipet procedure) for the coarse sediments and calculated with Stokes' Law for the fines.

For the fraction of the sediment below 100 µm in size, the PSDs and fall velocity distributions for the settled and suspended particles were remarkably similar. However, 90 per cent by weight of the sediment accumulated in the collecting basin had diameters larger than 100 µm. They state that these coarse sediments are easily settled and are not carried as suspended solids in run-off. In contrast to the settled sediments, 75 per cent by weight and volume of the suspended sediments in the run-off had a diameter less than 50 µm. For particles less than 50 µm in diameter, 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. The slow fall velocities for smaller particles as a result of density is likely to further hinder the removal of contaminants by settling.

Andral *et al.* (1999) state that the collecting basin acts like a decanter, removing particles greater than 100 µm. However, the majority of heavy metals are in the size range less than 100 µm and are present in the suspended sediments (Table 10). Thus, it was concluded that to effectively treat run-off, suspended particles smaller than 50 µm in diameter (which represented approximately three-quarters of the particulates analyzed, by weight) must be captured. The fall velocities of the particulates smaller than 50 µm ranged from 2.5 to 3.3 m/h with an average of 2.98 m/h, while the larger particles between 50 to 100 µm in diameter had fall velocities ranging from 5.7 to 13 m/h with an average of 9.8 m/h.

Table 10
Proportion of total metal mass contained per particle size fraction (Andral *et al*, 1999).

Metal	< 100 µm (%)	100-1000 µm (%)
Zn	96	4
Pb	90.2	9.8
Cu	98.4	1.6
Cr	91.6	8.4
Ni	94.5	5.5
Cd	100	0

3.5.3 Cristina *et al.* (2002)

Cristina *et al.* (2002) presented a granulometric-based analyses 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 run-off 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. They developed a fractionation model using previous experimental data which indicated that heavy metal mass is associated with these coarse particles. They state that sedimentation could remove 90 per cent of particles, by mass, within two hours for a typical roadway drainage design. It was found that particle density varies with particle size; 2860 kg/m^3 for coarse particles and 2750 kg/m^3 for fine. Albeit slight, the different densities were shown to have an impact on fall velocities.

3.5.4 Lin (2003)

Lin (2003) found much the same relationship between SSA, SA and particle size as Sansalone *et al*. (1998) and Sansalone and Tribouillard (1999). For equilibrium partitioning, particulate-bound heavy metal mass distributions have been strongly correlated to SA distributions and not to the distribution of SSA across the PSD. This finding is potentially at odds with other studies that link high contaminant loads with fine particulates – though the difference could be due to sampling methods which are biased towards the collection of fines. The implication is that devices for water treatment should be designed to preferentially remove particles with the greatest SA rather than SSA – in this case, coarse particles.

Lin's doctoral thesis (2003) contains a comprehensive review of granulometric methods including relevant literature and case studies. His work presents information on sampling and analytical methodologies and modelling of processes such as C/F and settling. Readers who are interested in granulometry are urged to read this document which is available as a PDF file on internet (address listed in reference section).

4 Review Summary

This literature review has been carried out for the ARC as an aid to evaluated the particle size distribution (PSD) and fall velocities used by the ARC for stormwater treatment design criteria. The values presented here could be used to test the design criteria for settling devices such as ponds and wetlands. The review has concentrated on the most recent and relevant research surrounding settling theory (including particle properties and concentration), sediment sampling and analytical techniques. The review also presents case studies for stormwater sediments and associated contaminant loads.

The criticisms outlined in the Humes (2006) presentation given to the ARC are well researched and well founded. Humes (2006) cites a good selection of the most recent research in the field, and has captured the mood of the latest thinking. Like Humes (2006), the over-arching message of this literature review is that the PSD and settling behaviour of particles and the partitioning and fractionation of contaminants found in stormwater show a wide range of values both spatially and temporally. Sediment loads and PSD, for instance, not only vary with land use, geology and topography but with accumulation times (ie, antecedent dry period) and rainfall dynamics. Even within a single event, load and PSD is likely to change between the first flush (hydrograph rising limb), peak flows and recession. Thus, the timing of sampling is crucial in order to gain a full picture of sediment and contaminant loads and transport. Moreover, the partitioning and fractionation of contaminants in stormwater is also heterogeneous and is related to land use (ie, source), sediment type and water chemistry.

This report concurs with Humes (2006) that there is a concern in the literature that data collected by different organizations may not be comparable due to differences in sampling programmes, analytical techniques and reporting of results. As such, there are implications for comparing the various studies of sediment sizes and settling behaviour. Zanders (2005) typifies this concern by sampling street dirt with a vacuum cleaner in order to provide data for improving the design of vegetated strips for treating road run-off. Other studies with similar objectives have focussed on the collection of suspended sediments in stormwater. Both sampling approaches have scientific precedents and are defensible despite their very different findings.

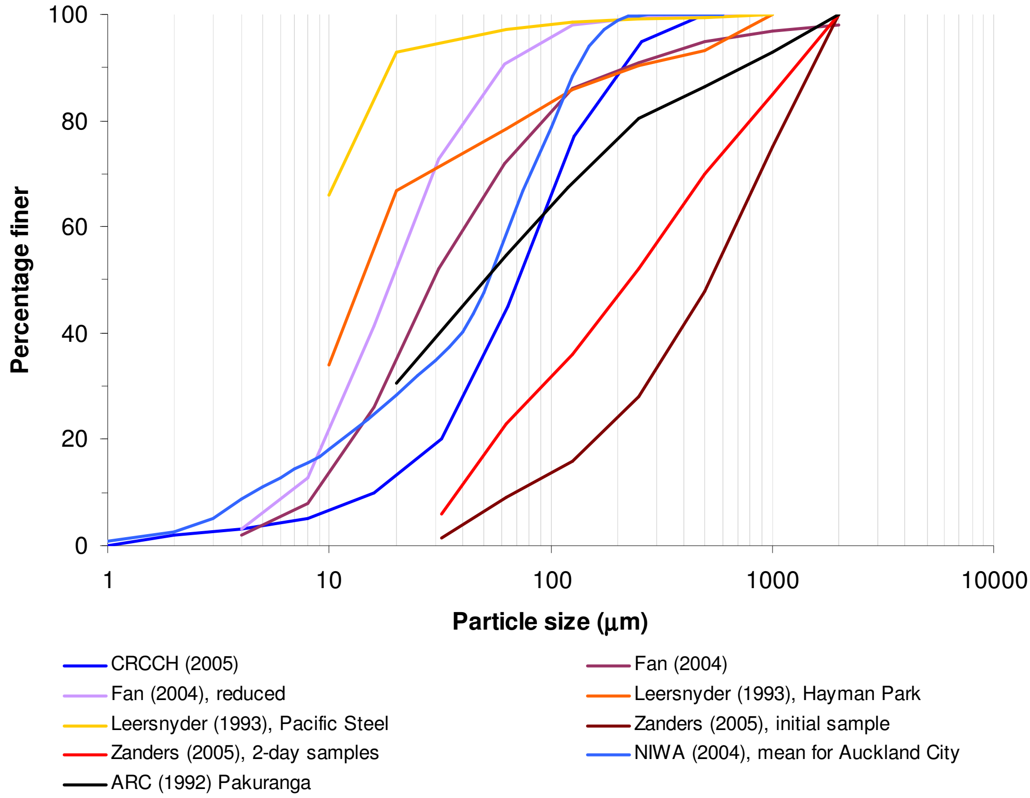
The concern over sampling methods can be illustrated by comparing more traditional stormwater studies where water samples have been taken either as grab-samples or using an automatic water sampler and granulometric studies which have more advanced sampling programmes. The former have found that the PSD is skewed towards fines while the latter tend to pick up more coarse sediments outside the range generally included in suspended sediments. Supporters of granulometric studies point out that stormwater treatment devices which rely on sedimentation can have coarse bottom sediments not found in stormwater samples of suspended sediments mid-stream – yet these sediments must be transported in the stormwater network to recipients through mechanisms such as saltation. Moreover, where metal fractionation has been carried out, the former have found that the finest particles (ie, greatest SSA) have the highest metal contents and loads, while the latter state that the greatest metal loads may be associated with coarser sediments despite lower metal content (ie, greatest SA). The granulometric studies are more holistic in their approach, not only in their sampling, but also in analyses that are carried out. These studies typically present PSD along with particle properties related to particle size (eg, shape, density, fractal nature, presence of flocs) and contaminant partitioning and fractionation. However, there are few examples of such in depth studies in the literature and none could be found for local stormwater sediments.

Both natural and chemically initiated coagulation and flocculation processes were covered in the review. It was found that in a stormwater system without the addition of coagulant aids, fine particles can form flocs if they are agitated, but these are easily broken up during turbulent flow. The size of flocs differs seasonally with larger flocs associated with warmer weather and increased biological activity. In comparison with chemically initiated flocs, these natural flocs can have low densities, particularly as floc size increases. This means that large flocs tend to remain in suspension rather than settling out during quiescent flow conditions in stormwater detention facilities. This result is counter-intuitive to those readers who are more used to C/F as a means of treating drinking and wastewater. The addition of coagulant aids to stormwater was shown to be effective for water treatment as these flocs do settle, however, the delivery of the chemicals can be problematic.

Figure 19 to Figure 21 give a summary of the PSDs and fall velocities presented in the review. There is a wide range of sediment sizes, even within the Auckland studies (Figure 19) with NIWA research for Metrowater and the Auckland City Council (Reed and Timperley, 2004; Timperley *et al.,* 2004 a and b) suggesting coarser sediment grades than Leersnyder (1993) but finer sediments than for Pakuranga (ARC, 1992). However, it should be noted that the NIWA curve is a composite and both coarser and finer gradations were found for different catchments in Auckland City. The PSDs found by Leersnyder (1993) are closer to the fine grade samples taken by NIWA for sites far from the stormwater and sediment source. That is, NIWA found that the PSD became finer as sediments were transported through the urban stream network towards the receiving environment. It was suggested that coarser sediment settle leaving fines to be transported downstream. It is worth pointing out again that the ARWB (1991) found a bimodal PSD for Pakuranga with peaks at 10 and 125 μm, but that it was assumed in TP 4 that the coarser particles would not reach treatment facilities.

The fall velocities by particle size show more agreement, at least for coarse particles (Figure 20). Only those studies where sediment size and fall velocities were presented together are plotted in the figure. Note that Fan (2004) and MUSIC (CRCCH, 2005) calculate fall velocities from particle size but the ARC (TP 4, 1992) values are the other way round where particle size was back calculated from fall velocities determined from column experiments. These fall velocities have themselves been summarised into five bands from the results of the NURP findings from the US EPA (Driscoll *et al*, 1986). The effect of varying density with particle size can clearly be seen for the MUSIC (CRCCH, 2005) curve whereas both the other calculated curves (Fan 2004) assume a constant density.

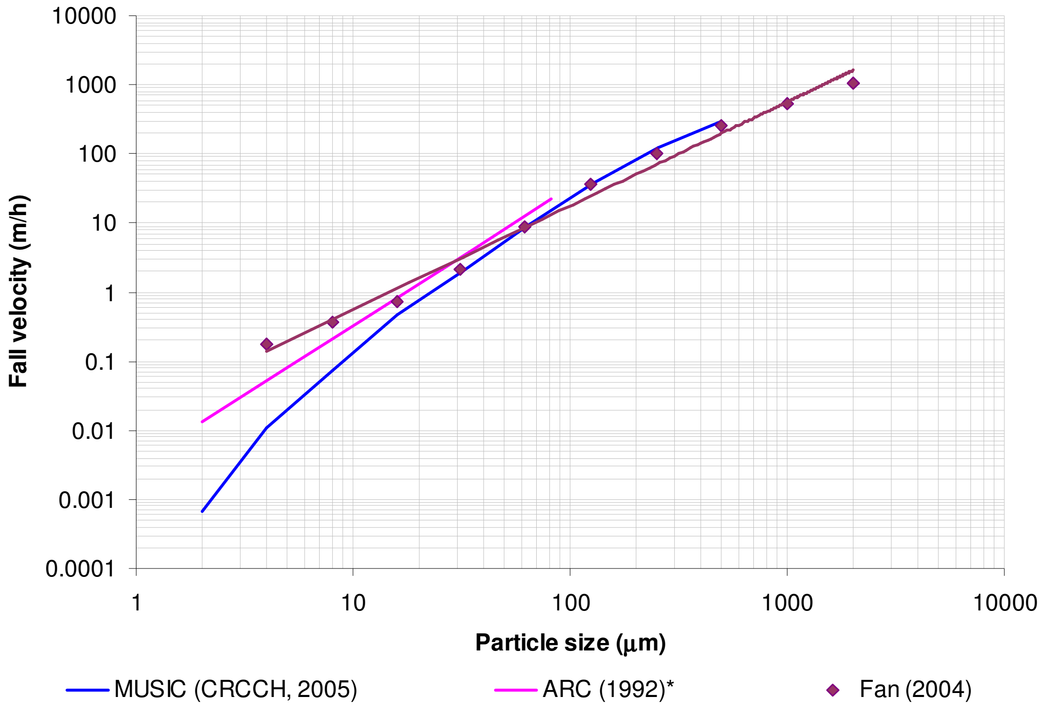
Figure 19
Pooled particle size distributions from studies cited in this review.



The probability distribution of fall velocities (Figure 21) is of more importance for simulating sedimentation than the PSD. While there is broad agreement between Driscoll *et al.* (1986), Pakuranga (ARC, 1992) and Leersnyder (1993), the other curves (Fan, 2004; CRCCH, 2005) suggest that there is a greater distribution of fall velocities found in stormwater. It is interesting to note that there is agreement between the curves from Hayman Park (Leersnyder, 1993) and Pakuranga (ARC, 1992) despite the difference in PSD. The spread between studies is related to both the PSD and particle physical properties such as shape, roundness, diameter, concentration, presence of flocs and, most notably, density. There is evidence in the literature that coarse sediments have higher densities compared to fines due to the make up of these sediments (ie, quartz vs. organics). However, sediment density is site specific and, where provided, varies greatly in the literature.

The review found that the number of studies in the literature where fall velocities had been determined analytically (column experiments) is more or less equal to those which calculate fall velocities from the PSD. It should be noted that the two techniques are not strictly comparable and that each has its advantages and disadvantages. Column experiments are time consuming and subject to observational errors while calculation requires either detailed examination of sediment properties (shape, roundness, diameter, density, concentration, presence of flocs) or assumptions about those properties. Generally, it is assumed that particles are spherical with a fixed density (following sedimentology conventions, normally quartz at 2650 kg/m^3). Up to a Reynolds number of one (ie, laminar flow) the fall velocity can be determined with Stokes' Law and thereafter by Newton's or Rubey's equations. There are also more sophisticated equations available that take shape, roundness and the presence of flocs into account. Where there is a choice, column experiments are more reliable than calculation as fall velocity can be determined directly without the need to first determine particle properties.

Figure 20
Pooled fall velocity against particle size for studies cited in this review.

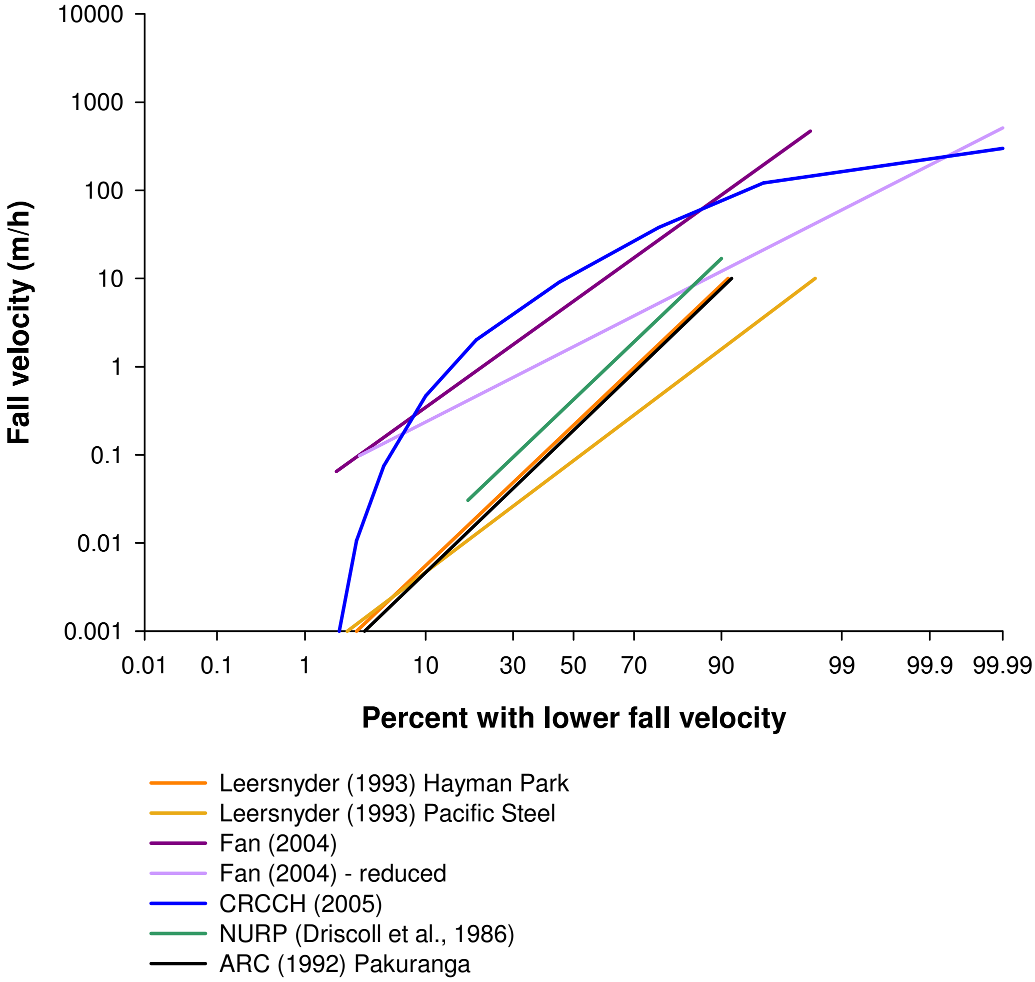


* Back calculated from Driscoll *et al.* (1986).

The partitioning and fractionation of metals was found to vary between both events and sites and is related to the metal source, accumulation time between events, particle concentration and PSD and rainfall intensity. Metal mobility (ie, dissolved fraction) was found to increase with stormwater acidity (ie, lowered pH). The common understanding is that the greater surface area by mass of smaller particles results in more surface sites bonding and therefore greater particulate metal contents. This intuitive relationship has been demonstrated by many researchers and is typical of suspended sediments sampled before the mid-1990s either with automatic water samplers or grab-samples. However, more recent granulometric studies of stormwater sediments including settleable solids have shown that metals can also be associated with coarse sediment classes and that the total surface area of a sediment class is more important than the specific surface area. It has also been found that coarse particles and flocs can have high internal which increases the surface area available for metal adsorption. The debate about fractionation is ongoing with champions of granulometric studies stating that earlier studies may have been flawed by sampling and analytical techniques which were biased towards small sediments.

Figure 21

Pooled probability distribution of fall velocities for studies cited in this review.



5 Recommended Fall Velocity Distribution

The literature review above has shown that sediment size distributions and fall velocities vary greatly from site-to-site and storm-to-storm. Given the uncertainty surrounding sediment sizes transported with stormwater, fall velocities and contaminant fractionation, particularly with regard to sampling and analysis, the concerns raised by Humes (2006) are understandable. They recommend that the existing PSD and fall velocities currently used by the ARC (TP 4, 1992) be replaced by the fall velocities determined for Pakuranga (ARWB, 1991; ARC, TP 4, 1992) which are similar but locally derived. Humes (2006) also suggested that the use of five 20 per cent settling bands be dropped in favour of the original setting rate probability distribution which has a greater number of percentage bands and therefore a better representation of coarse sediments. This is considered sound thinking as the NURP bands date from a time when computing power was limited (ie, Driscoll *et al.*, 1986). Humes (2006) states that while all the distributions they examined from the literature (many of which are also presented here) are acceptable and scientifically defensible; the use of data from Pakuranga is preferred as it is local and has ARC quality assurance. The closeness of the settling behaviour to both Driscoll *et al.* (1986) and Leersnyder (1993) is added as further support. However, it is worrying that Leersnyder's test catchments are also from South Auckland and that so few events have been sampled and analysed for the Auckland region. Moreover, the Pacific Steel site is atypical of urban conditions. This means that there could be some regional bias in the data as well as other biases associated with data collection and analysis.

A comparison of the Pakuranga measured fall velocities against fall velocities calculated using the mean PSD from the Auckland City data collected by NIWA (Reed and Timperley, 2004; Timperley *et al.,* 2004 a and b) is given in Figure 22 and Table 11. The fall velocities were derived using Stokes' Law (Equation 1) and Weber (1972: Equation 3) for laminar and transitional flow respectively. Water temperature was set to 20°C. Three sets of calculations are presented, each relating to different density assumptions: variable density (from 1100 to 2680 kg/m^3) adapted from values suggested for the MUSIC model (CRCCH, 2005) and constant density relating to high (2650 kg/m^3) and low densities (1100 kg/m^3; eg, Butler *et al.*, 1996; Sansalone and Tribouillard, 1999) found for stormwater sediments in the literature. The high-density is equivalent to quartz while the low-density is more typical of organic particles such as abraded tyres and leaf litter. Without details on particle concentration, shape or roundness, the calculations assume single spherical particles. The curve in Figure 22 for the lower constant density is similar to the curves given by Driscoll *et al.* (1986), Pakuranga (ARC, 1992 b) and Leersnyder (1993), but the higher density curve is closer to those given by CRCCH (2005) and Fan (2004). These results demonstrate just how important it is to have correct density measurements for determining fall velocity from PSD.

Figure 22

Fall velocities calculated (assuming spherical particles in water at 20°C) from the mean NIWA (Reed and Timperley, 2004; Timperley *et al.,* 2004 a and b) PSD for Auckland City compared to fall velocities in Pakuranga (ARC, 1992) and Fan (2004).

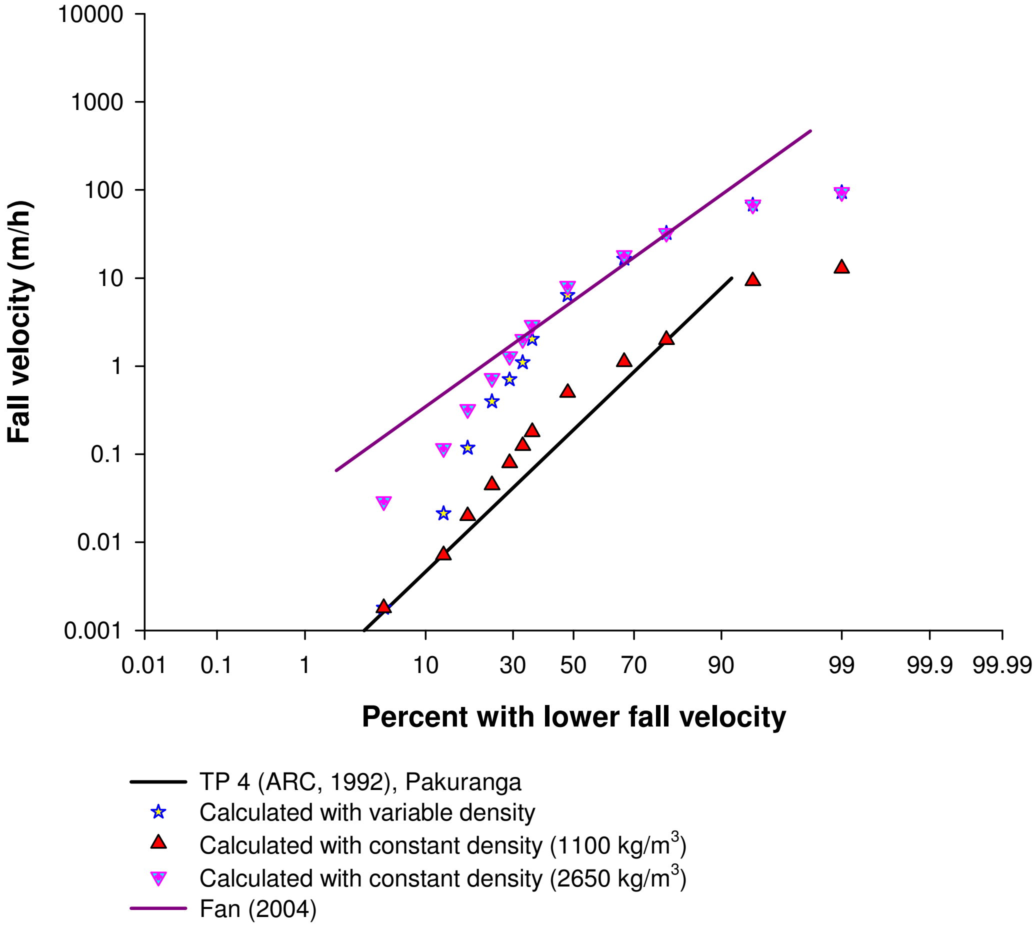


Table 11
Alternate PSD and fall velocities for Auckland based on NIWA stormwater samples (calculated assuming spherical particles in water at 20°C).

Particle size distribution			Calculated fall velocities					
Particle diameter (µm)	Proportion of particles (%)	Cumulative proportion finer (%)	Variable particle density (kg/m³)	Settling velocity (m/h)	Low particle density (kg/m³)	Settling velocity (m/h)	High particle density (kg/m³)	Settling velocity (m/h)
3	5	5	1100	0.002	1100	0.002	2650	0.029
6	8	13	1300	0.021	1100	0.007	2650	0.116
10	5	18	1600	0.118	1100	0.020	2650	0.323
15	6	24	1900	0.397	1100	0.045	2650	0.727
20	5	29	1900	0.706	1100	0.080	2650	1.292
25	4	33	1900	1.102	1100	0.124	2650	2.019
30	3	36	2150	2.028	1100	0.179	2650	2.908
50	12	48	2300	6.366	1100	0.498	2650	8.078
75	19	67	2500	16.524	1100	1.120	2650	18.174
100	12	79	2650	32.310	1100	1.991	2650	32.310
150	15	94	2650	67.732	1100	9.260	2650	67.732
200	5	99	2650	94.086	1100	12.863	2650	94.086
300	1	100	2650	149.517	1100	20.441	2650	149.517

The sediments in Pakuranga are somewhat coarser than the NIWA average so the fall velocities for Auckland City should theoretically be slower. Samples were taken from eight Auckland catchments over a number of rainfall events. Hence the mean PSD is arguably more representative of the Auckland as a whole than the PSD for Pakuranga. This has implications for the use of fall velocities from Pakuranga for design criteria across the region. However, a caveat must be added that the NIWA data cover only Auckland City and that other areas in the region could have different sediment sizes and characteristics.

Although the NIWA measured PSDs are arguably more representative of Auckland catchments and show that there could be coarser sediments than previously thought, presumably with more rapid fall velocities, the wide spread of PSDs between and within catchments and the unknown relationship between sediment size and density lead to uncertainty in settling calculations. There is a 10-fold discrepancy between the Pakuranga column test fall velocities and those calculated from the mean Auckland PSD with a high-density, but the differences are less when low-density is used in the calculation. It would thus be foolish to change fall velocities used by the ARC to calculated values bearing in mind these uncertainties, at least without also determining other sediment properties..

There are three alternatives open to the ARC regarding fall velocities for design:

1. The status quo – retain the five NURP settling bands derived in the USA from a number of settling column experiments carried out in the early 1980s. The advantage of this choice is that NURP is internationally recognised and the ARC will not need to revise their design criteria. The disadvantage is that NURP is not locally determined and has a possible bias towards fines due to sampling and analytical methods.

2. Pakuranga fall velocities – the Pakuranga data is local and is similar to the curves derived by Leersnyder (1993). Fall velocities were determined directly from column experiments. There are more than five bands and the PSD is more realistic than NURP in its representation of coarse sediments. However, given the similarity between Pakuranga and NURP, the effect on design criteria for sediment ponds and wetlands of adopting these fall velocities would be minimal. Indeed, the NURP data was chosen in the first case due to the similarity between the fall velocity distributions. The disadvantage is that the Pakuranga data come from a single catchment and only two storm events. Moreover, the sampling and analytical methods were possibly biased towards fines.

3. Sediment fall velocity determination by representative catchment across the Auckland region – this is the preferred option given the criticisms set out in the literature review. It is also the most expensive option. A new comprehensive sediment sampling campaign could take into account possible biases in sediment sampling and analysis. Further sampling should cover a range of catchment land uses and locations to give a representative picture of fall velocities Auckland wide. Metal partitioning and fractionation could be part of the study. As a starting point, a recent analysis of apparent settling velocities derived from settling column

experiments has been carried out by NIWA for the ARC (Semadeni-Davies *et al.*, 2008) using bed sediments collected from the Mangemangeroa Stream and Oakley Creek. Sediment concentrations and PSD were determined for sub-samples made throughout the experiments. The method tested was unable to determine the fall velocity beyond 8 to 12 hours of settling in the columns. This detention time equates to particles less than 2.5 μm, about 4 per cent of the initial sediment samples for both sites. Bearing in mind that settling columns represent ideal quiescent settling conditions, it would be unlikely that settling facilities designed according to TP 10 to have 24-hour extended detention would be able to remove particles less than 4 μm in diameter. At this stage, fall velocity distributions for the sediment samples have not been determined.

6 Acknowledgments

I would like to thank Peter Stahre of the Malmö Municipal Water and Waste Water Works, Sweden, and Juri Marsalek of Environment Canada, Burlington, Ontario for access to their data and personal comments.

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8 Appendix 1: Glossary

Term	Definition
Accumulation rate	Rate at which sediments and contaminants accumulate on surfaces such that they are available for wash-off during a flow event.
Adsorption	The take up of a gas or dissolved substance on the surface of a solid.
Aggregate	Assemblage of particles in a cohesive mass.
ASTM	American Society for Testing and Materials.
Apparent fall velocity	Average fall velocity for a group of particles which is a function of the PSD and the sediment concentration.
ARC	Auckland Regional Council.
ARWB	Auckland Regional Water Board.
Automatic water sampler	Device used to collect water samples via a suction tube. Sampling is generally set by time or flow volume. Samplers can be fitted with a carousel for collecting descrete samples over the course of an event.
Brownian motion	Small random movements of colloidal particles in the fluid medium due to fluctuations of surrounding medium molecules.
Catch pit	Inlet to the reticulated stormwater network which has a a sump for pre-settling.
Cationic ions	Positively charged ions.
Charge neutralization	Method of coagulation whereby a substance with the opposite charge (positive) to the colloid (negative) is added allowing the particles to combine.
Chemical oxygen demand (COD)	Measure of the amount of potassium dichromate needed to oxidise reducing material in water. An indicator of the amount of organic compounds in water.
Clay	Particles in the size range 1-3.9 μm.
Coagulant	Chemical additive used destabilise colloidal particles so that they aggregate into co-hesive particles.
Coagulation	Process where colloids are able to aggregate into cohesive particles.

Term		Definition
Coagulant aid		Collective term for coagulants and flocculants. Used to initiate flocculation colloidal particles into cohesive particles and larger settleable particles.
Cohesive particles		Clay and silt particles less than 2 ratio of absolute or dynamic viscosity to density m in diameter which can clump together due to electro-static forces.
Colloids		Evenly dispersed particles in a liquid that do not settle, <1 μm in diameter.
Combined sewer overflow	(CSO)	Overflow from combined sanitary sewers of untreated waste and stormwater following heavy rainfalls.
Computational fluid dynamics	(CFD)	Model of fluid mechanics that uses numerical methods and algorithms to solve problems that involve fluid flows.
Concentration		Mass by unit volume, more correctly called the mass concentration.
Content		Mass by unit mass concentration – in this report – refers to the mass of particulate contaminant per unit mass of particle.
Continuous-flow stirred tank reactor	(CSTR)	Conceptual model of dynamic settling in a detention basin.
Cooperative Research Centre for Catchment Hydrology	(CRCCH)	Developers of the MUSIC model.
Detention basins		Facilities such as wet ponds and wetlands which detain water for slow release or storage following flow events. Settling of suspended solids can occur during detention.
Differential settling		Mechanism for floc development whereby particles with different fall velocities collide.
Dissolved solids		Substances contained in a liquid which are present in a molecular, ionized or colloidal form.
Double layer compression		Method of coagulation whereby a electrolyte/salt (neutral charge) is added such that the repulsive energy barrier in the medium about the colloid is reduced allowing the particles to combine.
Dynamic flow		The period of flow event at a detention basin when there is through-flow.
Dynamic viscosity		Tangential force per unit area required to

Term	Definition
	move one horizontal plane with respect to the other at unit velocity when maintained a unit distance apart by the fluid.
EGME method	Method of determining the SSA of a sediment sample. EGME (HOCH2CH2OCH2CH3), a polar liquid, is added to a known weight of dried sediment sample. After application of the EGME, the sample is desiccated and weighed. The weight gain by the sample is a measure of the amount of adsorption of the EGME which, assuming a monolayer coverage of the EGME, indicates the surface area available for bonding.
Fractal	Self-similarity at different scales.
Fall diameter	Diameter of a sphere that has a density equivalent to quartz sand and has the same terminal fall velocity as the given particle in quiescent distilled water at a temperature of 24 °C.
Fall velocity	The rate at which a particle settlings in a still viscous fluid. Also known as the free settling velocity or terminal velocity.
First flush	First section of the rising limb of the stormwater hydrograph which coincides with the highest contaminant concentration (ie, due to wash-off) in the pollutograph
Flocculant	Chemical additive used to facilitate flocculation.
Floc	Loose network of cohesive particles forming a settleable mass.
Floculation	Formation of flocs from cohesive particles.
Fluid shear	Shear stress due to the movement of fluid over a surfaces or between fluid layers. Associated with orthokinetic flocculation.
Fraction	The proportion of the total particulate load with respect to the particle size class.
Galai particle size analyser	Laser sensor with imaging software used by NIWA to determine PSD.
Granulometry	Characterisation of sediments in terms of particle properties including PSD, metal partitioning and fractionation, fractal nature of particle size and shape, morphology,

Term		Definition
		chemical composition, and settling characteristics.
Isokinetic sampling		Sampling with an automatic water sampler whereby the sampler intake points directly into the flowing water and the suction velocity in the intake is the same as the flowing water.
Jar tests		Method of comparing the effectiveness of adding different coagulant aids or doses to waste or stormwater.
Kinematic viscosity		Ratio of dynamic viscosity to fluid density $\mu/\rho_{f.}$
Laminar conditions		Fluid flow around the falling particle whereby adjacent layers or lamina of the fluid do not mix. Associated with sediments <100 μm. Reynolds number, Re < 1.
Ligand		An atom, ion, or molecule that donates or shares one or more of its elections to bonds to a central atom or ion allowing the formation of complexes.
Model for Urban Stormwater Improvement Conceptualisation	(MUSIC)	Stormwater drainage and treatment model developed in Australia by the CRCCH.
Nationwide Urban Run-off Program	(NURP)	Programme dating from the early 1980s set up by the US EPA to characterise stormwater quality and treatment in the US.
Nominal diameter		Equivalent diameter of a sphere with the same volume as the particle.
Non-cohesive particles		Particles greater than 62 μm which do not form aggregates in suspension.
Optical backscatter sensor	(OBS)	Instrument which detects light scattering and attenuation from suspended particles in order to measure sediment concentration and turbidity in water samples.. Also known as a scatterometer.
Orthokinetic (fluid shear) flocculation		Refers to flocculation caused by movement (ie, gradients in the fluid flow velocity) in the fluid medium which cause particles to collide.
Particle size distribution	(PSD)	Proportional break-down of the size range of particles found in a sediment sample
Particulate		Associated with particules, used in this report to refer to the proportion of

Term	Definition
	contaminants which are bound to stormwater sediments.
Partitioning	Separation of stormwater contaminants into dissolved (ie, in solution) and particulate (bound to particles) proportions.
Pipet method	Standard method of determining particles fall velocity. Sub-samples of water with an initially known concentration of sediment is withdrawn from a settling tube at set depths and time intervals. The change in sediment concentration of with depth and over time is indicative of the fall velocity of the sediment particles.
Polycyclic aromatic hydrocarbons (PAH)	Fused aromatic rings which occur in oil, coal, and tar deposits and are produced as by-products of fuel burning.
Porosity	The fraction of void spaces (v/v) of a material.
Quiescent flow	Intervening period at a detention facility between flow events where there is no though flow.
Rain garden	Type of bio-filtration device for flow attenuation and water treatment.
Residence time	Period of time that stormwater (and contaminants including sediments) is detained within a treatment facility.
Reynolds number Re	Dimensionless number used to describe the flow conditions of a fluid around a falling particle.
Roundness	Curvature variation of a particle surface, ie, measure of smoothness.
Saltation	Bouncing movement of particles which are alternately lifted and deposited along a flow pathway.
Sand	Particles in the size range 125-2000 μm.
Sedimentation	Process of particle settling due to gravity in a fluid medium.
Sedimentation diameter	the diameter of a sphere that has the same density and fall velocity as the given particle in the same fluid under the same conditions.
Settling column	Large tube, usually plexi-glass, used to determine settling behaviour of suspended sediments in a fluid medium.

Term	Definition
Shape	Measure of particle "shape" with respect to the ratio between particle width, height and breadth, ranging from 0 for a plane to 1 for a sphere.
Shear stress	Parallel stress on a plane.
Sieve diameter	Length of the side of the smallest square opening through which the given particle will pass – this is equivalent to the sieve mesh (or filter).
Specific Surface Area (SSA)	Particle surface area per unit mass.
Steady state	Dynamic equilibrium, for flow, this means that inflow at a point equals outflow.
Stokes' Law	Equation for determining the fall velocity of a single, spherical particle in a viscous fluid.
Stokes' radius	Equivalent to the sedimentation radius (ie, half the sedimentation diameter).
Suspended sediment	Particles in a fluid that are supported by the turbulent motion of the fluid. In stormwater, the particles range from clays to very fine sands: 1 – 125 μm.
Suspended solid concentration (SSC)	Concentration of suspended sediments in a water sample, determination differs subtly from TSS in US EPA and ASTM standards which may cause some variation between the two measures.
Swales	Shallow channel, usually vegetated, for detention and infiltration of stormwater.
Total dissolved solids (TDS)	Proportion of solids in a water sample not retained by a filter. The filtrate is dried and weighed. Colloidal size range (<1 μm).
Total suspended solids	Settleable solids suspended in water. clays to very fine sands: 1 – 125 μm.
Transitional conditions (TSS)	Mixture of laminar and turbulent flow around the falling particle. Reynolds number, $1 < Re < 1000$.
Turbulent conditions	Flow stream of fluid around the particle is disrupted by vortices, eddies and wakes making flow path unpredictable. Reynolds number, $1000 < Re$.
Udden-Wentworth scale	Classification of particles by grain size.
US EPA	United States Environmental Protection Agency.

Term	Definition
Viscosity	Fluid resistance to shear or flowof a fluid.
Volumetric Concentration	Volume by unit volume concentration.

9 Appendix 2: Nomenclature

a	Longest axis of a particle (length)	m
b	Intermediate axis of a particle (breadth)	m
c	Shortest axis of a particle (width)	m
C_s	Volumetric concentration of particles	m^3/m^3
C_d	Concentration of dissolved contaminants	kg/m^3
C_p	Concentration of particulate contaminants	kg/m^3
D_*	Dimensionless grain size	-
g	Acceleration due to gravity	m/s^2
K	Co-efficient which describes the ratio of particulate to dissolved contaminants	-
p	Particle weight	kg
r	Stokes radius of a spherical particle	m
Re	Reynolds number	-
SF	Shape factor	-
SSC	Suspended solid concentration	kg/m^3
V_a	Apparent fall velocity of a group of sediments	m/s
V_f	Fluid velocity	m/s
V_s	Fall velocity	m/s
$\beta\beta$	Coefficient for the calculation of apparent fall velocity	-
μ	Fluid dynamic viscosity	Pa.s
$\nu\nu$	Kinematic viscosity (ie, μ/ρ)	m^2/s
$\rho\rho_f$	Fluid density	kg/m^3
$\rho\rho_s$	Particle density	kg/m^3