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Particle size and settling velocity distributions for the design of stormwater treatment devices in the Auckland region

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Particle size and settling velocity distributions for the design of stormwater treatment devices in the Auckland region

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1 Executive Summary

The design of engineered devices based on particle settling and/or filtration for the effective removal of suspended solids and attached chemical contaminants from stormwater requires a clear understanding of the physical characteristics of the suspended solids. These physical characteristics can be described by the particle size distribution (PSD) for filtration devices and settling velocity distribution (SVD) for settling devices. These distributions are also essential for calculating the removal efficiencies of treatment devices for suspended solids.

The PSD of a stormwater sample describes the range of suspended solids particle sizes present usually as a number of discrete size ranges or bands and the proportions of particles (by number), particle area or particle volume present within each of these bands. The SVD describes the proportions of particles (by number), particle area or particle volume that have settling velocities within each of several velocity bands.

This report uses particle data from several studies undertaken within the Auckland region to derive design PSD and corresponding SVD for the suspended solids in urban networks, urban streams and construction site runoff.

The designs PSD are the medians of the PSD determined for suspended solids in the Auckland region. The urban network samples were collected at eight network sites as part of the Auckland City stormwater monitoring programme between 2001 and 2003. The urban stream samples were collected from two urban streams in Auckland City during the same monitoring programme. The construction site samples were collected at the inlets to five sediment retention ponds during 2007 and 2009 at two different catchments Nukumea and Silverdale North.

Urban network and stream samples were collected by automatic samplers interfaced to either stage or discharge loggers using either time-based or flow proportional sampling. Between 7 and 16 events were sampled at each site and between 65 and 185 samples for each site were analysed for PSD. The samples were analysed for PSD using a Galai WCIS-100 particle size analyser, a "time of flight" instrument.

Construction site samples were collected by automatics samplers at the inlets and outlets of the retention ponds. Samples were collected for seven rainfall events in the Nukumea catchment and three rainfall events in the Silverdale North catchment. The Nukumea pond samples were analysed by Galai WCIS-100 particle size analyser and the Silverdale North pond samples were analysed by Mastersizer 2000 particle size analyser.

The design PSD are summarised in Table 1.

Table 1

Design particle size distributions

	Particle size (µm)		
% Finer	Construction site	Urban streams	Urban networks
10	-	4	14
25	-	12	42
50	6	32	69
75	14	55	95
100	126	100	150

Settling velocity distributions (SVD) were calculated for each of the design PSD using theoretical settling velocity equations and an assumed relationship between particle size and particle density. These three designs SVD are summarised in Table 2.

Table 2

Design settling velocity distributions

	Settling velocity (m hr^{-1})		
% non settleable particles	Construction site	Urban Streams	Urban networks
10	-	0.003	0.20
25	-	0.15	4.5
50	0.01	2.9	12
75	0.2	9	25
100	10	30	60

Overseas studies have also shown a similarly wide range of SVD for the suspended solids in stormwater from a variety of urban and highway catchments. The reasons for this wide range of both SVD and the corresponding PSD are that:

- clay-rich soils, common world-wide, produce very fine, slow settling particles and that
- urban network stormwater contains substantial proportions of larger, heavier particles some of which are abraded from the hard rock-types used world-wide on road surfaces.

2 Introduction

Suspended solids and chemical contaminants in stormwater pose a risk to the ecological health of urban streams and coastal marine environments adjacent to urban development throughout the Auckland region. Zinc and copper have been identified as two chemicals of immediate concern (Williamson and Kelly, 2003). The nature and behaviour of the suspended solids and chemical contaminants must be understood before they can be effectively removed from stormwater. For example, removing suspended solids also removes varying quantities of zinc and copper because of the tendency for these metals to attach to suspended solids (Moores et al., 2007). The removal of suspended solids depends very largely on its particle size distribution (PSD).

The PSD of suspended solids in a water sample is the distribution of either the total number of particles, total particle surface area or total particle volume, across the range of particle sizes in the sample.

Historically the PSD was determined by either dry or wet sieving but the distributions determined with these methods were limited partly by the difficulties of using sieves with pore sizes below about 20 μm.

Optical laser instruments are now commonly used for measuring the size of particles that can be readily retained in suspension but wet sieving is sometimes still used for larger particles. Some laser techniques can give a measure of particle shape, but for calculating particle area and volume, the assumption is generally made that the particles are perfect spheres with diameter equal to the measured particle size. Clay particles are more likely to be flat and so this assumption does not always hold.

PSD can also be derived indirectly from particle settling velocities measured in a settling column by assuming a particle size-density relationship and quiescent and turbulent settling for smaller and larger particles respectively.

If the PSD of suspended solids in a particular stormwater discharge is known then a stormwater treatment device can be designed to remove a specified proportion of the suspended solids and its associated chemical contaminants. The difficulty is that the PSD of stormwater suspended solids varies depending, among other things, on the nature of the soils in the catchment and the physical and chemical characteristics of anthropogenic particulate material in the catchment for example road gravels.

The PSD of soils across the Auckland region ranges from that of the coarse volcanic soils developed on Auckland's many volcanoes and their lava flows to that of the very fine clay-rich soils developed from sedimentary rocks, particularly those of the Waitemata series. These different soils contribute in variable proportions to the suspended solids in stormwater. The "natural" soil PSD can be skewed by the PSD of suspended solids produced by, for example, the abrasion of hard gravels sourced from outside the catchment and used on road surfaces. Another source of stormwater suspended solids common in urban catchments that skews the natural soil PSD is topsoil imported from outside the catchment.

A further influence on the PSD of suspended solids in stormwater is the ubiquitous catchpit. Several tens of thousands of catchpits have been installed within the Auckland region to intercept the runoff from all urban roads, most other paved surfaces and a large proportion of urban pervious surfaces. Catchpits retain the coarser fractions of stormwater suspended solids and thus shift the PSD of the discharged suspended solids to smaller size ranges.

There are many factors in addition to those discussed above affecting the PSD and it would be an excessively time-consuming task to determine the PSD of stormwater suspended solids at the site of every stormwater treatment device installed in the region. A realistic compromise is to define a small number of "typical" or design PSD for the main sources of suspended solids. Stormwater engineers can then select the most appropriate PSD for their particular source of suspended solids to use for design purposes.

This report describes three designs PSD and their settling velocity distributions (SVD) derived for the Auckland region. These PSD and SVD are considered to be representative of the suspended solids in the following waters in the Auckland region:

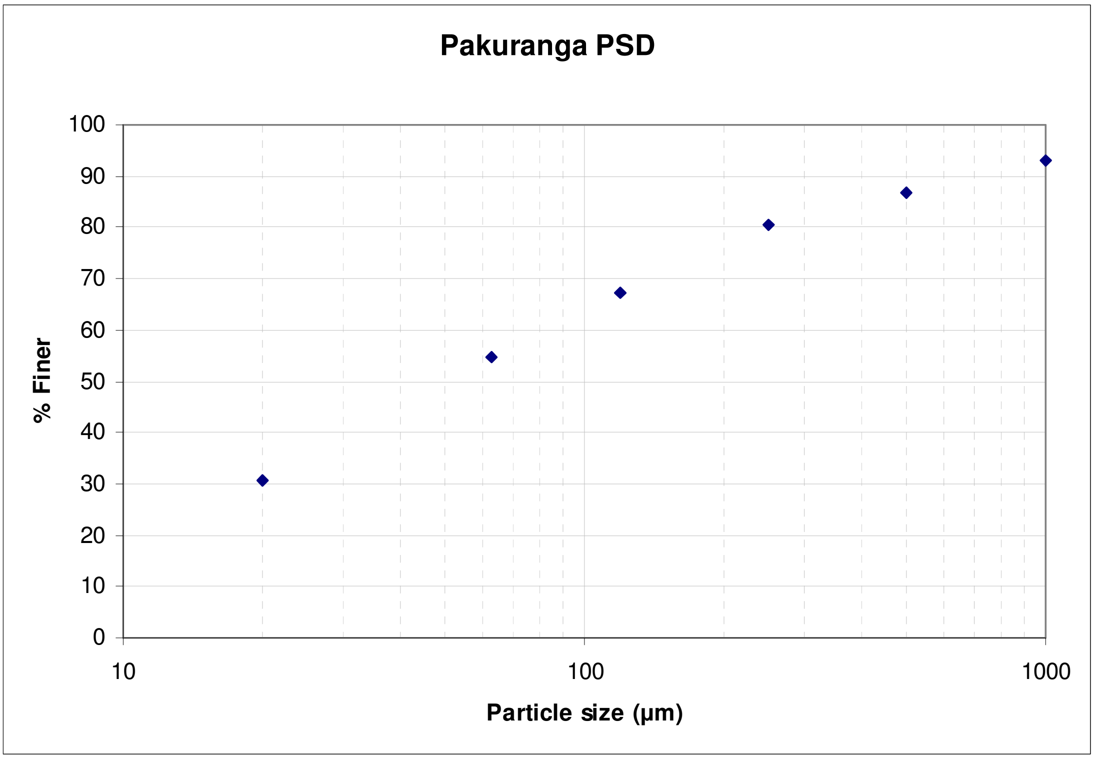
1. Stormwater in an urban network. The suspended solids in network stormwater is a catchpit-treated blend of solids originating in varying amounts, from volcanic and sedimentary soils, road gravels which are typically either andesite (volcanic) or greywacke (sedimentary) rocks, and both natural (to the catchment) and foreign topsoils. These topsoils can be amended in a variety of ways by the addition of other solid materials such as bark, pumice, vermiculite, etc.
2. Urban streams. The suspended solids in urban streams are a mixture of suspended solids delivered by stormwater networks and that eroded directly from adjacent pervious surfaces and stream channels. Attenuation by settling within the stream system further modifies the PSD.
3. Construction site runoff from urban subdivisions or other large-scale land clearing activities. Most remaining undeveloped areas within the Auckland Metropolitan Urban Limit are underlain by very fine clay-rich sedimentary soils, so suspended solids in runoff from future urban developments will mostly reflect these soils.

3 Particle size distributions

3.1 PSD currently in use for the Auckland region

The PSD currently recommended for use in the Auckland region (ARC, 2003b) was derived from data collected between 1990 and 1991 from sites in Wiri and Pakuranga. During this period the catchment of the Pakuranga site was mostly residential land use (ARC, 1992). Stormwater samples were collected from the end of a culvert adjacent to the Pakuranga Highway using an automatic ISCO sampler interfaced to a stage recorder on a V-notch weir. Four runoff events were monitored at this site and one event was monitored at a site in Wiri. The PSD of the samples were determined by wet sieving (ARC, 1992). The mean PSD is shown in Figure 1.

Figure 1
Mean particle size distribution for suspended solids collected from five runoff events, four from Pakuranga and one from Wiri (ARC, 1992).



The samples were analysed for PSD,total suspended solids, hydrocarbons, copper, lead, mercury, zinc and cadmium, Particle sizes ranged between 4 µm to 2000 µm. Approximately 55% (by weight) of the suspended solids particles were smaller than 63 µm in diameter, with particles greater than 1000 µm making up 7% of the total. On average 37% of copper, 32% of cadmium and 65% of zinc were present in dissolved state. Particles less than 47 μm usually had the highest heavy metal concentrations (ARC, 1992).

3.2 Auckland City stormwater network and stream monitoring programme

3.2.1 Site locations

Between 2001 and 2003 Auckland City Council (ACC) and Metrowater (MW) commissioned the monitoring of water quality and discharge at sites in eight stormwater networks and in two urban streams (Griffiths and Timperley, 2005). These sites and the predominant land uses in their catchments are listed in Table 3. The locations of these sites are shown in Figure 2.

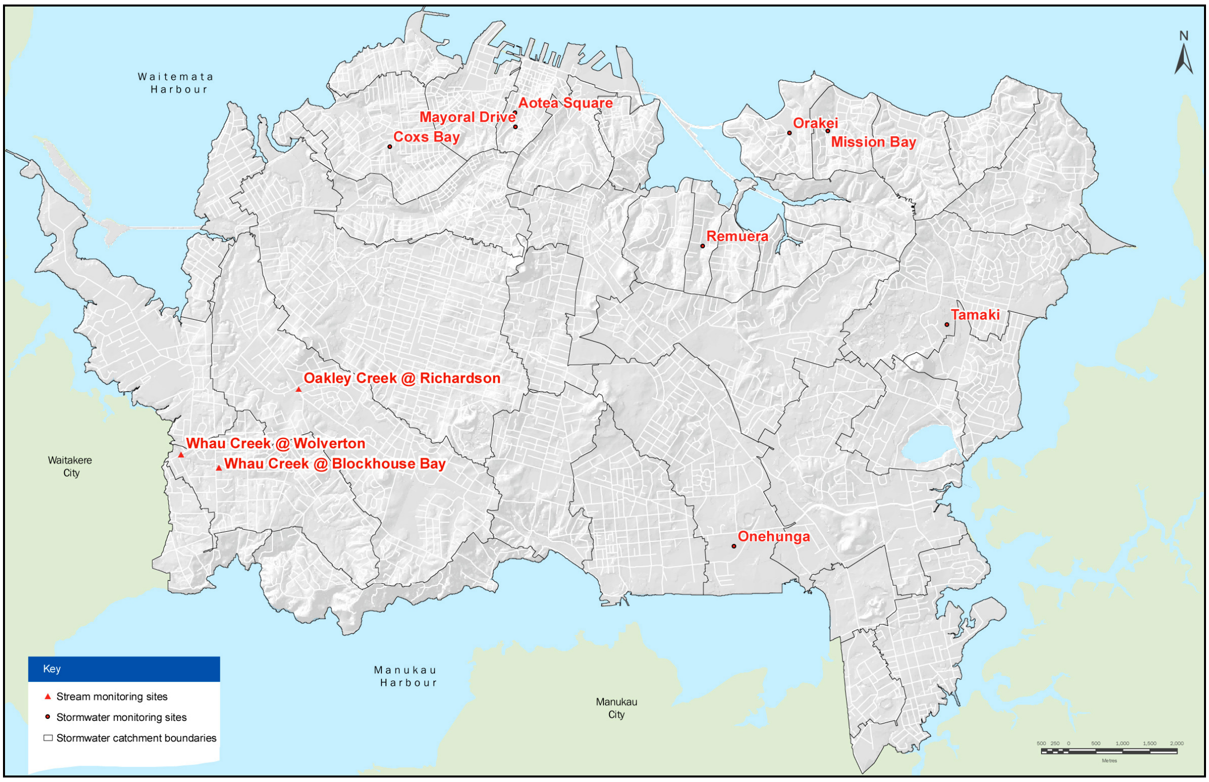
The stormwater network sites were distributed across the city, covering catchments with a range of landuses and soil types. The stream sites were Oakley Creek at Richardson Road and Whau Stream initially at Wolverton Road and subsequently at Blockhouse Bay Road (referred to as Whau 2 and Whau 1 respectively). The percentage imperviousness for the catchments of the monitoring sites were mostly between 60%and 80%.

Table 3.

Auckland City monitoring sites from which particle size data were collected between 2001 and 2003 (Griffiths and Timperley, 2005).

Location	Landuse	Site
Mayoral	Commercial	Piped network
Orakei	Residential	Piped network
Cox's Bay	Residential, commercial	Piped network
Aotea Square (CBD)	Commercial	Piped network
Mission Bay	Residential	Piped network
Remuera	Residential	Piped network
Tamaki	Industrial	Piped network
Onehunga	Residential, industrial	Piped network
Whau 1 (Blockhouse Bay)	Residential	Stream
Whau 2 (Wolverton)	Residential	Stream
Oakley	Residential, commercial, industrial	Stream

Figure 2.
Eleven Auckland City stormwater and stream water sites monitored between 2001 and 2003.



3.2.2 Sample collection and PSD analysis

Stormwater samples were collected by automatic samplers interfaced to either stage or discharge loggers using either time-based or flow proportional sampling. Between seven (Whau 2 is treated as a sub-set of Whau 1) and 16 events were sampled at each site and between 65 and 185 samples for each site were analysed for PSD (Timperley et al, 2004a). For most sites samples were collected across a wide range of event sizes (total volume recorded).

The samples were analysed for PSD at NIWA Hamilton using a Galai WCIS-100 particle size analyser, a "time of flight" instrument. Particle size and shape are measured for millions of particles as they cross a laser beam and the frequency of occurrence of particles in each size range is recorded. The instrument reports the PSD in terms of the total number of particles, the total particle surface area and the total particle volume within each of a number of narrow size bands within one of three operator-selectable scales. These scales are 0.5 to 300 µm, 2 to 600 µm, and 20 to 3600 µm, which have 28, 60 and 90 size bands respectively.

Table 4

Number of events and samples taken (Griffiths and Timperley, 2005)

Monitoring site	Events	Number of samples	Site
Aotea Square	15	160	Pipe
Mission Bay	15	185	Pipe
Orakei	14	105	Pipe
Mayoral	16	76	Pipe
Tamaki	16	101	Pipe
Cox's Bay	9	139	Pipe
Remuera	7	95	Pipe
Onehunga	11	160	Pipe
Blockhouse Bay (Whau 1)	7	65	Stream
Wolverton (Whau 2)	1	8	stream
Oakley Creek	8	182	stream

3.2.3 Statistical analysis of PSD Data

Auckland City Council (ACC) and Metrowater Ltd (MW) provided PSD for samples collected during their stormwater monitoring programme. The PSD were the cumulative volume percentages (percentage finer) for each sample over the particle size bands used for the PSD analysis.

The mean particle size (d50) across all samples ranged from 2 to 200 µm which implies the presence of outliers in the data. The presence of outliers was tested using the inter quartile range method. The quartile range is equal to the value of the upper quartile (Q3) minus the lower quartile (Q1) and an outlier is any value outside the range Q1- 1.5*(Q3-Q1) to Q3+1.5*(Q3-Q1). If a sample set contains more than two outliers the samples are excluded from the further analysis. All samples listed in Table 4 were processed using the quartile range method to eliminate outliers. With the exclusion of outliers, the d_{50} range reduced to between 7 and 150 µm (Table 5).

Table 5

Number of samples for each site after removing outliers and the resulting d_{50} range for each site. Data provided by Auckland City and Metrowater

Monitoring site	Number of samples remaining aft removal of outliers	d_{50} range (µm)
Aotea Square	87	50 - 100
Mission Bay	143	30 - 100
Orakei	76	30 - 150
Mayoral	60	9 - 80
Tamaki	62	50 - 110
Cox's Bay	113	15 - 65
Remuera	63	25 - 75
Onehunga	112	40 - 110
Blockhouse Bay (Whau 1)	44	7 - 60
Wolverton (Whau 2)	6	30 - 55
Oakley Creek	129	8 - 50

The median PSD for each site was calculated from the sample results remaining after the removal of outliers. These median PSD are plotted in Figure 3 and Figure 4 as the cumulative percentage of total particle volume (percentage finer) against the upper size of each particle size band. The suspended solids from streams (Oakley, Whau 1 and Whau 2) were clearly finer than were those from the networks.

Figure 3

Median PSD for the eight Auckland City stormwater network monitoring sites. Data provided by Auckland City and Metrowater

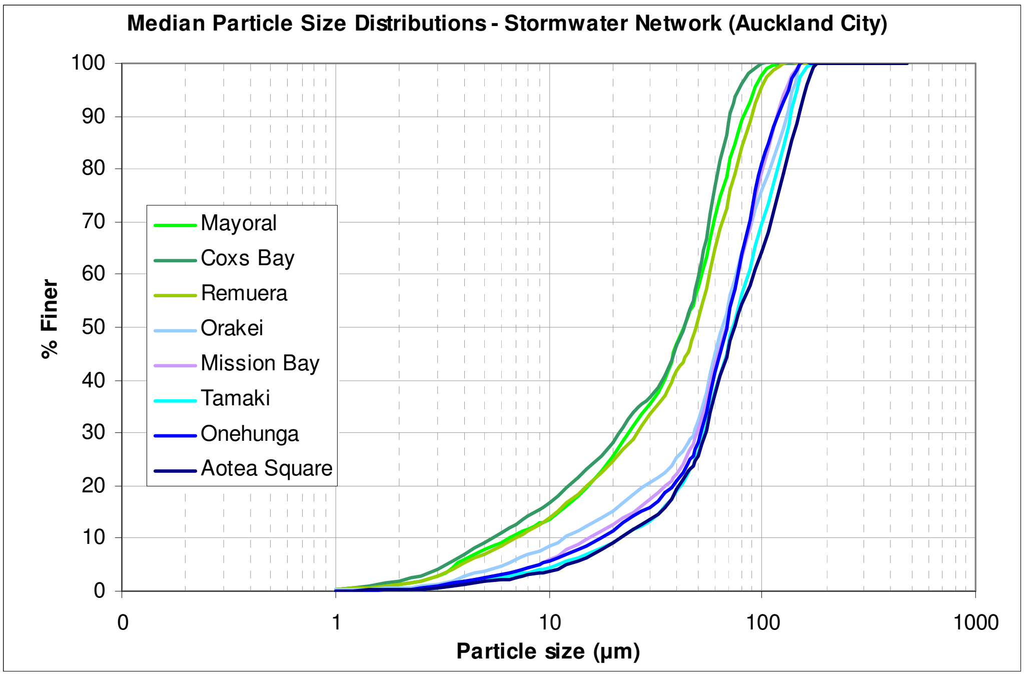
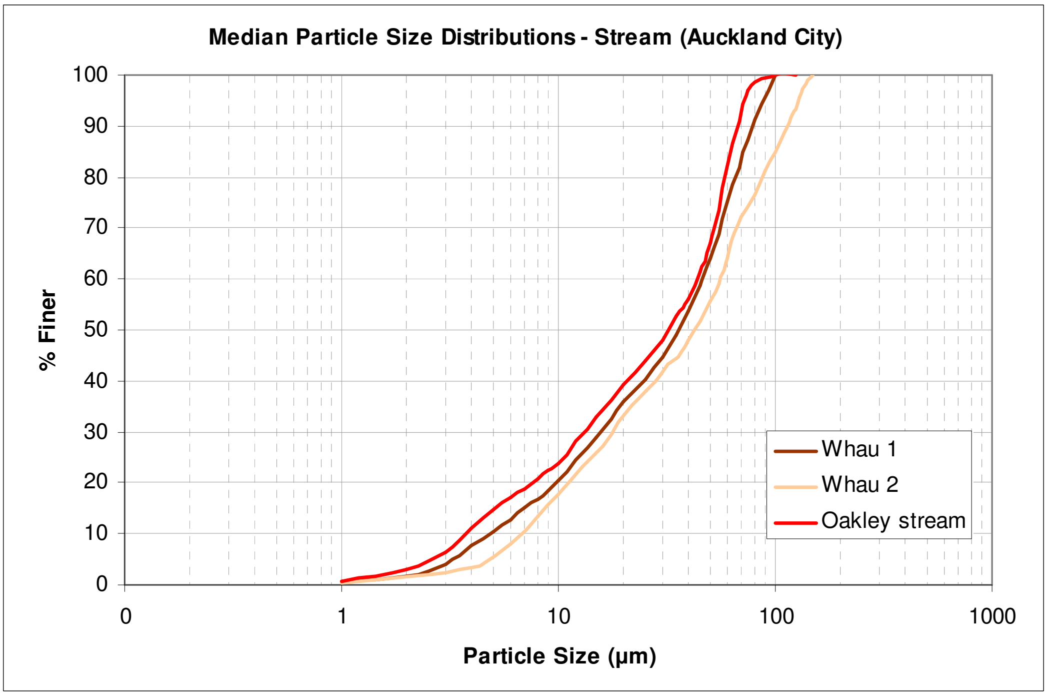


Figure 4

Median PSD for the three Auckland City urban stream monitoring sites. Data provided by Auckland City and Metrowater



3.3 Construction site monitoring

3.3.1 Nukumea flocculation pond monitoring programme

The Auckland Regional Council (ARC) commissioned a study during 2007 to evaluate the effectiveness of flocculation with polyaluminium chloride (PAC) to improve the removal of suspended solids from earthworks runoff in a sedimentation pond. A pair of matched ponds was constructed in the Nukumea stream catchment between the Northern end of the Nukumea viaduct and the Hillcrest Rd Bridge. The soils of this catchment are dominated by fine clays derived from sediments of the Waitemata series. Water samples were collected by automatic sampling during seven rainfall events between March and December 2007 (Moores and Pattinson, 2008).

Both pond inlet and outlet samples were analysed for PSD using the Galai laser instrument described in Section 3.2.2. For the purposes of this report only the inlet data were used. No inlet data were collected for one event so the PSD described below is based on six events with between three and seven samples per event giving a total of 34 samples. The median PSD for suspended solids entering the flocculation pond was calculated from the percentage finer data based on particle volume for the 34 samples .The median d_{50} for the suspended solids entering the ponds was about 7.2 µm.

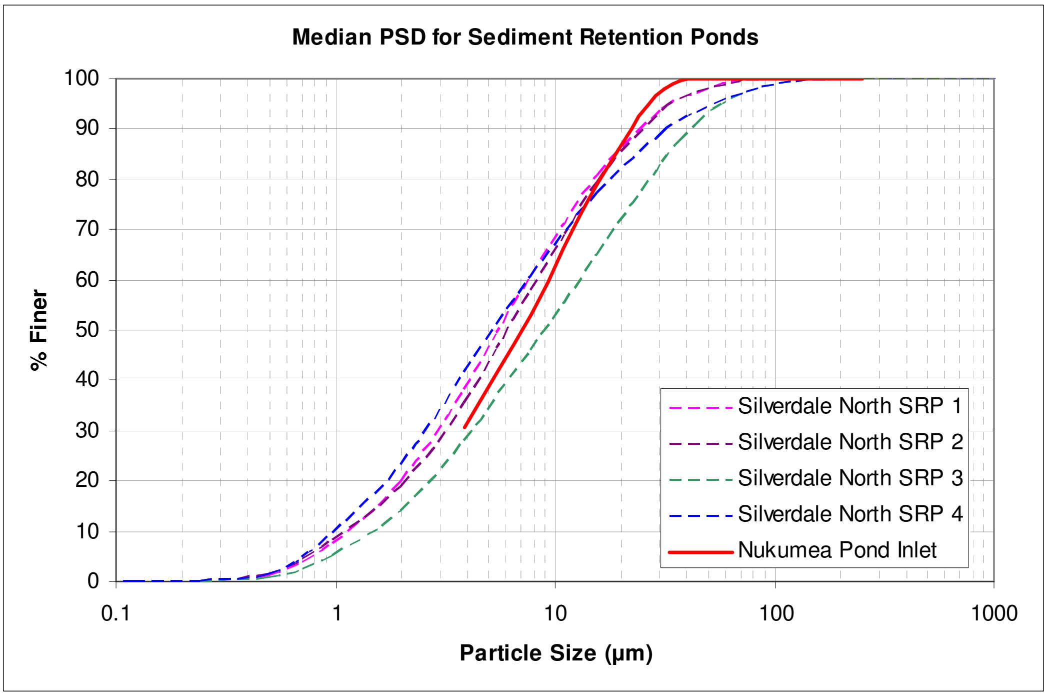
3.3.2 Silverdale North pond monitoring programme

Inlet samples to four sediment retention ponds located in the Silverdale North catchment were collected during rainfall events between December 2008 and May 2009. One to three events were monitored for each pond, with between three and 12 samples taken per event. The catchments draining to the ponds at the time of the rainfall events were bare clay-rich sub-soil developed from sediments of the Waitemata series. The PSD of the samples were determined using a Mastersizer 2000 at Waikato University (ARC, unpublished data). The Mastersizer 2000 uses a laser and a series of light detectors to measure the light pattern produced over a range of particle sizes (Malvern, 2008).

The median PSD of the suspended solids in samples from each pond inlet are shown in Figure 5. The median d_{50} were between 5 µm and 9 µm and the PSD are very similar to the PSD of samples from the inlet to the Nukumea ponds which had a median d_{50} of 7 2 µm.

Runoff samples from all the construction sites had a relatively large number of particles under 4 µm, between 30% and 40%, compared to 10% for the samples from urban streams and networks (Figures 3 and Figure 4).

Figure 5
Particle size distribution of suspended solids from the inlets to construction site retention ponds (ARC, 2008; ARC unpublished data)



3.4 Discussion on the different PSD

Particle size distributions for the suspended solids in samples collected from the Auckland region after the year 2000 have been determined using optical laser instruments. These methods are more accurate than traditional sieving methods for fine solids. For this reason, the design PSD described in this report are based on data collected after the year 2000.

As mentioned briefly in the introduction, the differences among the PSD shown in Figure 3 to Figure 5 for suspended solids in stormwater networks, construction site runoff and urban stream waters are due to different catchment characteristics including land use and associated activities, catchment lithology, presence of imported material, etc. The most obvious difference is between the PSD for construction sites on the one hand and urban networks and streams on the other. The approximate d_{50} values are 7, 60, and 40 µm respectively.

The construction sites examined in this report have a silt/clay soil texture which is common to over 80% of the Auckland region (Leathwick, 2002, Appendix 1). It is partly because of this soil characteristic that the construction site PSD are so fine. Another reason may be the near absence of topsoil and vegetation from which larger particles and aggregates could be generated.

The difference between the PSD for suspended solids in urban stream water and for network stormwater is consistent with streams having a higher proportion of pervious surface runoff and the fine particles it carries and the retention of larger particles by settling.

The suspended solids in the stream water at the Whau 1 site which drains a fully residential catchment were much finer than were the suspended solids at the Whau 2 site (downstream of the Whau 1 site). This might be a consequence of the commercial activities and a heavily used road in the sub-catchment of the Whau 2 site. On the other hand, the suspended solids in the network draining the fully residential Orakei were coarser than were the suspended solids in the network draining the fully commercial Mayoral catchment. Clearly, land use alone does not directly influence PSD.

Other possible influences on the PSD of suspended solids in network stormwater are catchment slope and the presence of short sections of open stream channels in the network. Steep catchments would be expected to facilitate the transport of coarse solids in suspension. This is consistent with the PSD (d_{50} of approximately 70µm) for suspended solids at the Mission Bay and Orakei sites both of which have relatively steep fully residential catchments. The Remuera site, however, also has a fully residential, similarly steep catchment but has finer suspended solids in its stormwater (d_{50} of approximately 50**µm).** This network includes a considerable length of open stream channel through the Waiata Reserve which may contribute finer suspended solids and retain coarser suspended solids.

PSD also varies with event characteristics, particularly rainfall intensity and duration, but this was not examined in this study.

3.5 Design particle size distributions

Three design PSD were derived for stormwater and runoff suspended solids in the Auckland region. The design urban network PSD is the median of the PSD determined for the suspended solids in all samples collected from the eight network sites of the Auckland City stormwater monitoring programme (Figure 3, Section 3.2.3). The design urban stream PSD is the median of the PSD for suspended solids in all samples collected from the three sites on the two Auckland City streams (Figure 4, Section 3.2.3). The design construction site PSD is the median PSD for suspended solids in all samples collected at the inlets to the five construction site retention ponds (Figure 5). These designs PSD are shown in Figure 6 and numerical summaries are given in Table 6..

Figure 6

Design particle size distributions for suspended solids in urban network stormwater, urban stream water and construction site runoff in the Auckland region.

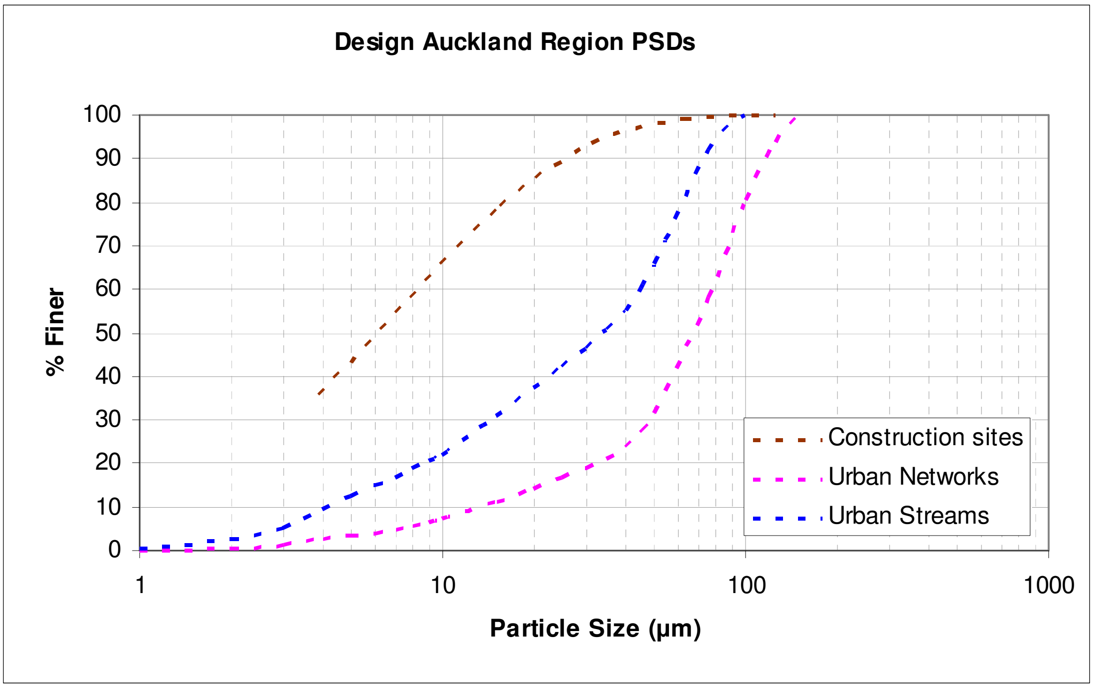


Table 6

Design particle size distributions for suspended solids in urban network stormwater, urban stream water and construction site runoff in the Auckland region.

	Particle size (µm)		
% Finer	**Construction sites**	**Urban streams**	**Urban networks**
10	-	4	14
25	-	12	42
50	6	32	69
75	14	55	95
100	126	100	150

Note: Appendix 1 provides more detail of the PSD

Clearly, the suspended solids contained in runoff from construction sites on clay-rich soils derived from sediments (the Waitemata series in Auckland) is very fine.

4 Settling velocity distributions

4.1 Why determine settling velocities?

The PSD describes the physical character of suspended solids and this description is required for the design of stormwater treatment devices based on filtration. For the design of treatment devices based on particle settling, however, the suspended solids settling velocity distribution (SVD) is required. Settling velocities based on a few discrete suspended solids particle sizes have been documented to guide stormwater treatment device design (ARC, 2003b) but complete settling velocity distribution profiles are required for estimating suspended solids removal efficiency.

4.2 Calculating settling velocity from particle size

Settling velocities can be measured directly in a settling column by timing how long it takes a quantity of solids to settle through a known depth under quiescent conditions. This is, however, a time consuming exercise. An alternative, although much less accurate procedure, is to calculate the settling velocity from the known particle size by assuming particle and fluid densities, particle shape , and the effects of interactions between particles and of flocculation. It is also necessary to select which of several theoretical settling equations to use for the calculations (more than one might be used).

4.2.1 Particle and fluid densities

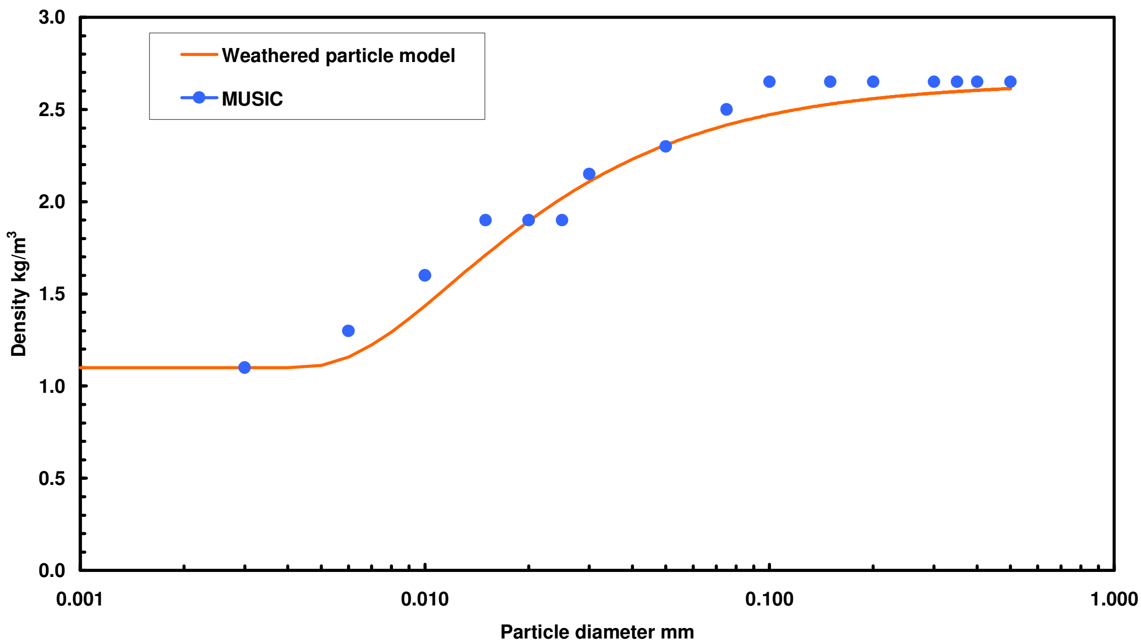
Particles are usually assumed to have the density of quartz, 2650 kg m^{-3} and water is assumed to have a density of 998 kg m^{-3} (density at 20°C). A density of about 2650 kg m^{-3} is reasonable for unweathered mineral particles but in the natural environment weathered mineral particles commonly have coatings of amorphous material. This material is usually a mixture of organic matter and amorphous secondary minerals, particularly iron and manganese oxides, produced by weathering of the primary minerals. This amorphous coating would be expected to have a lower density than that of crystalline minerals. As the proportion of organic matter in a particle increases, the density tends towards 1100 kg m^{-3}.the approximate density of the organic matter (Semadeni-Davies, 2009). Decreasing density with decreasing particle size is assumed in the MUSIC model (CRCCH, 2005) based on an analysis of PSD by Lawrence and Breen (1998).

Organic matter, particularly from decaying plant matter, can make up a substantial quantity of larger suspended solids particles (Lin, 2003). These large organic-rich particles or fragments are not efficiently trapped by settling devices, so for the purposes of the settling velocities determined below, these particles are ignored.

A relationship between particle size and density was calculated assuming a crystalline mineral core of density 2650 kg m^{-3} and a 2 μm thick amorphous coating of density 1100 kg m^{-3}. With this "weathered particle" model the influence of the amorphous coating on particle density increases as the particle size decreases. The particle density decreases to 2470 kg m^{-3} at 100 μm, 2307 kg m^{-3} at 50 μm, 1894 kg m^{-3} at 20 μm, 1665 kg m^{-3} at 10 μm and 1100 kg m^{-3} at 4 μm, at which point the particle is 100% amorphous material, i.e., a mixture of clay and organic matter. The resulting relationship is shown in Figure 4.1 together with the equivalent relationship derived from data used in the MUSIC model (Semadeni-Davies, 2009). There is a strong similarity between the two relationships.

Figure 7

Relationship between particle size and density calculated using the "weathered particle" model and derived from data used in the MUSIC model (Semadeni-Davies, 2009).



4.2.2 Particle shape, flocculation and viscosity

The derivation of SVD from PSD was based on the assumption that each particle is a perfect sphere with a diameter equal to the particle size. Quiescent settling was assumed and interactions between particles including flocculation were ignored.

The viscosity of water at 20°C, 0.001003 kg $m^{-3}.s^{-1}$, was assumed.

4.2.3 Conversion equations

Stokes law is appropriate for particles with Reynolds number (Re) <1 i.e., laminar flow. For particles with Reynolds number between 1 and 1000 (transitional zone between laminar and turbulent flow) Weber's equation applies. The equations used in settling rate calculations are:

$$\mathrm{Re} = \frac{2rV_f\rho_f}{\mu}$$ Reynolds number

$$V_s = \frac{2}{9}\frac{r^2 g(\rho_s - \rho_f)}{\mu}$$ Stokes law Re<1

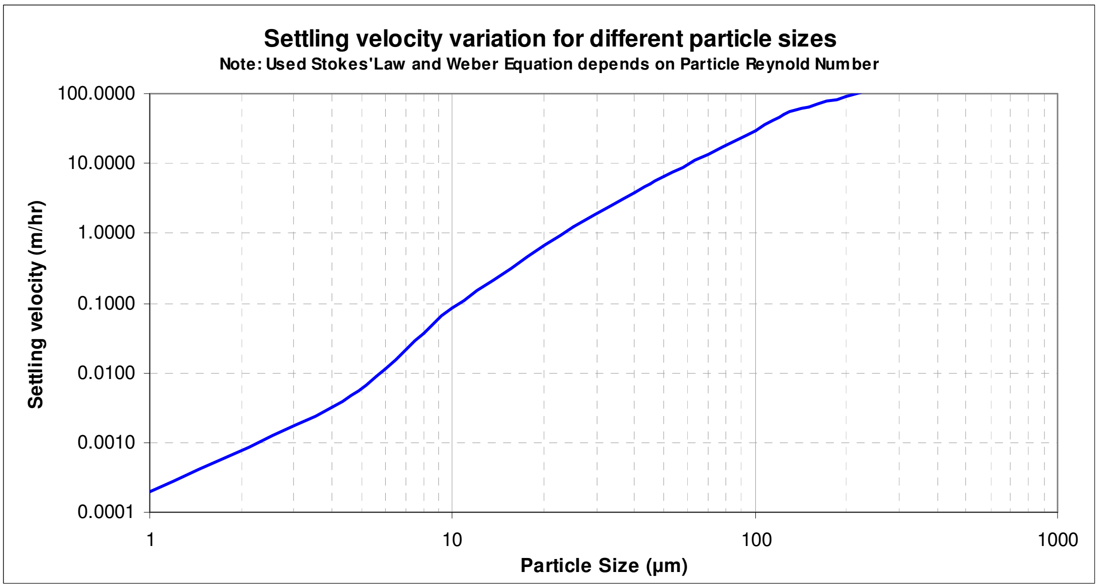
$$V_s = \left[2.23(\rho_s - \rho_f)r^{1.6}\rho_f^{-0.4}\mu^{-0.6}\right]^{0.714}$$ Webers equation 1<Re<1000

Where

r :	particle radius	V_f :	velocity = V_s if fluid is still
ρ_f :	fluid density	ρ_s :	particle density
μ :	fluid viscosity	V_s :	settling velocity

Figure 8 shows the SVD for particles ranging in size from 1 – 240 μm calculated using these equations and the particle size-density relationship from the weathered particle model (Figure 7).

Figure 8
Settling velocity distribution for suspended solids particles between 1 and 240 μm in diameter.



4.2.4 Design settling velocity distributions

The SVD calculated from the design PSD for suspended solids in network stormwater, urban stream water and construction site runoff are shown in Figure 9. Numeric data from the SVD are given in Table 7.

Figure 9

Calculated settling velocity distributions for suspended solids in network stormwater, urban stream water and construction site runoff in the Auckland region.

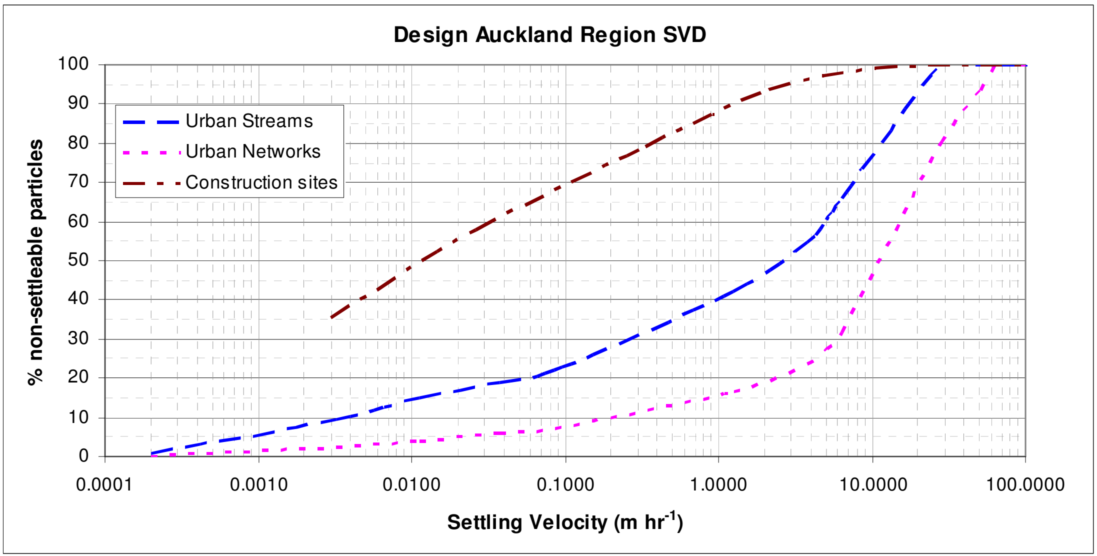


Table 7

Settling velocity distributions for suspended solids in network stormwater, urban stream water and construction site runoff in the Auckland region.

% non-settle able particles	Settling velocity (m h^{-1}) Construction sites	Urban streams	Urban networks
10	-	0.003	0.20
25	-	0.15	4.5
50	0.01	2.9	12
75	0.2	9	25
100	10	30	60

Note: Appendix 2 provides more detail for the SVD

5 PSD and SVD from other studies

5.1 Local studies

There are two sets of urban stormwater data collected from the Auckland region with which the three designs SVD described above can be compared.

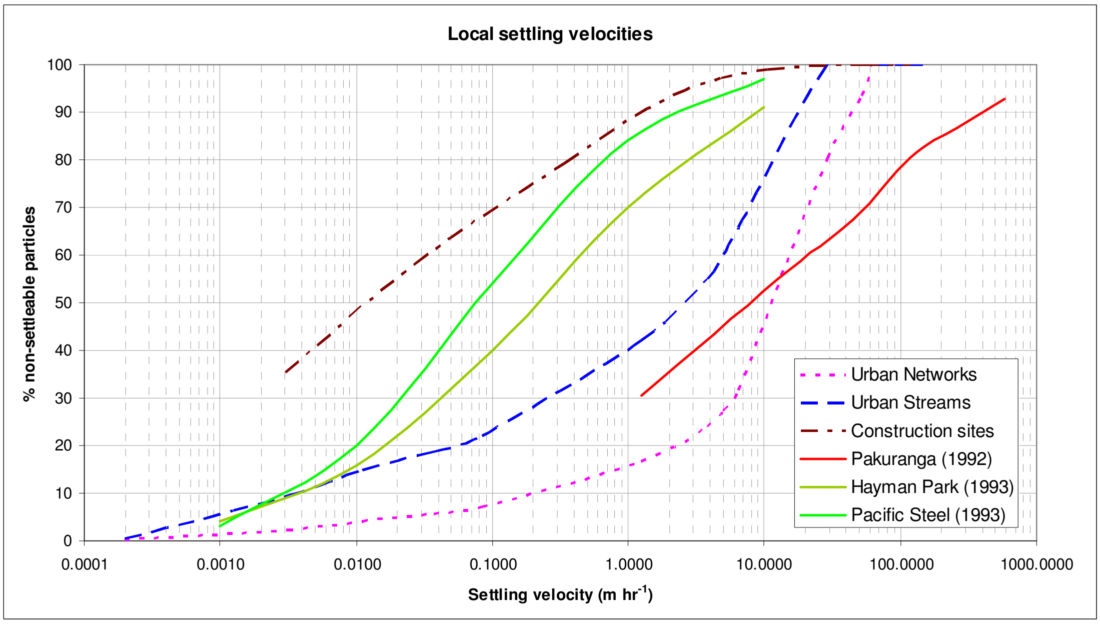
The SVD for suspended solids in samples collected from the Pakuranga site described in Section 3.1 were calculated using the measured PSD and the particle size-density relationship shown in Figure 7. This calculated SVD is very approximate because of the uncertain assumption that the particle size-density relationship of Figure 7 applies to the suspended solids from the Pakuranga site. This limitation of calculated SVD applies, of course, to the suspended solids from all sites for which a particle size-density relationship is unknown. It is, however, a necessary assumption for calculating SVD. As noted previously, a similar assumption is made in the MUSIC model.

The Hayman Park and Pacific Steel sites were at the inlets to wet detention ponds receiving stormwater from a small commercial catchment in Manukau and a small industrial site in Otahuhu respectively (Leersnyder, 1993). Leersynder (1993) measured the settling velocities for suspended solids in samples collected from these sites using the settling column procedures described by Driscoll et al (1986).

Figure 10 compares the three design SVD with the SVD calculated from the PSD for suspended solids from the Pakuranga site and measured for the suspended solids from the Hayman Park and Pacific Steel sites.

Figure 10

The three design SVD and SVD measured or calculated for suspended solids in stormwater at other sites in Auckland



The measured settling rates of the suspended solids in stormwater from both the Hayman Park and Pacific Steel sites were higher than were the calculated settling rates for the suspended solids in construction site runoff, but mostly lower than were the calculated rates for suspended solids in urban streams and urban networks. The obvious explanation for this is that the suspended solids in the samples collected from the Hayman Park and Pacific Steel sites were, on average, coarser than were the suspended solids in the construction site runoff and finer than were the suspended solids in urban stream waters and network stormwater. This explanation cannot be confirmed, however, because the PSD of the suspended solids in the samples from the Hayman Park and Pacific Steel sites sites were not measured.

In contrast to the results for the Hayman Park and Pacific Steel sites, about 25 percent by weight of the stormwater suspended solids at the Pakuranga site was calculated to settle faster than any of the suspended solids in the design network. The same particle size-density relationship was assumed for calculating the design and Pakuranga SVD so the differences can result only from different PSD. This is confirmed by a comparison of the PSD in Figure 1 for suspended solids from the Pakuranga site with the PSD in Figure 9 for the design network. The d_{50} for suspended solids from the Pakuranga site and the design network were 45 and 32 μm respectively which is consistent with the respective percent slower settling rates of eight and 2.5 m h^{-1} (Figure 10). Similarly, the d_{80} (particle size of 80 percent finer) for suspended solids from the Pakuranga site and the design network, 250 and 60 μm, are consistent with the respective percent slower settling rates of 120 and 13 m h^{-1}.

5.2 International studies

The three designs SVD are compared in Figure 11 with SVD either reported in, or calculated from, the international literature. In 1979 the United States Environmental Protection Agency (EPA) initiated the Nation Wide Urban Runoff Program (NURP) which was the first comprehensive study of urban stormwater pollution across the United States. In 1985, as an output from the NURP, a report entitled Methodology for Analysis of Detention Basins for Control of Urban Runoff Quality was released http://www.epa.gov/ednnrmrl/publications/reports/epa440587001). This report contained a typical probability distribution of settling velocities in United States urban runoff derived from pooled data for seven urban catchments across the United States. This distribution is shown in Figure 11 labelled as "NURP (1985)".

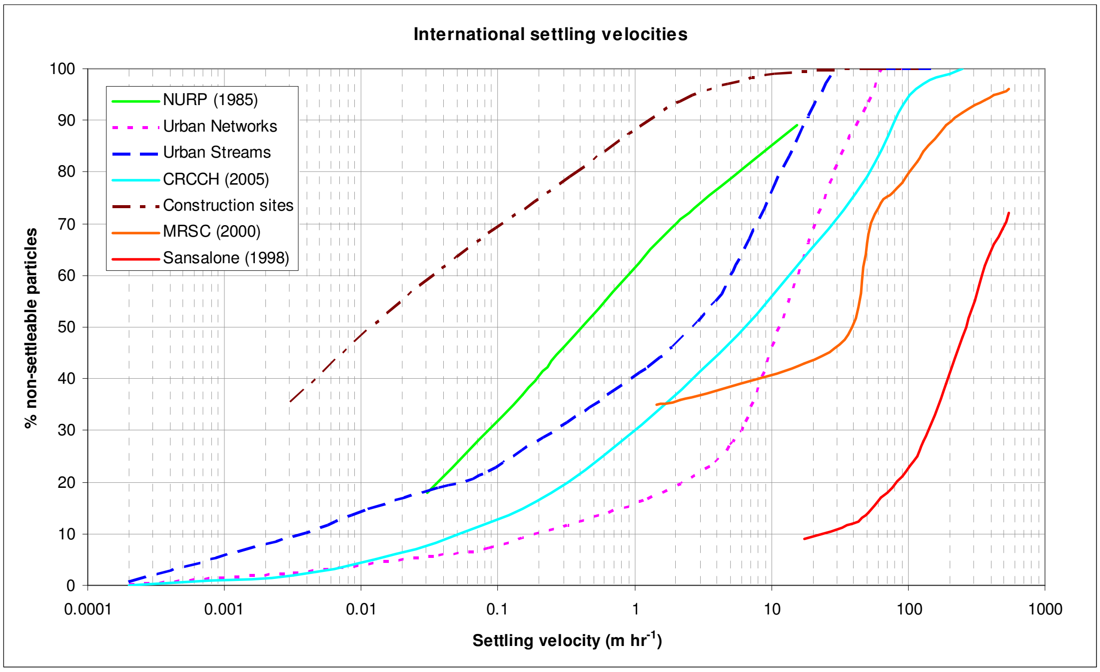
The SVD labeled "CRCCH (2005)" in Figure 11 was calculated from a PSD for stormwater suspended solids reported in the MUSIC manual (Cooperative Research Center for Catchment Hydrology, 2005) using the procedure described above for the Pakuranga site SVD. The PSD in the MUSIC manual was for suspended solids in stormwater from a fully developed urban catchment in Melbourne (Lloyd et al, 1998; Lloyd and Wong, 1999).

The two remaining SVD labeled "MRSC (2000)" and "Sansalone (1998)", both from studies in the United States, were calculated from PSD by the procedure used for the Pakuranga site SVD. The MRSC (1999) PSD was a typical stormwater PSD derived from data collected at a number of sites in urban catchments (Municipal Research and Services Center, 1999) and the Sansalone (1998) PSD was for suspended solids in runoff at one freeway site (Sansalone et al, 1998).

It is acknowledged that the validity of applying the assumed particle size-density relationship shown in Figure 4.1 to the PSD from Melbourne and the United States is unknown. Consequently, the reliability of the comparisons made below among the SVD shown in Figure 11 is somewhat uncertain.

Figure 11

The three design SVD and several SVD from the international literature



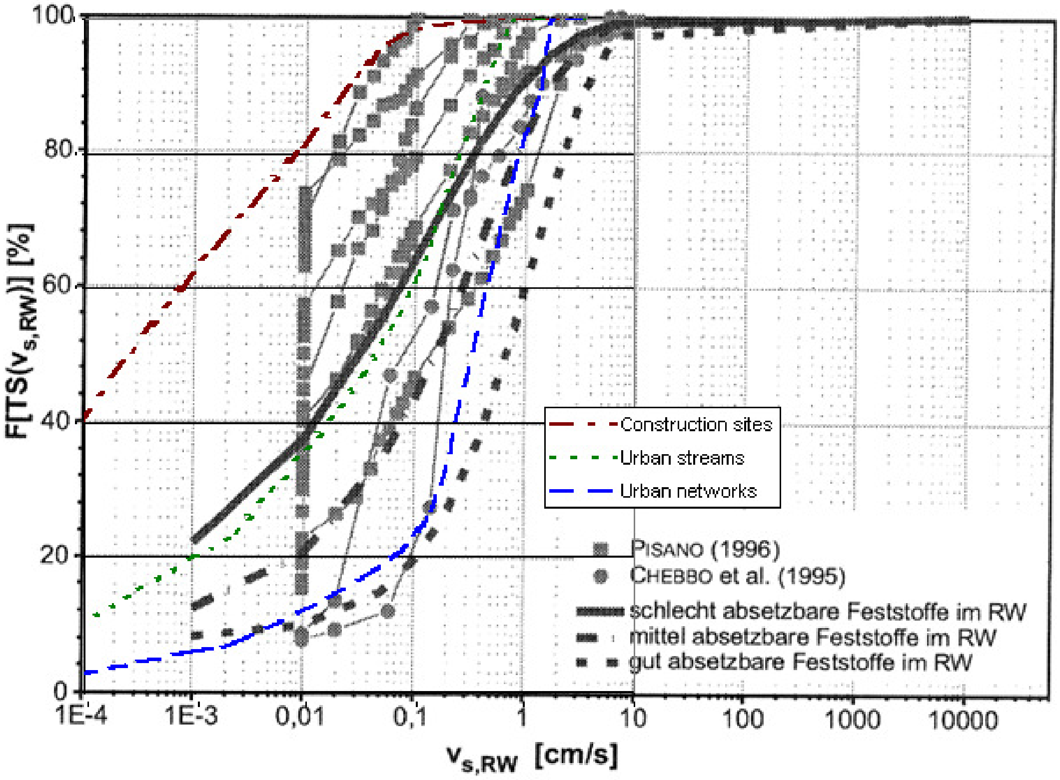
Suspended solids from the Auckland construction sites have the slowest settling velocities in Figure 11. The NURP (1985) SVD lies closest to the urban stream SVD with both having about 20% of their particles settling at rates of less than 0.05 m h^{-1}. The Melbourne (CRCC 2005) urban catchment stormwater suspended solids have a SVD lying between the SVD for the design network and the design urban stream with all three having 50% of their suspended solids settling at rates between 2.5 and 12 m h^{-1}. In sharp contrast, only 10% of the suspended solids in the freeway runoff studied by Sansalone (1998) settled at rates less than 20 m h^{-1}. Clearly the suspended solids in this runoff comprised mostly large particles.

A study by Kutzner and Geiger (2005) compared data from a number of overseas studies. The original data from these studies were unattainable but Figure 12 shows the three design SVD for Auckland superimposed on Kutzner's summary diagram of SVD.

Kutzner's SVD span almost exactly the range between the Auckland SVD for construction sites and urban networks thus illustrating the consistency of the Auckland design SVD with these international data.

Figure 12

The three designs SVD superimposed on the SVD from Kutzner (2005) Note: the scale on the x-axis is cm s^{-1}. One cm s^{-1} equals 36 m h^{-1} and 0.36 m h^{-1} is the lowest velocity plotted).



The wide range of SVD shown in Figure 12 from Kutzner and Geiger (2005) supports the validity of the range covered by the three designs SVD developed for the Auckland region. The rationale for the wide range of settling velocities shown by both sets of SVD is simply that:

- clay-rich soils, common world-wide, produce very fine, slow settling particles and that
- urban network stormwater contains substantial proportions of larger, heavier particles some of which are abraded from the hard rock-types used world-wide on road surfaces.

The message to take from Figure 12 is that the use of a single SVD for the design of all settling devices irrespective of catchment soil texture will result in variable performance of the stormwater treatment devices.

6 Discussion and Summary

The PSD for Auckland region was derived based on particle size distribution data collected from 2001 – 2003 and 2007 – 2009 within Auckland region. The data gathered at different sites were grouped into three categories, construction sites, urban streams and urban networks. Construction site suspended solids have the finest PSD followed by streams. Urban stormwater networks display the coarsest PSD.

The SVD were derived for each of the design PSD based on theoretical settling velocity equations.

It is noted that while three categories are mentioned here, the PSD from a site can vary within these categories depending on catchment type (industrial, commercial, residential), sub soil present (clay, volcanic), top soil present, the presence of open streams and factors such as road usage, heavy vehicle numbers etc.

Comparing the three design curves to overseas literature, all fit generally within the range of studies investigated.

The recommended design PSD and SVD for suspended sediments in Auckland's network stormwater, urban stream water and construction site runoff are summarised in the following tables.

Table 8

Design particle size distributions for suspended solids in urban network stormwater, urban stream water and construction site runoff in the Auckland region.

	Particle size (µm)		
% Finer	**Construction sites**	**Urban streams**	**Urban networks**
10	-	4	14
25	-	12	42
50	6	32	69
75	14	55	95
100	126	100	150

Note: Appendix 1 provides more detail for the PSD.

Table 9.

Design settling velocity distributions for suspended solids in urban network stormwater, urban stream water and construction site runoff in the Auckland region.

	Settling velocity (m hr^{-1})		
% non-settleable particles	**Construction sites**	**Urban streams**	**Urban networks**
10	-	0.003	0.20
25	-	0.15	4.5
50	0.01	2.9	12
75	0.2	9	25
100	10	30	60

Note: Appendix 2 provides more detail for the SVD

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Appendix 1

Design particle size distributions for suspended solids in urban network stormwater, urban stream water and construction site runoff in the Auckland region.

	Particle size (µm)		
% Finer	Construction sites	Urban streams	Urban networks
5	-	3.0	7.0
10		4.0	14.0
15	-	6.0	21.0
20		9.0	32.0
25		12.0	42.0
30		15.0	48.0
35	3.9	17.0	53.0
40	4.5	22.0	58.0
45	5.1	29.0	61.0
50	6.0	33.0	68.0
55	7.0	40.0	72.0
60	8.5	45.0	78.0
65	9.5	50.0	82.0
70	12.0	53.0	90.0
75	14.0	57.0	95.0
80	16.0	61.0	100.0
85	20.0	69.0	110.0
90	26.0	72.0	120.0
95	36.0	80.0	130.0
100	126.0	100.0	150.0

Appendix 2

Design settling velocity distributions for suspended solids in urban network stormwater, urban stream water and construction site runoff in the Auckland region.

	Settling velocity (m hr-1)		
% non-settleable particles	Construction sites	Urban streams	Urban networks
5		0.0009	0.02
10		0.0030	0.20
15		0.01	0.90
20		0.05	2.50
25		0.15	4.50
30		0.25	6.00
35	0.0030	0.50	7.00
40	0.0050	1.00	8.00
45	0.0075	1.70	9.80
50	0.0130	2.90	12.00
55	0.0200	4.00	14.00
60	0.0320	5.00	16.00
65	0.06	6.00	18.00
70	0.12	7.50	20.00
75	0.20	9.00	25.00
80	0.38	12.00	29.00
85	0.70	15.00	35.00
90	1.40	18.00	43.00
95	3.00	22.00	52.00
100	10.00	30.00	60.00

Appendix 3

Figure A.1

Physical characteristics of soil profiles in the Auckland region (Leathwick, 2002)