Particle Removal Efficiency from Stormwater

A Thesis
Submitted in Partial Fulfillment of the Requirements
For the Degree of
Bachelor of Engineering/Science
In
Civil Engineering (Environmental)
By

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School of Civil Engineering
University of Sydney, NSW 2006
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October 2013

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Summary

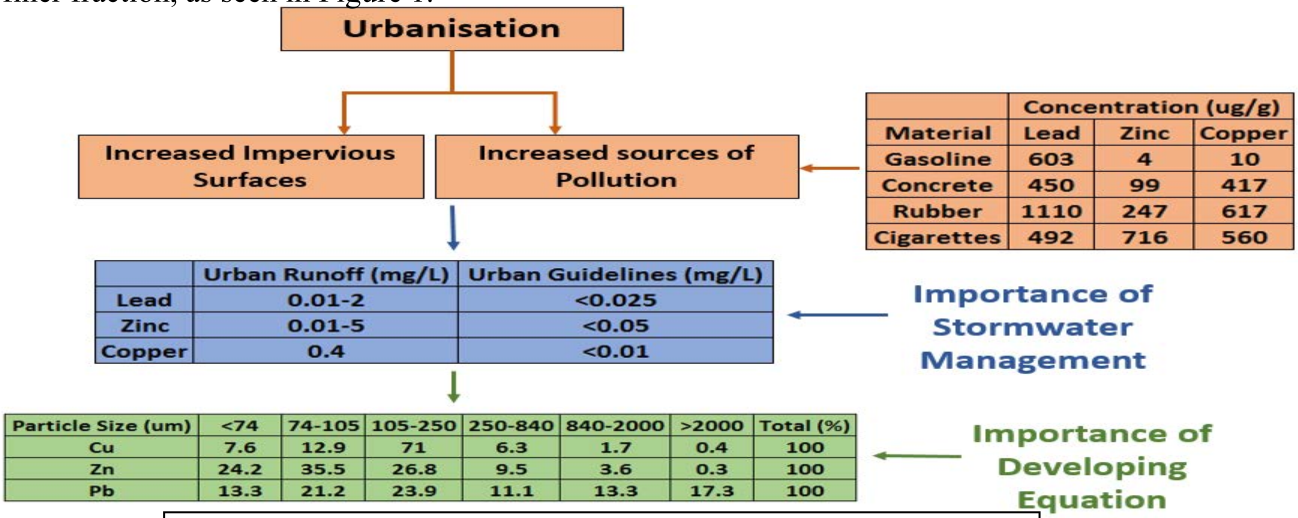
As urbanisation increases so to do impervious surfaces, as well as contaminant sources such as roads, residential and industrial precincts which has led to an overall decline of water quality through stormwater pollution. Typically, the hydrophilic nature of heavy metals and certain nutrients means that pollution generally travels as sediment bound contaminants to larger water bodies, with smaller particles such as silt and clay retaining a greater proportion of this pollution. The objectives of this thesis are therefore to analyse how certain factors influence the removal of particles from stormwater. This includes the particle ratio 'R', which is defined as the ratio between particle diameter and screen aperture, the water velocity 'v' and the total suspended solid (TSS) concentration 'c'. The aim was therefore to develop an equation encompassing these three variables to predict the removal efficiency of particles from suspension. The experiment was set up using the relatively new stormwater device the 'Tumblemate' produced by Water Decontamination Technologies Pty Ltd. Results demonstrated that removal efficiency was largely governed by the particle ratio, with a positive correlation forming parallels with theoretical pore and fibre models. Velocity had a moderate impact on particle removal, with faster velocities corresponding to lower efficiencies. The TSS concentrations was found to be relatively negligible, having little impact on the total particles captured by the screening system, which was supported by the literature which did not mention the parameter in equations defining screening efficiencies. The final equation developed was found to be a good fit with an adjusted R value of 0.945 and a significance of $p < 0.05$ and therefore can be used to predict the removal of particles from stormwater for the Tumblemate system.

Contents

Introduction

There is substantial research indicating the environmental importance of removing particles from water, particularly in regards to runoff from impervious catchments. The hydrophilic nature of pollution such as heavy metals and certain nutrients mean that many pollutants in stormwater are transported as sediment bound contaminants. This is especially the case in urban environments, where runoff contaminate concentrations of both total suspended sediment (TSS) and pollutants are much higher than pristine or rural areas (Sartor and Boyd 1972; Chiew et al 1997), evident in the Australian Runoff Quality Table in Figure 1. In addition, as urbanisation increases, there is an additional amount of pollution sources also evident in Figure 1 (University of California. 2003).

Practical mechanisms to remove pollution from stormwater are largely focussed on removing finer particles from suspension. Many investigations have found the concentration of contaminants to vary with particle size, with large amounts attached to the smaller particles such as the clay and silt region (Sartor and Gaboiry, 1984). This is largely due to the fact that these fine grained deposits have a high capacity for exchanging ions and therefore have a tendency to adsorb pollutants (Teisson, 1991). This is demonstrated in Woodward-Clyde (1994) and Chiew et al (2004), who both showed that higher concentrations of pollutants, such as heavy metals, are associated with the smaller particle size fractions of urban dust and dirt. Dempsey et al (1993) derived data that indicated that almost half of the heavy metals found on street sediments are associated with particles of 60-200 µm in size, and 75% are associated with less than 500 µm diameter. This is supported through the Australian Runoff Quality Guidelines which shows that the majority of the contaminants are associated with the finer fraction, as seen in Figure 1.



	Concentration (ug/g)		
Material	Lead	Zinc	Copper
Gasoline	603	4	10
Concrete	450	99	417
Rubber	1110	247	617
Cigarettes	492	716	560

	Urban Runoff (mg/L)	Urban Guidelines (mg/L)
Lead	0.01-2	<0.025
Zinc	0.01-5	<0.05
Copper	0.4	<0.01

Particle Size (um)	<74	74-105	105-250	250-840	840-2000	>2000	Total (%)
Cu	7.6	12.9	71	6.3	1.7	0.4	100
Zn	24.2	35.5	26.8	9.5	3.6	0.3	100
Pb	13.3	21.2	23.9	11.1	13.3	17.3	100

Figure 1: Diagram depicting the importance of undertaking the thesis

Finally, the importance of removing particles is focussed on fine-grained fluid aggregates being deposited in river areas or estuaries with a low transport capacity and high salinity. The problematic effect of such deposits is related to navigation canals, where work is regularly required to dredge sites to ensure depth of waterways are great enough.

This experiment is being undertaken due to the importance of particle removal from stormwater systems and the notable phenomenon that particles smaller than mesh aperture sizes in stormwater quality improvement devices (SQUIDS) are routinely captured. As finer particles have chemical properties that allow common urban pollutants to be adsorbed out of solution, it is of primary importance to attempt to quantify the ability of certain filters in water sensitive urban design (WSUD) to remove particles.

The three objectives of this experiment were to determine how velocity, TSS concentration and the particle ratio relate to primary screen efficiency in the Tumblemate system. The aim is to combine all three parameters to develop a single equation that will be able to estimate the particle removal efficiency for a range of sized particles, as seen in Figure 2.

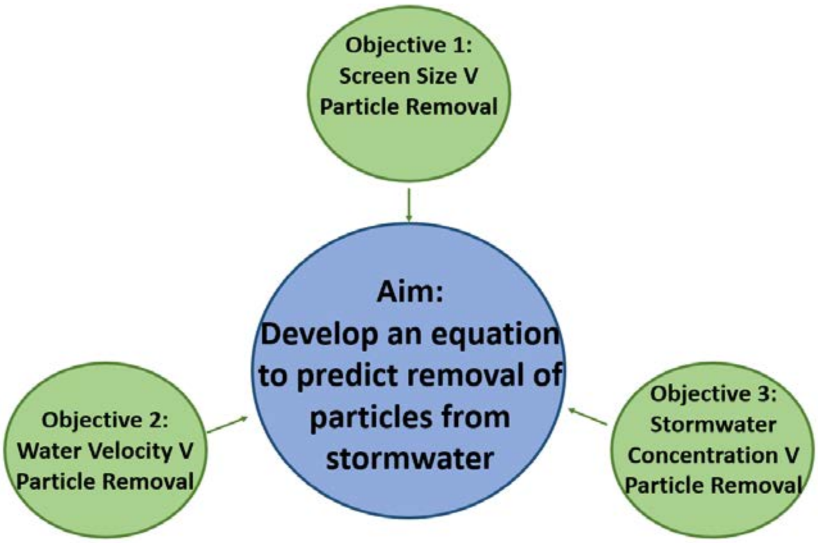


Figure 2: Aims and objectives of this thesis report

Literature Review

The aim of this literature is to provide a qualitative and quantitative analysis for aquasol removal using filtration. This section details and critically analyses theoretical predications and modelling as well as practical experiments to determine the most up to date knowledge of removal efficiencies of filters. In addition, deficiencies in current literature such as the absence of considering flocculation in solution are highlighted, with research used to bridge these uncertainties.

Theoretical Modelling

Whilst most fibre filtration models were developed to predict the removal of aerosol particles, they have been adapted (Yao et al, 1971; Rubenstein and Koehl; 1977; Silvester, 1983) to describe particle removal in aqueous systems. In Yao et al (1971), the particle capture is given by the addition of three dimensionless efficiencies (Figure 3) that take into account the transport mechanisms of interception (n_I), gravity (n_G) and diffusion (n_D), and are given by:

$$n_D = 0.9\left(\frac{kT}{\mu d_p d v_o}\right)^{\frac{2}{3}} \quad [1]$$

$$n_I = \frac{3}{2}\left(\frac{d_p}{d}\right)^2 \quad [2]$$

$$n_G = \frac{(\rho_p - \rho) g d_p^2}{18\mu v_o} \quad [3]$$

where K is Boltzmann's constant, T is the absolute temperature, μ is the water viscosity, d and d_p are the collector and particle diameter respectively, g is the acceleration due to gravity, ρ_o and ρ_p are the density of water and suspended particles respectively, and v_o is the local water velocity.

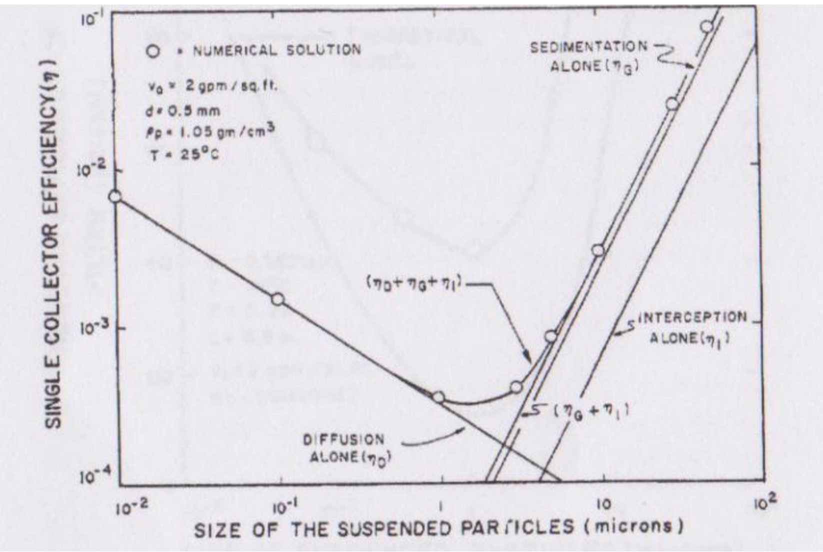


Figure 3: Three dimensionless equations as described in the Yao model. Source Yao et al, 1971

A more commonly used fibre filter model is one proposed by Rubenstein and Koehl (1977). This includes particles with radii between 10-7 and 10-1 cm (Fuchs, 1964), with low settling velocities in the fluid, as well as where particle motion is dominated by viscous forces (Hidy and Brock, 1970). Similar to Yao (1971), gravitation, interception and diffusivity on the fibre is considered, however the Rubenstein and Koehl (1977) model extends the idea of particle capture to incorporate inertial impaction as well as electrostatic attraction. Rather than quantifying removal efficiency, the model contains equations that determine the relative importance of each mechanism for particle removal, including:

1. Direct interception: occurs when the centre of a particle following a streamline comes within one particle radius of the fibre, contacting it and becoming captured. The dimensionless index for this removal mechanism to determine the relative weighting of removal to other mechanisms is dependent only on the size of the particle, given by Pich (1966).

$$N_{RF} = \frac{d_p}{d} \qquad [4]$$

2. Inertial impaction: fluid will generally move in a straight line under laminar flow until it is diverted around a fibre. When this occurs, particles of sufficient mass will have enough inertia to be intercepted by the fibre. The equation of relative importance is given by Fuchs (1968).

$$N_{If} = \frac{\left[(\rho_p - \rho)d_p^2 v_o\right]}{18\mu d} \qquad [5]$$

3. Gravitational deposition: particles denser than the fluid in which they are dispersed tend to sink, therefore if a particle falls within a one particle radius of the fibre it will be intercepted. The dimensionless index expressing the intensity of the particle capture due to gravitational sedimentation is given by Chen (1955) and is found to be:

$$N_{Gf} = \frac{\left[d_p^2 g(\rho_p - \rho_m)\right]}{18\mu v_0} \qquad [6]$$

4. Diffusion: this is where very small particles display random Brownian motion. As a result the trajectories of these particles deviate from the streamlines. The dimensionless index is given by Pich (1966) and is found to be:

$$N_{MF} = \frac{KT}{d_p}\left(\frac{1}{3\pi\mu v_0 d}\right) \qquad [7]$$

5. Electrostatic attraction: If the particle and the fibre are opposite in charge then there will be an electrostatic force leading to the capture of these particles. The dimensionless parameter is given by Pich (1966):

$$N_{Ef} = \frac{4qQ}{3\pi\mu V_0 d_f} \qquad [8]$$

where q and Q are the potential of the particle and filter material respectively.

The Rubenstein and Koehl model shows that for any given particle size only one or two of the mechanisms in equations 4-8 will be significant. This is because as particle size is reduced, collection by diffusion is increased, however when particle size becomes larger the filtering elements ability to collect particles by inertial deposition, gravitational sedimentation, and direct interception is improved. Therefore there is an intermediate range of particle sizes for which the intensity of capture reaches a minimum. Similarly, for a given particle size the capturing ability of a filtering element depends on velocity. As demonstrated in Figure 4, a reduction in velocity will increase gravitational deposition whilst an increase will promote capture by inertial impaction. The main mechanism for a given filtration situation is that having the largest dimensionless index; the other mechanisms may be ignored as a first approximation if they are substantially smaller (Pich, 1966).

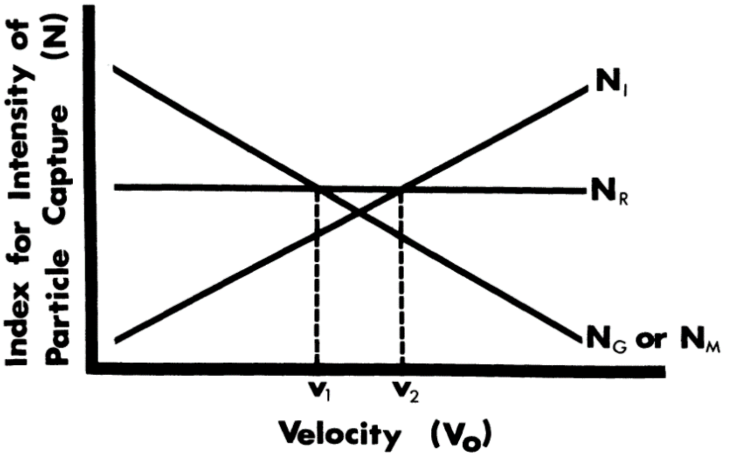


Figure 4: Hypothetical effect of velocity (V_0) on the intensity of particle capture (N) for a given fibre (d_f), particle (d_p,p_p) and fluid medium. Source: Rubenstein and Koehl (1977)

The results of the Rubenstein and Koehl model are demonstrated through Logan (1993) who simulated the filtration of particles through different media. Particles up to a diameter of 100 μm were sent through a filter of an aperture of 30 μm (nylon), as well as 230μm and 1000μm (polyethylene). The major finding was that despite the largest filter being 10 times as large as the largest particle, 1-10% of the particles between 25-100μm ranges were removed by the mesh as seen in Figure 5.

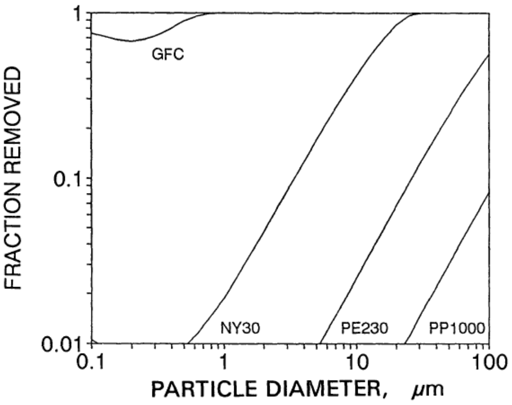
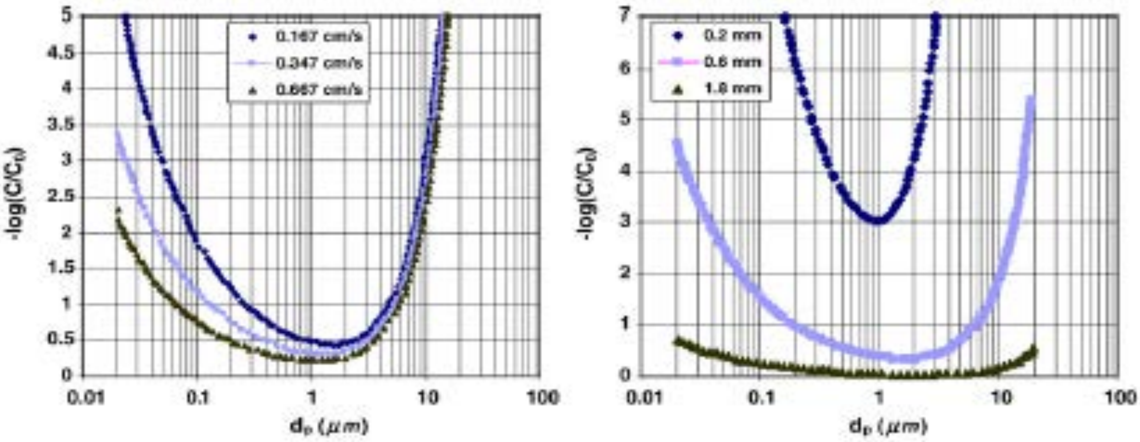


Figure 5: The fraction of particles removed by three screens and a glass-fibre filter from theoretical modelling. Source: Logan (1993)

To confirm these results a recent theoretical experiment using mechanisms as described in equations 4-8 was analysed. Zamani and Maini (2009) varied flow rates as well as mesh aperture to demonstrate the simultaneous effects of the five mechanisms in equations 4-8. Figures 2 and 3 meet the results from Logan (1993) in that particles smaller than the aperture were captured. In addition, it was shown that an increase in the flow rate will lead to an overall reduction in capture efficiency as well as that smaller mesh sizes will have a greater removal efficiency (Figures 6 and 7).



Figures 6 and 7 (above left and right): Theoretical removal of particles under differing velocities and screen sizes. Source: Zamani and Maini 2009

Contrasting to the fibre model is the capillary pore model as described by Logan (1993). For aerosol particles, capillary pore models have been shown to be more accurate then fibre models in predicting particle removal by polycarbonate filters, and therefore it is reasonable to assume that these models can predict aquasol particle removal (Logan, 1993). The removal of aquasols is given by:

$$E_t = \alpha * (n_{DC} + n_{RC} - n_{DC} n_{RC}) \qquad [9]$$

$$n_{DC} = 2.56 D_c^{\frac{2}{3}} - 1.2 D_c - 0.177 D_c^{\frac{4}{3}} \qquad [10]$$

$$D_c = \frac{4 L D_p}{d_h^2 U_0} \qquad [11]$$

$$n_{RC} = (2R_h - R_h^2)^{\frac{3}{2}} \qquad [12]$$

where L = length of the filter, D_p is the particle diameter, d_h is the pore diameter and U_0 is the water velocity. As this method accounts for a mesh filtration mechanisms by comparing particle size to mesh aperture, it has the advantage over the fibre model in that it will accurately predict that particle sizes larger than the mesh aperture will be retained 100% of the time as it takes into account the sieving mechanism and not just on particle capture by a single fibre.

Many investigators have used Rubenstein and Koehl (1977) and capillary pore models to predict an aerosol size for minimum efficiency through filters, generally based on mechanisms of diffusion, interception and impaction whilst usually ignoring electrostatic charge and gravitational effects (Stafford and Ettinger, 1972). Theoretical calculations predict and aerosol size of 0.1-0.4 microns for minimum efficiency with this being verified by some experimental investigators (Rimberg, 1968; Lindeken et al 1963; Dyment, 1963), whilst others have demonstrated that efficiency generally decreases with particle size (Stern et al 1960; LaMer, 1951). The most recent investigation was carried out by Wu et al (2013) who demonstrated that this minimum occurred at approximately 0.25 µm evident in Figure 8. However these models have failed to take into account factors such as pH as well as potentially repulsive particle-particle interactions and therefore are limited in terms of their reliability. Furthermore, particles within the 0.1 - 0.4 µm range are not the major carriers of contaminants, and therefore the fact that these sizes have the lowest removal efficiency is not significant in regards to WSUD.

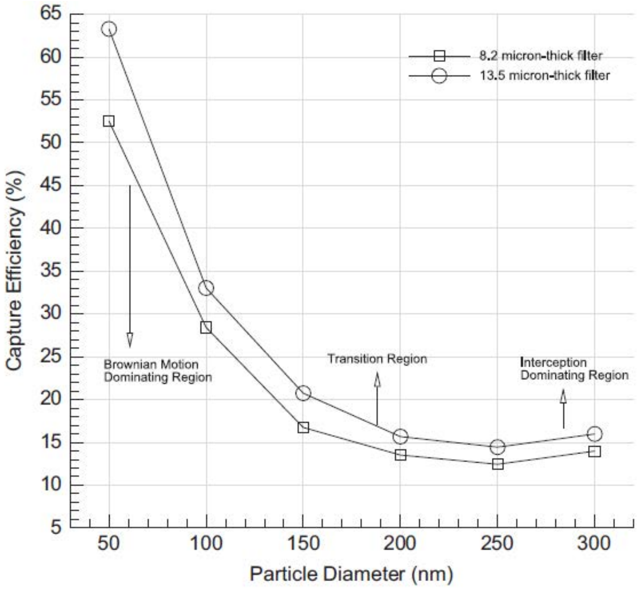


Figure 8: Theoretical particle capture efficiency for a numerical simulation. Source Wu et al (2013).

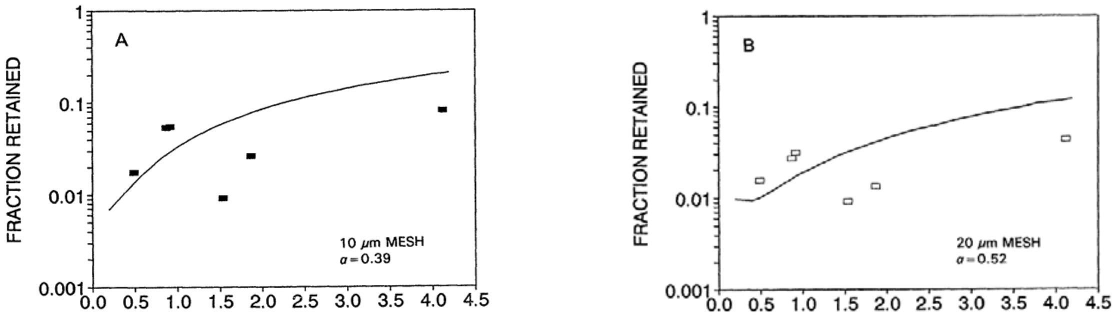
A factor that must be considered for these theoretical models is the physical clogging of the screens that is not taken into account. As particles become attached to screen fibres, pore sizes will decrease which will result in a reduction of flow but an increase in the removal efficiency. This has been demonstrated by Buffle et al (1992), who showed that there was a marked difference in removal of particles as well as flow rate as the filter system progressively became clogged.

Another potential issue with theoretical model is to do with the assumption that the sticking coefficient is unity. LaBarbera (1984) acknowledges that built into the assumptions of the Rubenstein and Koehl (1977) model is the fact that particles will strike the collector at 100% efficiency. In a real life application this value will vary with screen and particle type as well as water chemistry which will have an impact on the net charge of the particle. Previous experiments have found this sticking coefficient to be as low as 0.44 (Yao et al , 1971), and therefore it is advised that the final output from computer modelling be taken with some caution, especially for screen types that are known to be uncohesive.

Previous and Current Experiments of Filtration

Originally the idea of filtration followed the sieve theory, which states that only particles too large to pass through the filtering apparatus will be captured (Alder and Hancock; 1851, Dral, 1967; Pich, 1966). Whilst nets preferentially retain particles at the larger end of the size-frequency distribution (Brown et al , 2005), it was proposed (Wallengren, 1905) that even particles less than the mesh size could be captured simply by striking and adhering to the sticky structural elements of a filtering apparatus. This has been proven through experiments including mechanical means of removal as well as removal of particles from natural systems, in which it was found that captured particles were smaller then the mesh size (Tachet, Pierrot & Bournaud, 1987).

An early experiment that has conducted a thorough analysis of the removal of particles from water was Logan (1993). To verify these results, particle removal from natural screens produced by micro-organisms were analysed to determine whether results derived from Logan (1993) were both qualitatively and quantitatively significant. The experiment involved filtering microbeads ranging up to 4.12 μm through nylon mesh sizes of 10, 20 and 30 μm. The results indicated that the retention of these particles ranged from 0.26 - 8.2% for the 30 micron filter, with increasing capture efficiencies for the smaller sized apertures as seen in Figures 9-11.



Figures 9 and 10 (above left and right): Observed and predicted fraction of microspheres removed on 10 and 20 micron mesh respectively. Source: Logan (1993)

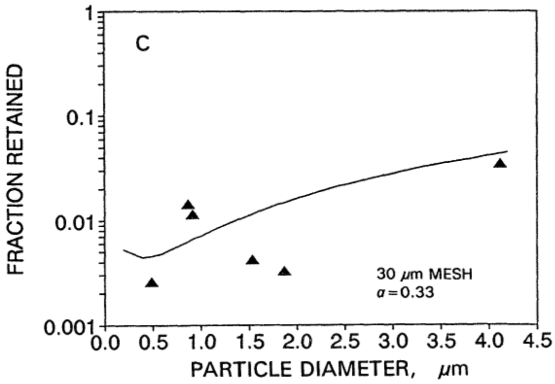


Figure 11: Observed and predicted fraction of microspheres removed on 30 micron mesh. Source: Logan (1993)

As only six data points were collected these results could not entirely be relied upon. A recent study conducted by Cripps (1995) who studied particle removal in aquaculture effluent demonstrated that the average diameter of captured particles were always less than the mesh aperture as demonstrated in Figure 12. Particle sizes ranged between 1and 160 µm, and therefore as a significant number of particles smaller than the aperture were collected the conclusion that mesh sizes can capture particles with a smaller radius is valid. However, the linear model proposed by Logan (1993) cannot be validated through this experiment alone and further rigorous testing is required to determine a relationship between particle capture and diameter.

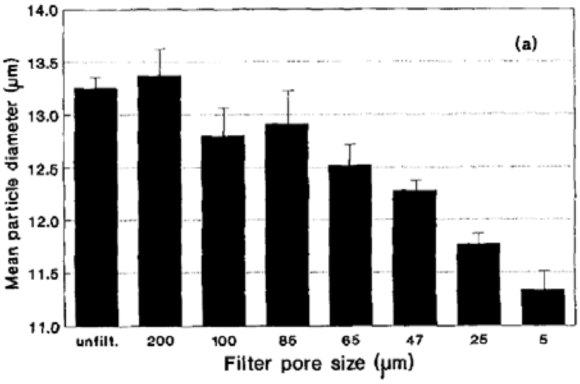
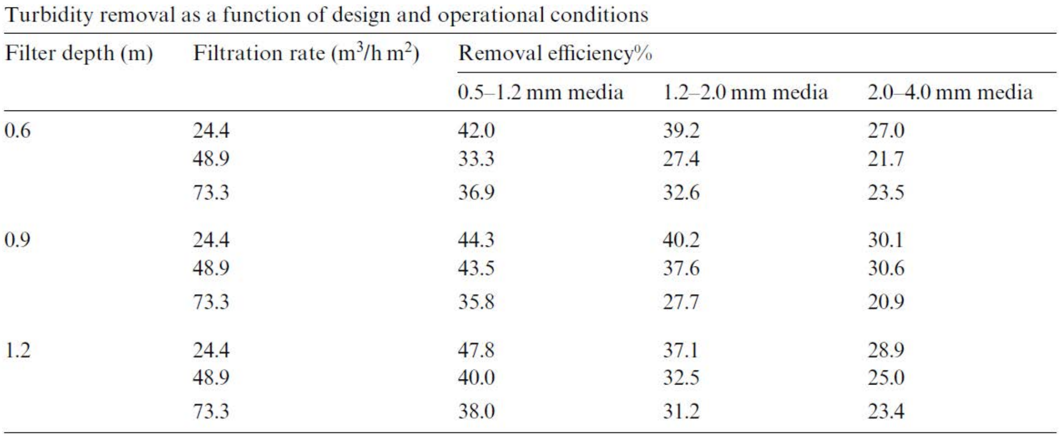


Figure 12: Filter pore size versus mean particle diameter captured by the filter. Source: Cripps (1995)

A more recent experiment was carried out by Tang et al (2005) where removal of suspended particles in ballast was determined. Particles within a range between 2 and 60 µm were sent through three filters with apertures of 0.5 – 1.2 mm, 1.2mm – 2.0 mm and 2.0 – 4.0 mm, with efficiencies of these filters are depicted in Table 2. The results derived from this experiment were similar to those from Logan and Cripps in the fact a considerable amount of smaller particles were retained, including a capture efficiency of 40-64% for particles between 1-20 µm passing through the smallest of the filters. The validity of this study can be confirmed by comparing to another recent experiment (Kazumi et al, 2004) which analysed particle removal for the same flow rates in similar mesh apertures and concluded that 47% of suspended particles between the range of 8 and 240 microns were removed. This compares to a removal efficiency of 21-37% from Tang et al, with the lower values being attributed to a slight increase in the mesh size.



Turbidity removal as a function of design and operational conditions

Filter depth (m)	Filtration rate ($m^3/h\ m^2$)	Removal efficiency%		
		0.5–1.2 mm media	1.2–2.0 mm media	2.0–4.0 mm media
0.6	24.4	42.0	39.2	27.0
	48.9	33.3	27.4	21.7
	73.3	36.9	32.6	23.5
0.9	24.4	44.3	40.2	30.1
	48.9	43.5	37.6	30.6
	73.3	35.8	27.7	20.9
1.2	24.4	47.8	37.1	28.9
	48.9	40.0	32.5	25.0
	73.3	38.0	31.2	23.4

Table 2: Results of suspended particle removal from Tang et al (2005)

To confirm these results experiments undertaken on natural filters were analysed. Filtration through natural filters has most recently been analysed by Brown et al (2005), in which size-frequency distribution of particles captured by the nets of Hydropsyche siltalai were recorded. These nets are anchored in the substratum perpendicular to the flow (Giller and Malmqvist, 1998), with mesh sizes generally greater than 50 µm (Williams and Hynes, 1973; Wallace, 1975; Wallace, Webster & Woodall, 1977, Edington & Hildrew, 1995). Particle sizes ranged from 1-70µm, however similar to Logan (1993) it was found that the nets preferentially retained particles at the larger end of the size-frequency distribution. In addition, the fact that the predominant capture of particles were between 1-40 µm meant that it could be concluded that sieving was not the only mechanism responsible for particle capture. However, it must be noted that the relative lack of large particles (Figures 13-14) means the capture efficiency estimates are not as precise for that of the smaller particles which can potentially influence the total volume of particle capture. Applying the theoretical aerosol model by Rubenstein and Koehl (1977), the dominant mechanism for water velocities of 10-30 cm/s for small particles (10µm) is direct interception, with mechanisms of gravitational deposition and inertial impaction increasing to 10-33% of direct interception when particle diameter reaches 50µm according to calculations undertaken from Shimeta and Jumars (1991). This is supported through Malone et al (1980), who concluded that the mechanism of Brownian motion is that small particles only applies to particles generally less than 1 micron, and that larger particles will be transported by interception and gravity.

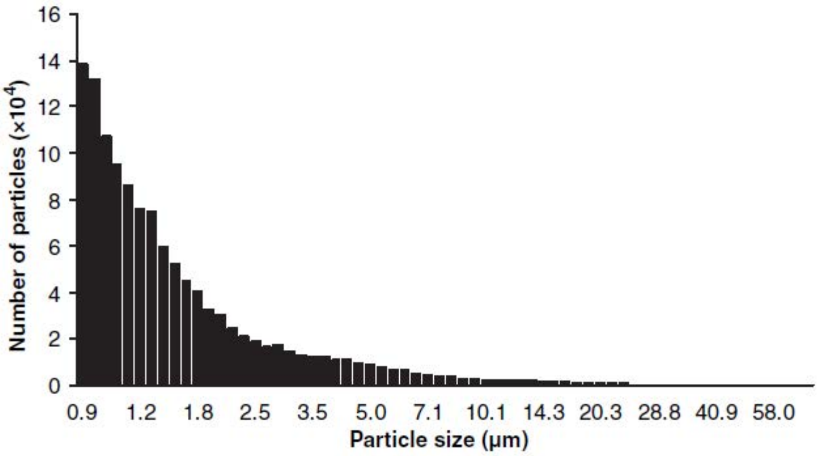


Figure 13: Combined size frequency of particles in water.
Source: Brown et al (2005)

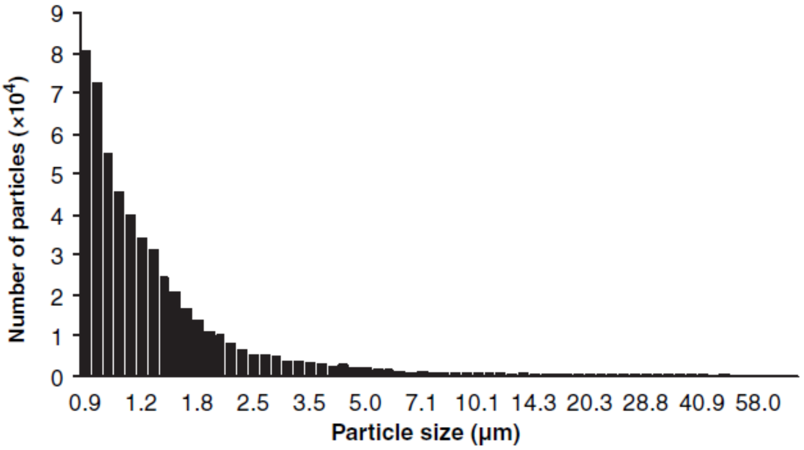


Figure 14: Combined size frequency of particles retained in nets. Source Brown et al (2005)

These findings in regards to natural filters are supported through many similar tests, with the majority of particles captured being smaller than mesh apertures. For example, Fuller et al (1983) and Loudon (1990) showed that 30 µm particles were captured relative to the 50µm nets. This is reinforced with Malone et al . (1971) who demonstrated that 50% of material with a mean diameter of 16 µm was captured by mesh with the smallest diameter of 22 µm, therefore forming similarities with Logan (1993) and Brown et al (2005) in the fact that sieving cannot be the only mechanism.

To analyse the potential of particle removal by sieving and therefore potentially be able to quantify the magnitude of particle removal by solely investigating other mechanisms, an analysis was undertaken by Palmer et al (2004) in which particle capture for a single filter was measured. As with previous findings, Palmer showed that an increase in Reynolds number lead to increased particle capture, as did an increase in the particle ratio 'R' (between 0.008-0.03). It must be noted that capture is more responsive to R then Re, as to double the capture R would need to be increased by 1.5 whilst Re would need to be tripled to have the same effect. It was expected that direct interception was the major mechanism of particle removal, with the estimation of total efficiency from experimental results given by Palmer et al (2004):

$$n = 0.224(Re)^{0.718}(R)^{2.08} \quad [9]$$

where Re is the Reynolds number and R is the particle ratio, defined as the particle diameter to fibre diameter.

The main concern of these practical results is to do with the simplified testing procedures. Capture efficiencies can be altered depending on the type of particles, as it has been demonstrated that hydrophobic particles will attach in preference to hydrophilic particles (Gerritsen and Porter, 1982). In addition, the above experiments did not take into account the numerous factors that cause particle flocculation which would alter the size and weight of the particle and would therefore influence results. This means that relying on previous experiments as a basis for a new analysis may be a problem, as obtaining reliable quantitative data may be impeded and therefore the interactions between particles between other particles as well as screens must be further researched.

Another potential issue includes comparing silk and metal mesh for removing pollutants. To determine if particle capture from metallic screens and silk nets were comparable an empirical test undertaken by Loudon (1990) was analysed. The paper demonstrated how the velocities through both steel and silk nets behaved, and under the assumption that velocity was directly proportional to particle capture could then conclude on the ability of both materials to retain particles. Similar regression lines and intercepts for both nets in terms of velocity through the filter mean that both nets will behave in similar ways provided that similar apertures are present, and therefore the results from the experiments previously mentioned can be compared with a degree of accuracy.

Flocculation

Analysing how particles interact with each other in regards to flocculation may be able to increase reliability when looking at previous experiments and theoretical modelling. The deposition and capture of cohesive sediment is strongly dependent on the process of flocculation, as it increases the particle size and settling velocity of the particles itself (Kranck, 1975).

The settling behaviour of a clay suspension is strongly controlled by water chemistry, electrolyte concentration and particularly pH (Shaw 2003). These factors will impact on the net surface charge on the particles, where the van der Waals force is dominant for suspended clay particles, while the electrostatic force is the main repulsive force due to the cloud of positive ions surrounding each particle. Lagaly et al (1997) gives the van der Waals potential:

$$V(r) = -\frac{A_H}{12}\left(\frac{d^2}{r-d^2} + \frac{d^2}{r^2} + 2\ln\left(\frac{r^2-d^2}{d^2}\right)\right) \quad [10]$$

where A_H is the Hamaker coefficient, usually equal to 10-19 J, d is the distance between the radius of the particle of filter fibre, and r is the distance between the surfaces of the particles.

Meanwhile the repulsive electrostatic force is given by:

$$V_{el} = \pi\varepsilon_r\varepsilon_o \text{ x } \left(\frac{4k_BT}{Z_e}\tanh\left(\frac{Z_e\varphi_o}{4k_BT}\right)\right)^2 \text{ x } d \text{ x } exp\big(-k(r-d)\big) \quad [11]$$

where ε_r and $\varepsilon_o$is the surface charge of the particle and filter fibre respectively, k_b is the Boltzmann constant, Z_e is the distance between the particle and fibre, φ_0 is the surface potential of the fibre and T is the absolute temperature.

Therefore the total inter-particle potential energy is the summation of equations 10 and 11 and will therefore dictate if there is an attraction or repulsion.

The effect of salinity on the settling of mud flocs has been the focus of various studies (Whitehouse et al 1960, Mehta, 1986) which have concluded that higher salinity will increase flocculation. This is confirmed by a recent study undertaken by Kim and Nestmann (2009), who demonstrated that NaCl concentration in water will impact on the rate of particle flocculation. This is because the Na+ concentration strongly influences flocculation when positively charged cations in the suspension formed a cloud around the negatively charged particles. At low NaCl concentration of 0.2g/L, the net interaction potential is repulsive as a function of distance between the particles, due to the lower number of positive ions (Na+) surrounding each negatively charged particle in the water. Conversely, the attractive potential became stronger than the repulsive force with a sufficient number of positive ions (at 4g/L), and hence it was observed that particles settled at a faster rate. The experiment concluded that in distilled water, negatively charged suspensions repelled each other whilst clusters increased with increasing salinity concentrations, and therefore experiments undertaken by Logan (1993) as well as those looking at natural filters may underestimate the maximum efficiency of filters to remove particles.

The same experiment also implied that the flocculation of quartz not only depended on salinity but also on an increase in the concentration of particles (Kim and Nestmann, 2009). Whilst general literature shows that hindered settling occurs as concentrations reach 10g/L, this experiment indicated that it wasn't until a concentration of 20g/L was achieved until quartz deposition rates were significantly reduced due to the increased negative charges that were present in the water.

Other water properties that can impact on flocculation is the solution pH which significantly affects the dispersion and cohesive behaviour of the model materials. The test undertaken by Kim and Nestmann (2009) showed that under acidic conditions, the settling velocity of alumina was decreased, whereas in alkaline solution, the settling velocity was increased. Furthermore, within a pH range of 6.5 to 8, Al experienced agglomeration and the particles were attracted to each other as van Der Waals dominated. Meanwhile, in an alkaline medium, a low settling velocity was measured for quartz, which then increased under acidic conditions, further highlighting the limitations in theoretical and practical experiments in regards to filtration efficiency.

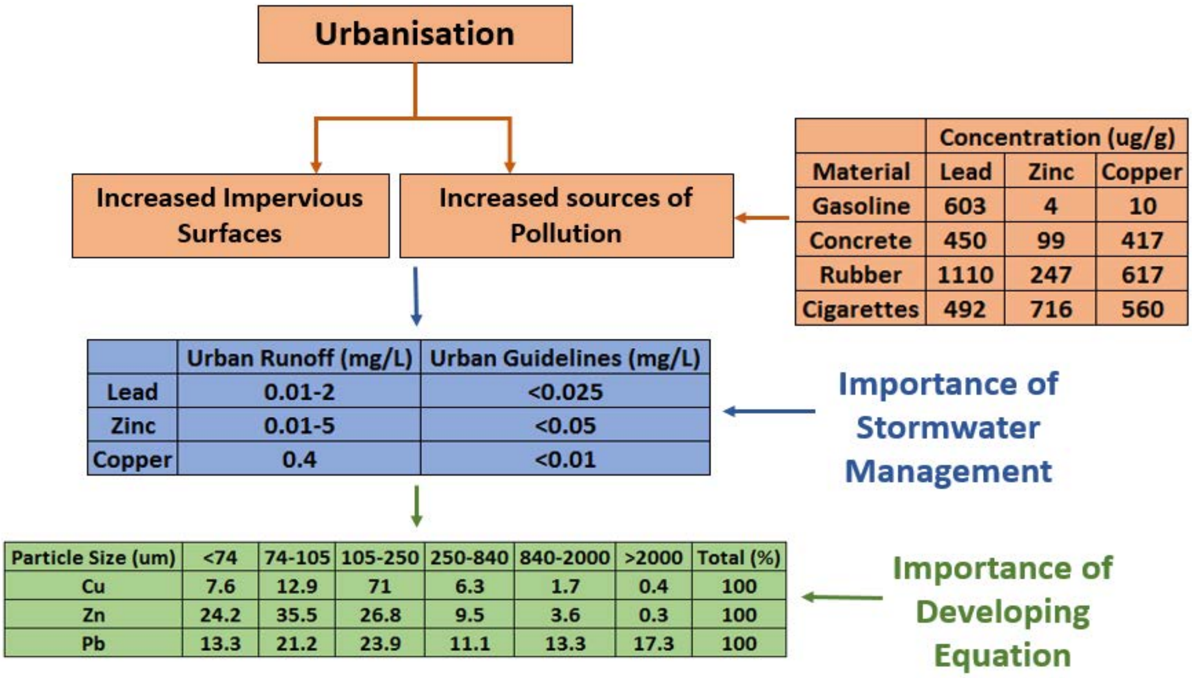
Differential settling is another factor besides an increased net attraction between particles that can lead to floc growth, until the limiting size is reached in which large shearing forces in the fluid break them up (van Rijn, 1993, Haralamphides et al 2003) as hydrodynamic forces exceed floc strength. Similar to pH and particle concentration, this notion means that experiments above can potentially be incorrect as the concentration of particles were not considered as potential mechanisms impacting of the size distribution of particles.

Conclusion

In conclusion, based on the theoretical output of certain models, it was assumed that the capillary pore model is the most accurate estimate for particle removal by a filter. These theoretical models combined with results derived in the field conclusively prove that sieve theory is not the sole mechanism that hinders particle movement through a filter, as aquatic particles are removed from water largely through interception and to some degree impaction and gravitational methods. Limitations are present in both theoretical and practical experiments due to the inability to quantify sticking coefficients as well as the potential of clogging after a certain duration, however the most significant absence is the notion of flocculation which is a function of numerous factors such as pH and particle size, which leads to altered size-distributions retained by the filter.

Method

The testing procedure undertaken is shown below in Figure 15.



	Concentration (ug/g)		
Material	Lead	Zinc	Copper
Gasoline	603	4	10
Concrete	450	99	417
Rubber	1110	247	617
Cigarettes	492	716	560

	Urban Runoff (mg/L)	Urban Guidelines (mg/L)
Lead	0.01-2	<0.025
Zinc	0.01-5	<0.05
Copper	0.4	<0.01

Particle Size (um)	<74	74-105	105-250	250-840	840-2000	>2000	Total (%)
Cu	7.6	12.9	71	6.3	1.7	0.4	100
Zn	24.2	35.5	26.8	9.5	3.6	0.3	100
Pb	13.3	21.2	23.9	11.1	13.3	17.3	100

Figure 15: Layout of the experimental design

Each round of testing consisted of one of three velocities (0.18 m/s, 0.12 m/s or 0.08 m/s) with a certain screen aperture (180um, 500um or 840um) and material (Blackwattle Bay or Tumblemate material). For each round, four concentrations were tested as shown in Figure 15 which corresponded to 1, 1.5, 2 and 2.5 (equating to 1.62, 2.43, 3.24 and 4.05 g/L) the average high stormwater concentration as set out in the Australian Runoff Quality Guidelines, which are standards used in the stormwater industry for pollution levels.

The setup of the Tumblemate system in the Environmental Lab is shown in Figure 16.

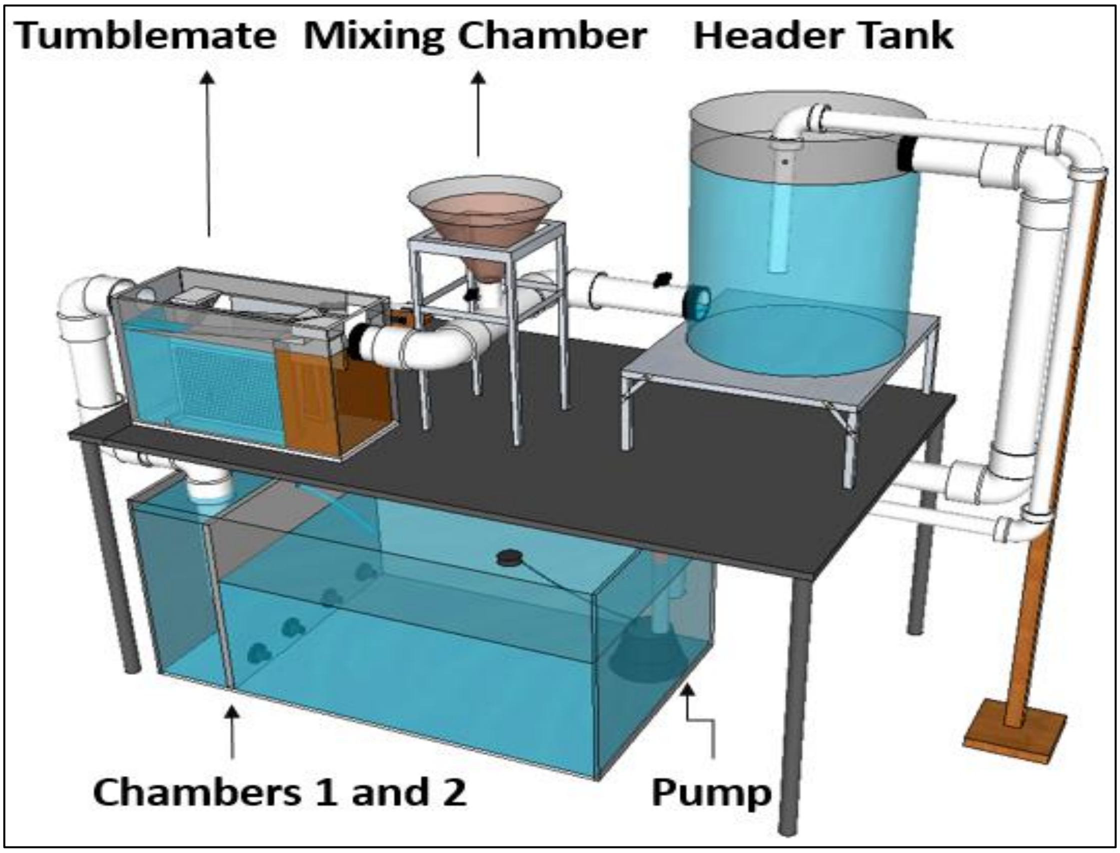


Figure 16: Setup of the Tumblemate prototype in the Environmental Lab

The first step was to calibrate flow rates for different openings of the ball valve from the header tank and the mixing chamber. Pipe 1 was disconnected from the setup to allow water to flow into a 5L container from the header tank. The time taken to fill this bucket was then used to calculate the flow rates as demonstrated in Equation 12. Pipe 2 was then disconnected so as to allow flow rates to be determined from the mixing chamber.

$$flow\ rate\ \left(\frac{L}{\min}\right) = \frac{Volume}{Time} \qquad [12]$$

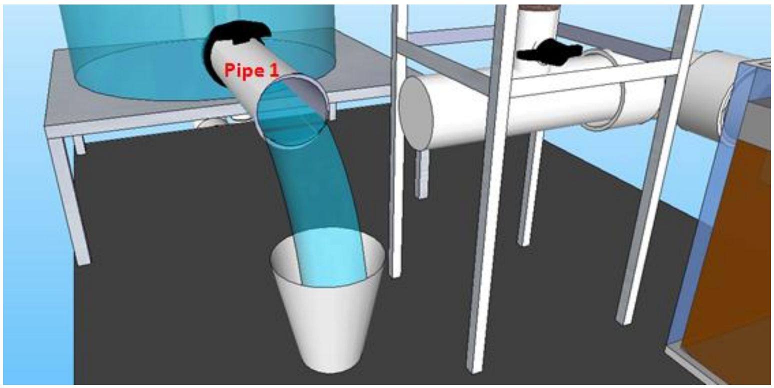


Figure 17: Calibration of the header tank ball valve

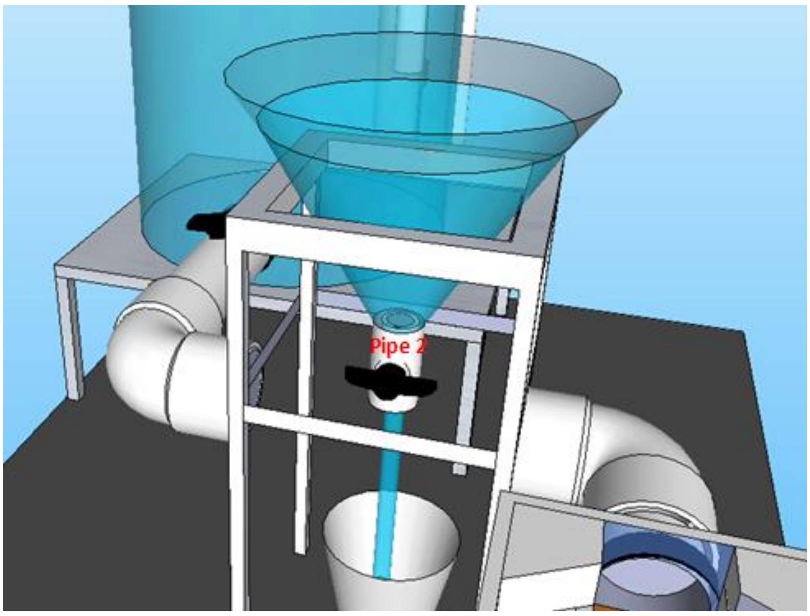
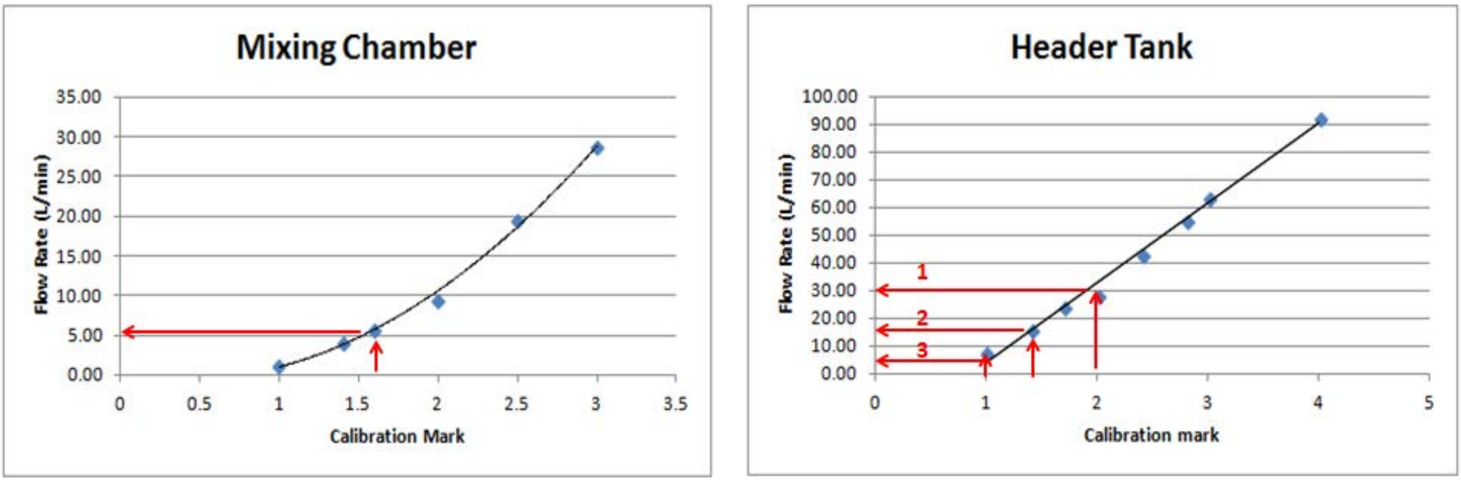


Figure 18: Calibration of the mixing chamber ball valve.

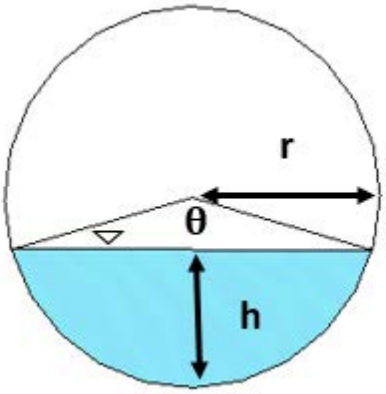
The mixing chamber was kept at a constant flow rate of 5 litres/minute during the experiment. A bucket was filled with 5 litres of water from the header tank every minute to use for the mixing chamber to ensure the total volume of water within the system remained constant throughout the experiment.

The ball valve from the header tank was calibrated to allow flow rates of 5L/min, 15L/min and 30 L/min to create total flow rates of 10L/min, 20L/min and 35L/min as seen in Figures 19 and 20.



Figures 19 and 20: Calibration curves for Mixing Chamber and Header Tank respectively with the calibration marks that were used labelled

To correlate these values into a flow velocity, the depth of water flow in pipe 4 was measured at the given flow rate. The cross sectional area of the water flow was calculated through equation 13 and 14, with the flow velocity being determined by equation 15.



$$\theta = 2\arccos\left(\frac{r-h}{r}\right) \quad [13]$$

$$A_{flow} = \frac{r^2(\theta - \sin\theta)}{2} \quad [14]$$

$$v = \frac{Q}{A} \quad [15]$$

Figure 21: Diagram for parameters used in equations 13-14.

To maintain a constant concentration, a series of cups with equal amounts of soil were weighed prior to testing, to be poured in at one minute intervals for the duration of the experiment. The amount of soil in each cup was determined by equations 16.

$$weight\ in\ cup\ \left(\frac{g}{cup}\right) = Q\ \left(\frac{L}{minute}\right) * concentration\ \left(\frac{g}{L}\right) * 1\ \left(\frac{minute}{cup}\right) \quad [16]$$

The number of cups for the entire experiment was dependant on the total load as demonstrated in equation 17 for Blackwattle Bay material and equation 18 for Tumblemate material. Note the Blackwattle Bay material was more abundant and therefore more could be used to reduce relative error.

$$Weight\ in\ each\ cup\ (g) * Number\ of\ Cups > 1300g \quad [17]$$

$$Weight\ in\ each\ cup\ (g) * Number\ of\ Cups > 600g \quad [18]$$

To start, water was added to the header tank from a nearby tap and allowed to flow through the system. In the experiment, constant head in the tank was maintained by a ball pump in chamber 2 which allowed water to flow into the header tank once the water reached a certain height in the chamber. To ensure a constant water volume (and hence water height) for each experiment, the height in the header tank once water was pumped from chamber 2 was marked and taken as the reference for each experiment.

The duration of the experiment was time between the first cup being poured into the mixing chamber until all material from the last cup had filtered through. The new concentration was then calculated from the new time using equation 19.

$$conc\ \left(\frac{g}{L}\right) = \frac{1}{flow\ rate}\left(\frac{min}{L}\right) * \frac{1}{time}\left(\frac{1}{min}\right) * weight(g) \quad [19]$$

After all soil had either been subject to screening the water flow was turned off and any suspensions allowed to settle for an appropriate amount of time. Soil was removed from each compartment using a hand held pump (Figure 25) to create a wet vacuum action (Figure 26) and placed in its corresponding bucket for further analysis.

Soil in Compartment 3 was the first to be removed from the system due to ease of access which was followed by compartment 1. Proceeding this, the two screens were removed with the remaining soil being pumped out of the system belonging to compartment 2.

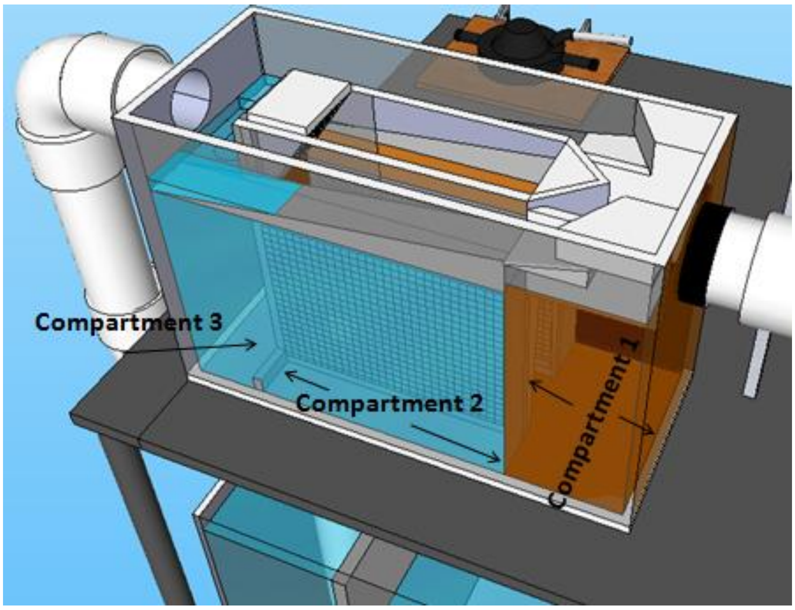


Figure 22: Diagram showing the three different compartments of the Tumblemate setup

For Blackwattle Bay tests, soil passing through the system was collected in the header tank and chambers one and two at the end of each round (four tests) as it was deemed that very little concentration remained in suspension and hence would not be recirculated through the system. For the Tumblemate material this was done after every test to ensure minimal particles that passed through the screen made its way back into the system. Material that was classed as passing through the system is depicted in Figures 23 and 24.

Four sieves were used to fraction out the soil from solution, measuring 20um, 75um, 105um and 150 um. Once the solution passed through the sieves the weight of the soil could be determined by any additional increase in weight of the sieves.

For Compartment 1 a jar was used in addition to the sieves to carry the extra load of soil. This was done by placing some of the soil captured by the 150um sieve into a jar as the scales could only handle weights under 1.1 kg.

After weighing, all soil was collected and each compartment was placed in a separate jar. This soil was then dried out for several days until moisture content was small enough so that it was evident that no particles were sticking together or water droplets were seen under the microscope.

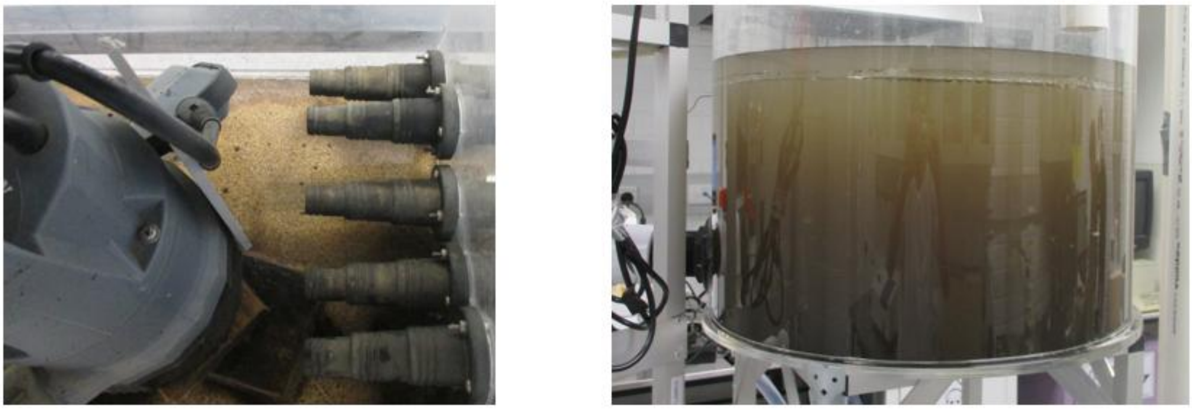
Once the soil was deemed to be dry, random samples were taken to be analysed under the microscope for size distribution analysis. Images that were taken from the USB microscope was then scanned through the software program Matlab to determine particle size (Figure 27). The code was able to read the amount of pixels that each particular particle represented which could be converted to an area and hence diameter knowing the dimensions of the original photo as evident in equation 20. The code for this script is in Appendix A.

$$1600\ horizontal\ pixels = 5.2mm$$

$$\therefore 1\ horizontal\ pixel = 3.25\ \mu m$$

$$Area_{pixel} = 3.25^2 = 10.56\ \mu m$$

$$Size\ (\mu m) = Diameter = 2 * \sqrt{\frac{Area_{pixel} * no.of\ pixels}{\pi}} \qquad [20]$$



Figures 23 and 24: Material that was classed as ‘missing’ in the Chambers 1 and 2 and the header tank respectively

Figure 25: Hand held pump used to create a wet vacuum to suck particles out of each compartment

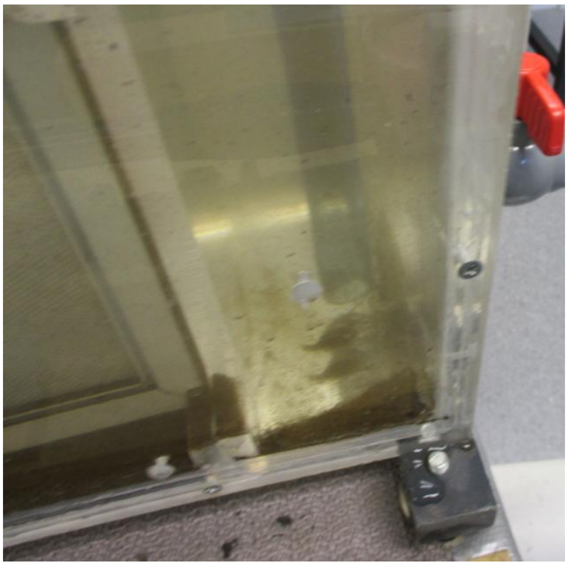
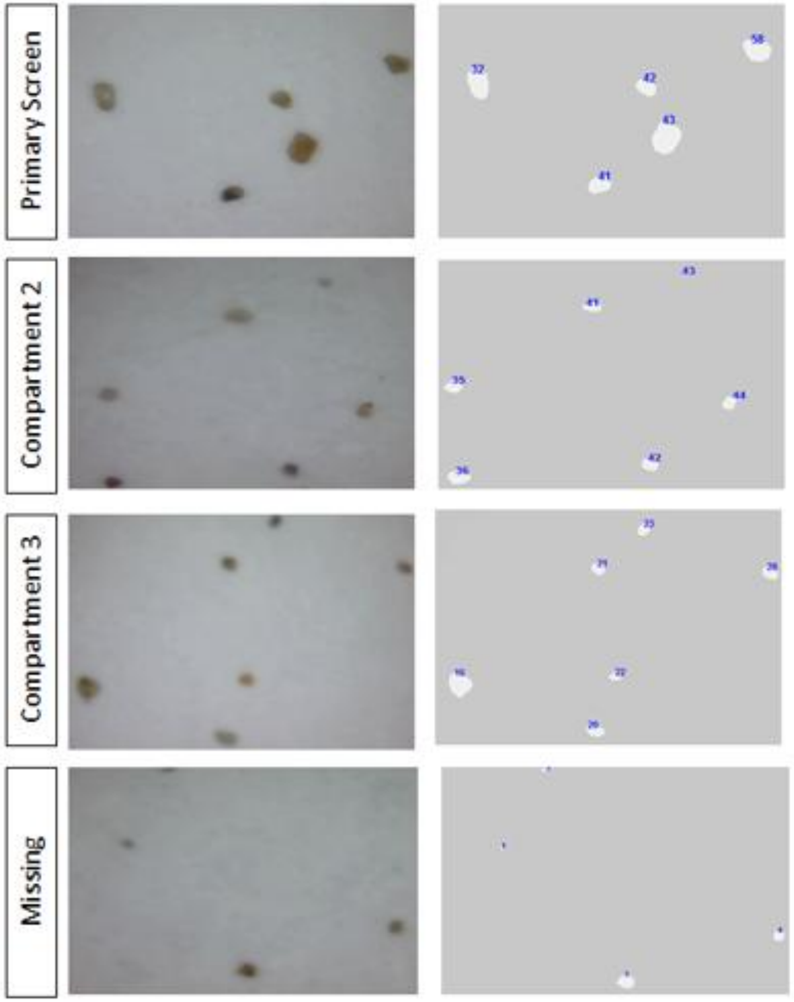


Figure 26: Wet vacuum obtaining material from Compartment 3

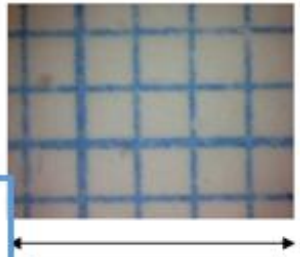


Particle ID	Pixels	Size (um)
32	3939	115.31
41	2372	89.48
42	2162	85.43
43	5585	137.31
58	3767	112.77

Particle ID	Pixels	Size (um)
35	1474	70.54
36	2106	84.32
41	1313	66.58
42	1558	72.52
43	152	22.65
44	1458	70.16

Particle ID	Pixels	Size (um)
16	4973	129.57
20	1913	80.36
21	1511	71.42
22	859	53.85
23	1369	67.98
28	1846	78.94

Particle ID	Pixels	Size (um)
1	82	16.6
2	129	20.87
3	1316	66.65
4	717	48.85



5.2 mm = 1600 pixels

$1\ pixel\ length = 3.25\ \mu m$

$Area_{pixel} = 10.6\ \mu m$

$Assume\ A = \pi r^2$

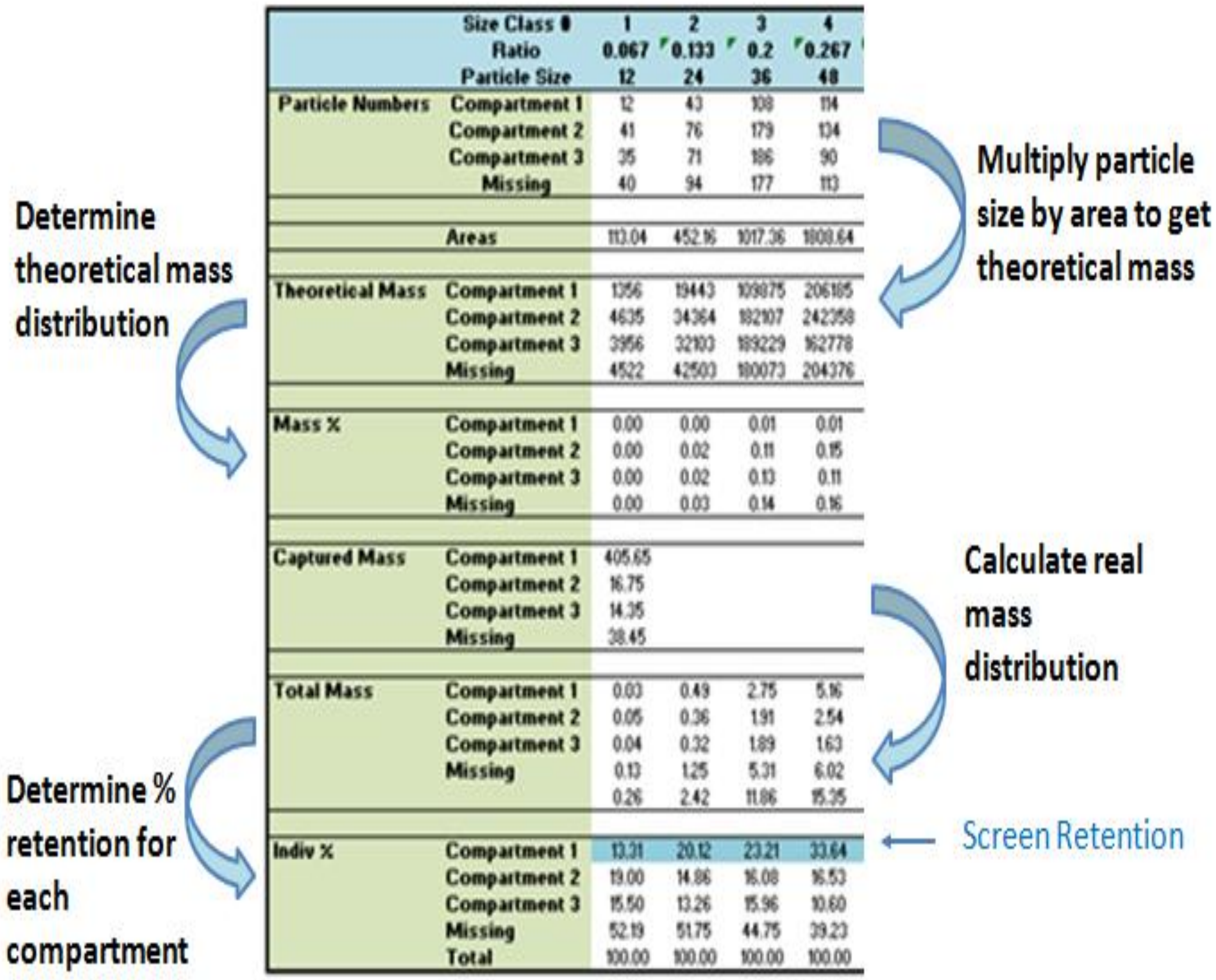
$$r = \sqrt{\frac{A}{\pi}}$$

Particle #	1	2	3	4	5	6	7	8	9
Primary Screen	115	89	85	137	113	187	190	35	77
Comp 2	71	84	67	73	23	70	70	91	40
Comp 3	130	80	71	54	68	79	64	61	51
Missing	17	21	67	49	55	13	29	45	66

Figure 27: Method for determining particle size in each compartment using the microscope

For the microscope analysis, individual particles were placed in 'particle ratio' classes for each compartment. Each particle class represented 1/15 of the screen aperture, with particles larger than this being broken down into classes of approximately 100 microns. By undertaking the analysis using particle ratios, all three screen apertures could then be compared to each other so as to yield more data to develop the relationship between particle ratio and removal efficiency.

The theoretical mass for each size class was calculated using areas of the middle value in the particular class which allowed the theoretical mass distribution to be determined. By multiplying this with the actual mass caught in the compartment, the total mass in each size class was calculated which allowed the primary screen efficiency to be determined. An example of this is shown in Figure 28, with full results for individual tests are shown in Appendix B.



	Size Class #	1	2	3	4
	Ratio	0.067	0.133	0.2	0.267
	Particle Size	12	24	36	48
Particle Numbers	Compartment 1	12	43	108	114
	Compartment 2	41	76	179	134
	Compartment 3	35	71	186	90
	Missing	40	94	177	113
	Areas	113.04	452.16	1017.36	1808.64
Theoretical Mass	Compartment 1	1356	19443	109875	206185
	Compartment 2	4635	34364	182107	242358
	Compartment 3	3956	32103	189229	162778
	Missing	4522	42500	180073	204376
Mass %	Compartment 1	0.00	0.00	0.01	0.01
	Compartment 2	0.00	0.02	0.11	0.15
	Compartment 3	0.00	0.02	0.13	0.11
	Missing	0.00	0.03	0.14	0.16
Captured Mass	Compartment 1	405.65			
	Compartment 2	16.75			
	Compartment 3	14.35			
	Missing	38.45			
Total Mass	Compartment 1	0.03	0.49	2.75	5.16
	Compartment 2	0.05	0.36	1.91	2.54
	Compartment 3	0.04	0.32	1.89	1.63
	Missing	0.13	1.25	5.31	6.02
		0.26	2.42	11.86	15.35
Indiv %	Compartment 1	13.31	20.12	23.21	33.64
	Compartment 2	19.00	14.86	16.08	16.53
	Compartment 3	15.50	13.26	15.96	10.60
	Missing	52.19	51.75	44.75	39.23
	Total	100.00	100.00	100.00	100.00

Multiply particle size by area to get theoretical mass

Determine theoretical mass distribution

Calculate real mass distribution

Screen Retention

Determine % retention for each compartment

Figure 28: Example of the methodology used to convert microscopic images to particle and mass distributions to determine primary screen efficiencies

To determine a single equation for primary screen efficiency with respect to particle ratio, velocity and concentration equations 21 to 25 were used.

$$E = C_1 R^{\alpha 1} + C_2 v^{\alpha 2} + C_3^{\alpha 3} + C_4 \quad [21]$$

where C1, C2, C3, C4, α1, α2 and α3 are all constants.

$$\log E = \log C_1 + \alpha_1 \log R + \log C_2 + \alpha_2 \log v + \log C_3 + \alpha_3 \log c \quad [22]$$

$$E' = C_1' + \alpha_1 \log R + C_2' + \alpha_2 \log v + C_3' + \alpha_3 \log c \quad [23]$$

$$E' = K + \alpha_1 lo\,g\,R + \alpha_2 lo\,g\,v + \alpha_3 c' \quad [24]$$

$$E' = K + \alpha_1 R' + \alpha_2 v' + \alpha_3 c' \quad [25]$$

The coefficients were then determined using matrix operations.

Linear regression was then performed to determine coefficients in equation 21 and hence the final equation for particle removal in the Tumblemate system.

Results

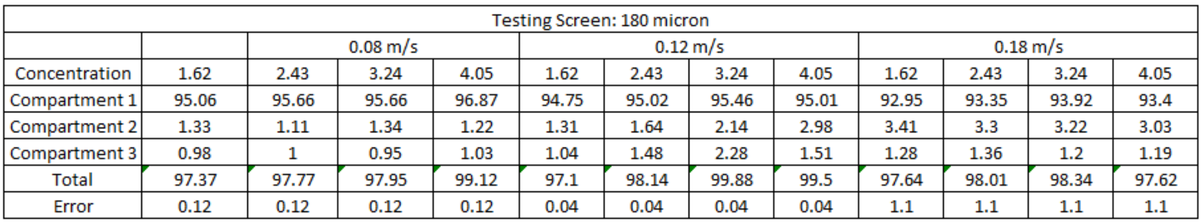
The final equation that governs particle removal is given by equation 26.

$$E = 0 < -71.82 + 4.33R^{0.692} + 42.43v^{-0.179} + 12.10c^{0.041} < 100 \qquad [26]$$

where E is the efficiency of the primary screen in %, R is the particle ratio as a %, defined as the ratio between particle diameter and screen aperture, v is the water velocity in metres per second, c is the total suspended concentration in grams per litre.

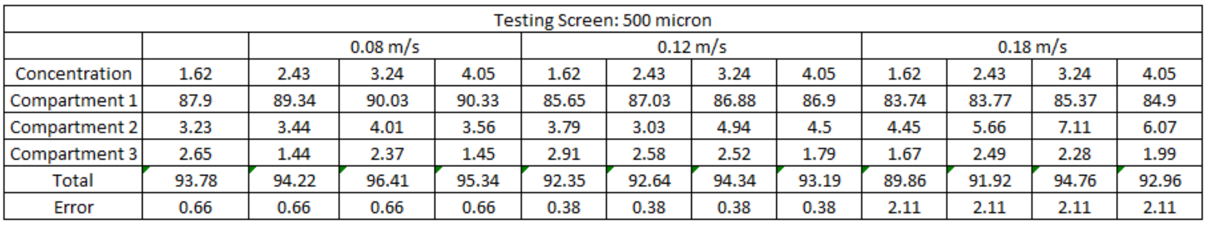
The equation has an adjusted R value of 0.945 and a p value < 0.05 using SPSS software.

Particle removal percentages for all tests and all compartments are shown in Tables 3-7.



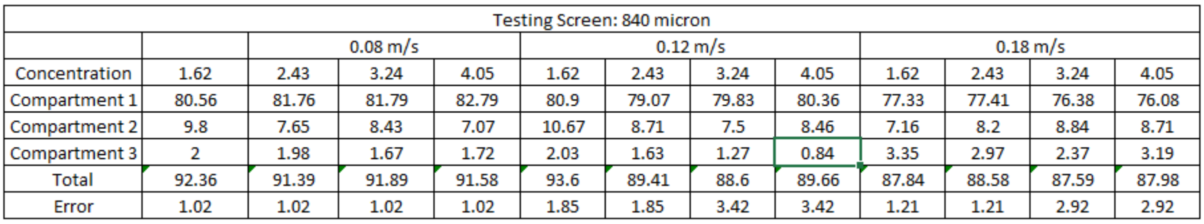
Testing Screen: 180 micron												
	0.08 m/s				0.12 m/s				0.18 m/s			
Concentration	1.62	2.43	3.24	4.05	1.62	2.43	3.24	4.05	1.62	2.43	3.24	4.05
Compartment 1	95.06	95.66	95.66	96.87	94.75	95.02	95.46	95.01	92.95	93.35	93.92	93.4
Compartment 2	1.33	1.11	1.34	1.22	1.31	1.64	2.14	2.98	3.41	3.3	3.22	3.03
Compartment 3	0.98	1	0.95	1.03	1.04	1.48	2.28	1.51	1.28	1.36	1.2	1.19
Total	97.37	97.77	97.95	99.12	97.1	98.14	99.88	99.5	97.64	98.01	98.34	97.62
Error	0.12	0.12	0.12	0.12	0.04	0.04	0.04	0.04	1.1	1.1	1.1	1.1

Table 3: Results for Blackwattle Bay testing for 180um screen



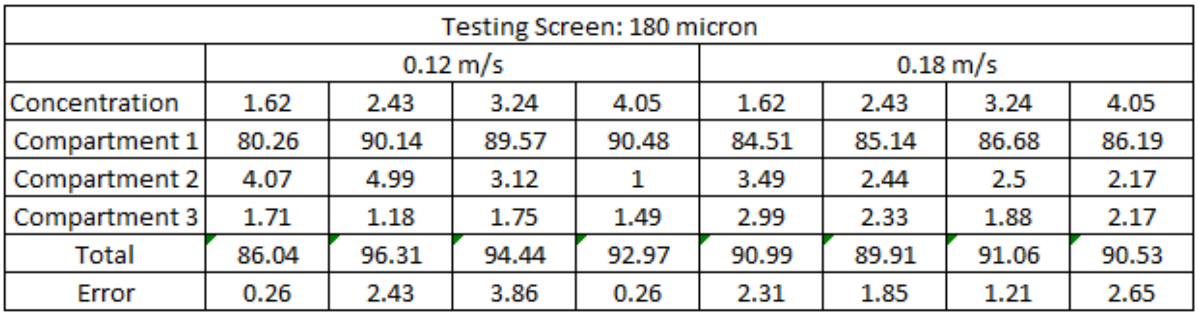
Testing Screen: 500 micron												
	0.08 m/s				0.12 m/s				0.18 m/s			
Concentration	1.62	2.43	3.24	4.05	1.62	2.43	3.24	4.05	1.62	2.43	3.24	4.05
Compartment 1	87.9	89.34	90.03	90.33	85.65	87.03	86.88	86.9	83.74	83.77	85.37	84.9
Compartment 2	3.23	3.44	4.01	3.56	3.79	3.03	4.94	4.5	4.45	5.66	7.11	6.07
Compartment 3	2.65	1.44	2.37	1.45	2.91	2.58	2.52	1.79	1.67	2.49	2.28	1.99
Total	93.78	94.22	96.41	95.34	92.35	92.64	94.34	93.19	89.86	91.92	94.76	92.96
Error	0.66	0.66	0.66	0.66	0.38	0.38	0.38	0.38	2.11	2.11	2.11	2.11

Table 4: Results for Blackwattle Bay testing for 500um screen



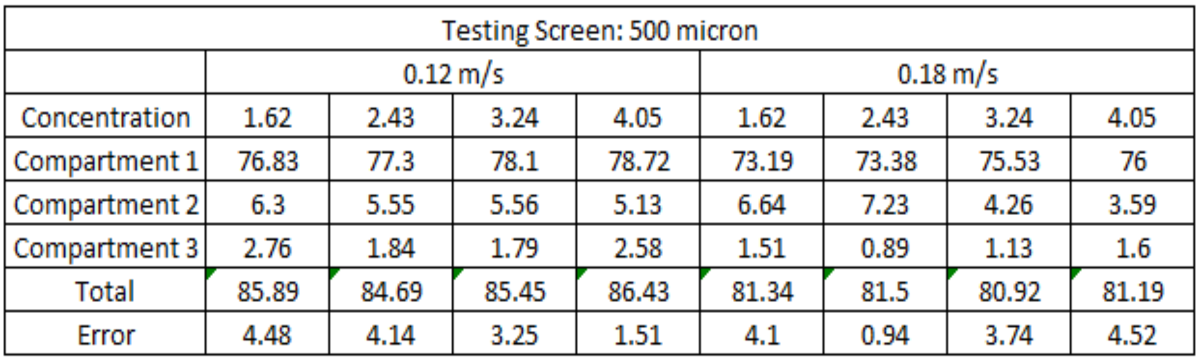
Testing Screen: 840 micron												
	0.08 m/s				0.12 m/s				0.18 m/s			
Concentration	1.62	2.43	3.24	4.05	1.62	2.43	3.24	4.05	1.62	2.43	3.24	4.05
Compartment 1	80.56	81.76	81.79	82.79	80.9	79.07	79.83	80.36	77.33	77.41	76.38	76.08
Compartment 2	9.8	7.65	8.43	7.07	10.67	8.71	7.5	8.46	7.16	8.2	8.84	8.71
Compartment 3	2	1.98	1.67	1.72	2.03	1.63	1.27	0.84	3.35	2.97	2.37	3.19
Total	92.36	91.39	91.89	91.58	93.6	89.41	88.6	89.66	87.84	88.58	87.59	87.98
Error	1.02	1.02	1.02	1.02	1.85	1.85	3.42	3.42	1.21	1.21	2.92	2.92

Table 5: Results for Blackwattle Bay testing for 840um screen



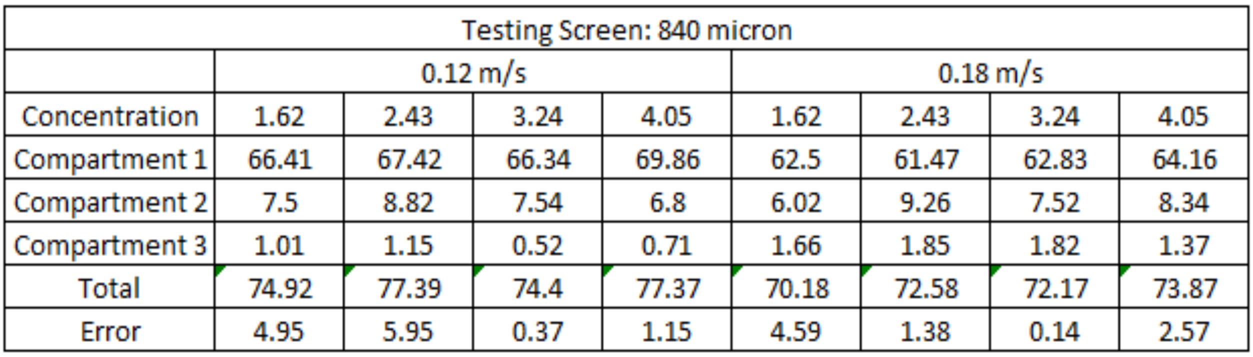
Testing Screen: 180 micron								
	0.12 m/s				0.18 m/s			
Concentration	1.62	2.43	3.24	4.05	1.62	2.43	3.24	4.05
Compartment 1	80.26	90.14	89.57	90.48	84.51	85.14	86.68	86.19
Compartment 2	4.07	4.99	3.12	1	3.49	2.44	2.5	2.17
Compartment 3	1.71	1.18	1.75	1.49	2.99	2.33	1.88	2.17
Total	86.04	96.31	94.44	92.97	90.99	89.91	91.06	90.53
Error	0.26	2.43	3.86	0.26	2.31	1.85	1.21	2.65

Table 6: Results for Tumblemate material testing for 180um



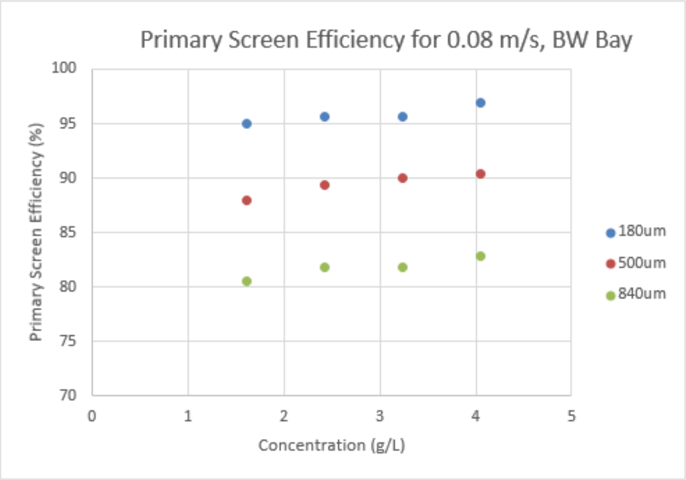
Testing Screen: 500 micron								
	0.12 m/s				0.18 m/s			
Concentration	1.62	2.43	3.24	4.05	1.62	2.43	3.24	4.05
Compartment 1	76.83	77.3	78.1	78.72	73.19	73.38	75.53	76
Compartment 2	6.3	5.55	5.56	5.13	6.64	7.23	4.26	3.59
Compartment 3	2.76	1.84	1.79	2.58	1.51	0.89	1.13	1.6
Total	85.89	84.69	85.45	86.43	81.34	81.5	80.92	81.19
Error	4.48	4.14	3.25	1.51	4.1	0.94	3.74	4.52

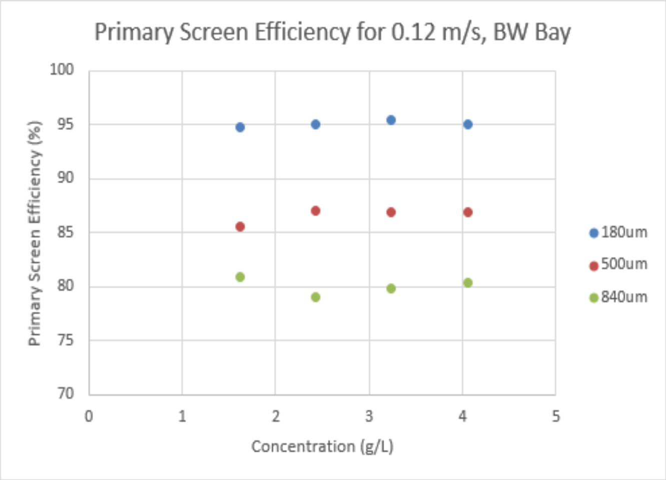
Table 7: Results for Tumblemate material testing for 500um



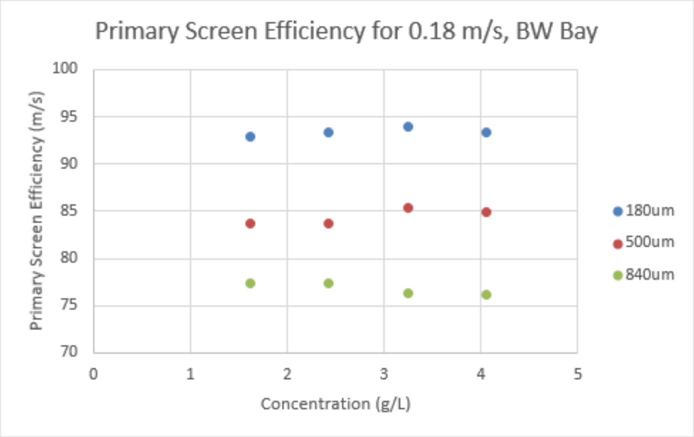
Testing Screen: 840 micron								
	0.12 m/s				0.18 m/s			
Concentration	1.62	2.43	3.24	4.05	1.62	2.43	3.24	4.05
Compartment 1	66.41	67.42	66.34	69.86	62.5	61.47	62.83	64.16
Compartment 2	7.5	8.82	7.54	6.8	6.02	9.26	7.52	8.34
Compartment 3	1.01	1.15	0.52	0.71	1.66	1.85	1.82	1.37
Total	74.92	77.39	74.4	77.37	70.18	72.58	72.17	73.87
Error	4.95	5.95	0.37	1.15	4.59	1.38	0.14	2.57

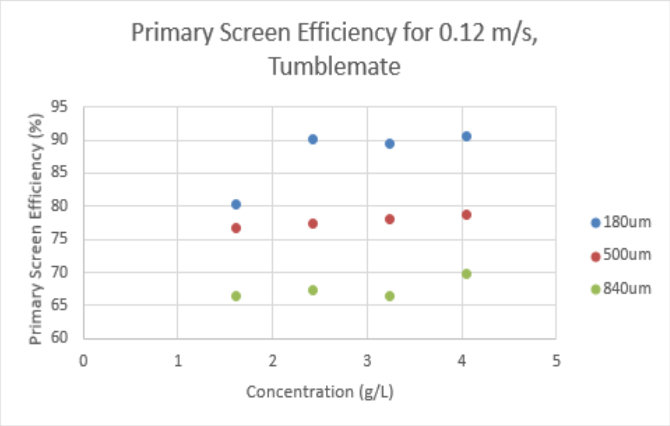
Table 7: Results for Tumblemate material testing for 840um





Figures 29 and 30: Primary screen efficiencies for velocities of 0.08 m/s and 0.12 m/s respectively for Blackwattle Bay material





Figures 31 and 32: Primary screen efficiencies for velocities of 0.18 m/s for Blackwattle Bay material and 0.12 m/s for Tumblemate material respectively

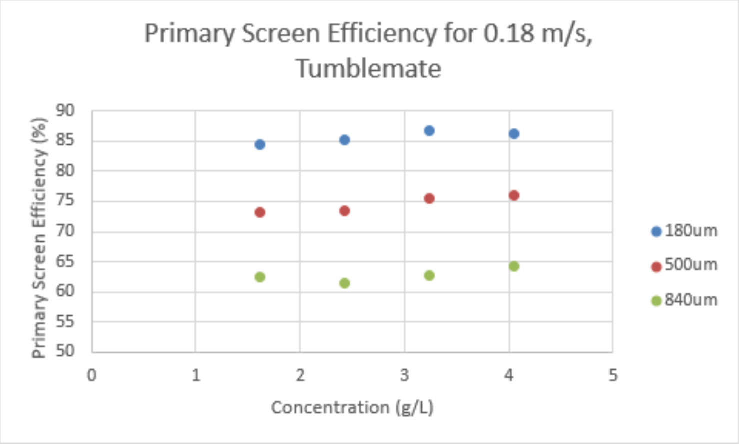
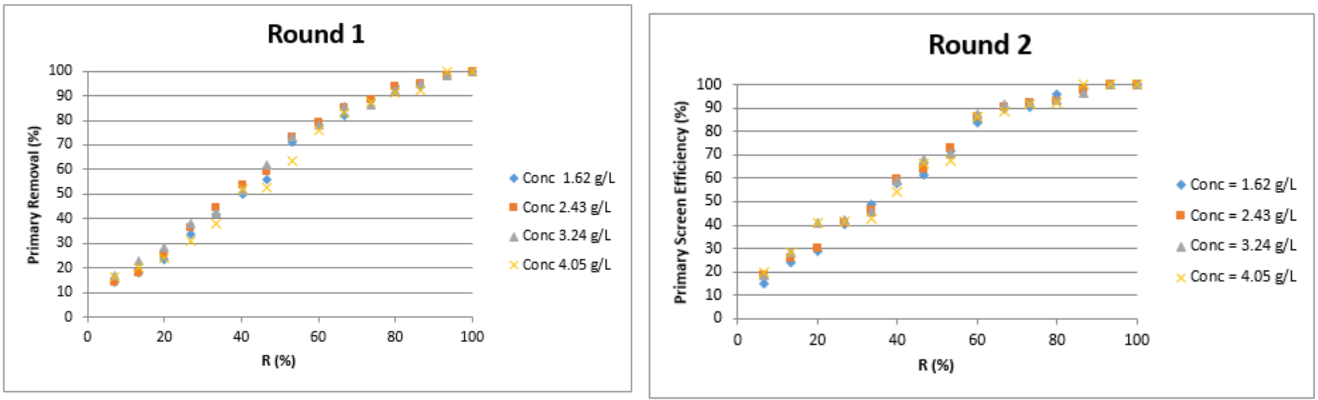
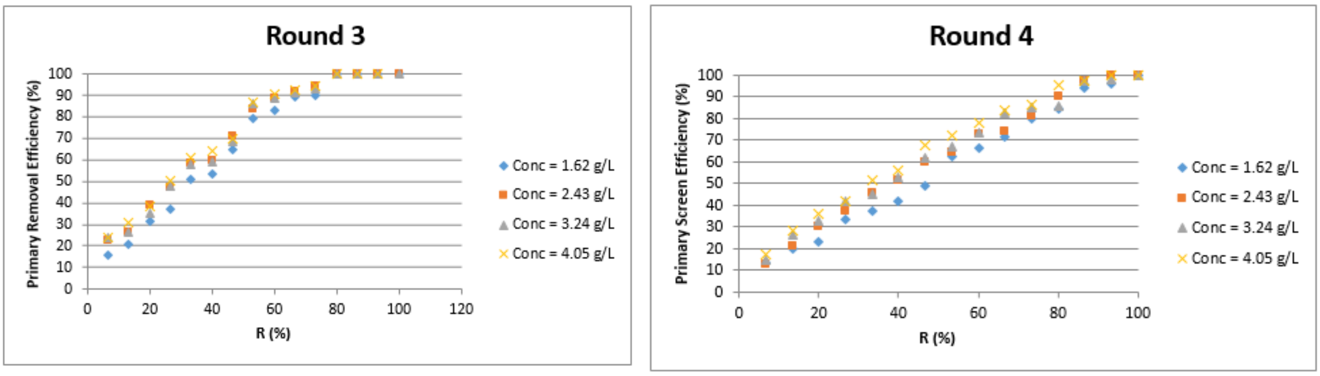


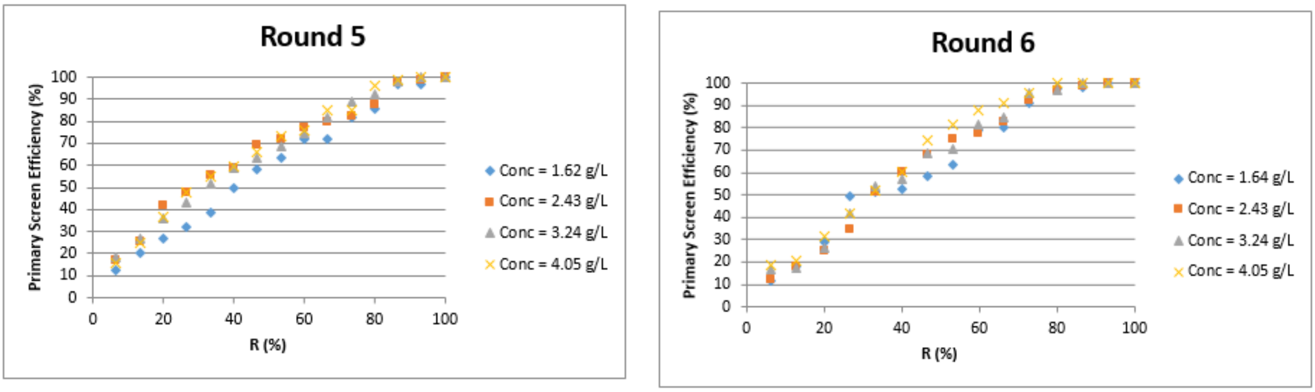
Figure 33: Primary screen efficiency for a velocity of 0.18 m/s for Tumblemate material



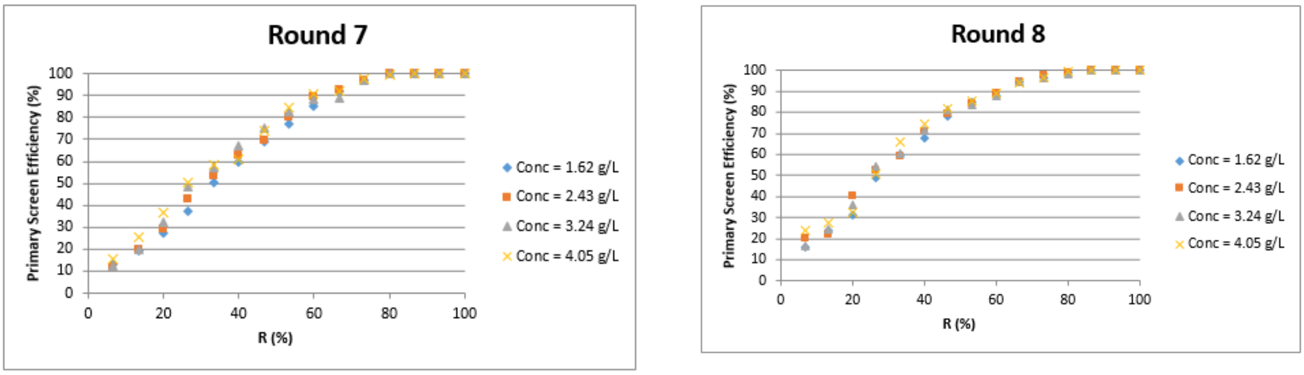
Figures 34 and 35: Results for rounds 1 and 2 of testing



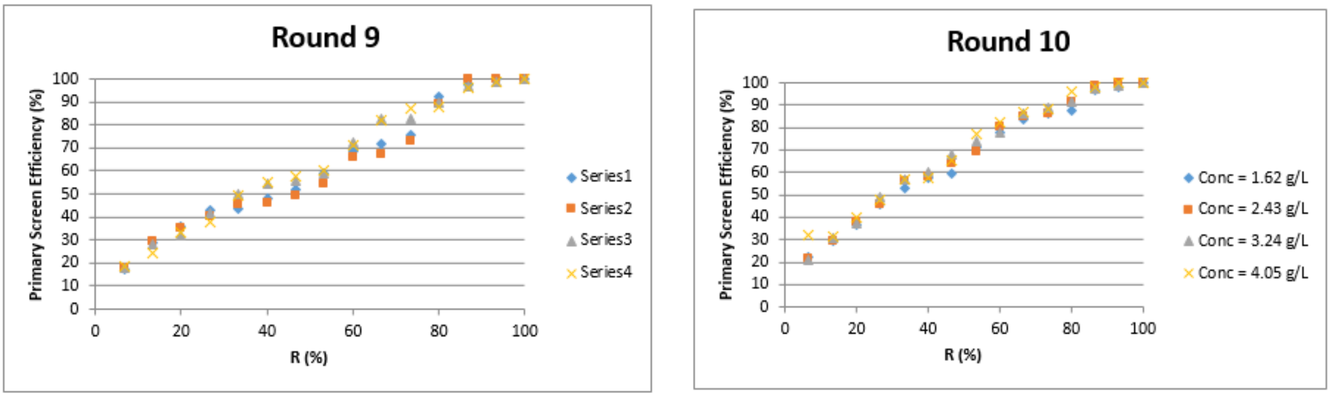
Figures 36 and 37: Results for rounds 3 and 4 of testing



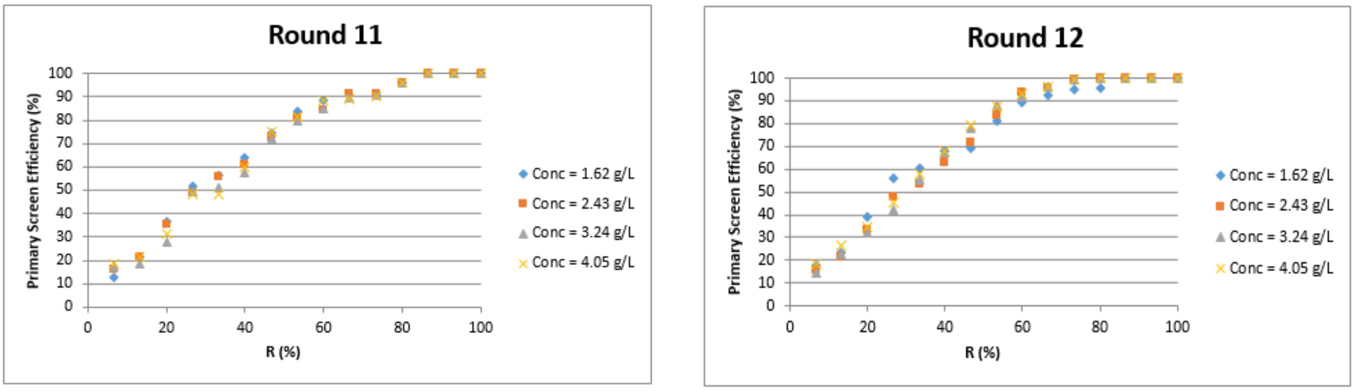
Figures 38 and 39: Results for rounds 5 and 6 of testing



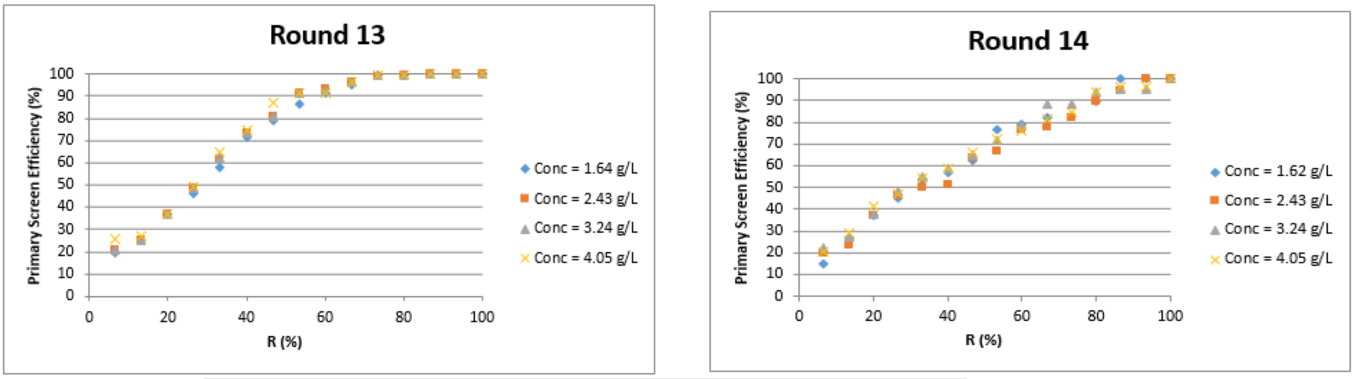
Figures 40 and 41: Results for rounds 7 and 8 of testing



Figures 42 and 43: Results for rounds 9 and 10 of testing



Figures 44 and 45: Results for rounds 11 and 12 of testing



Figures 46 and 47: Results for rounds 13 and 14 of testing

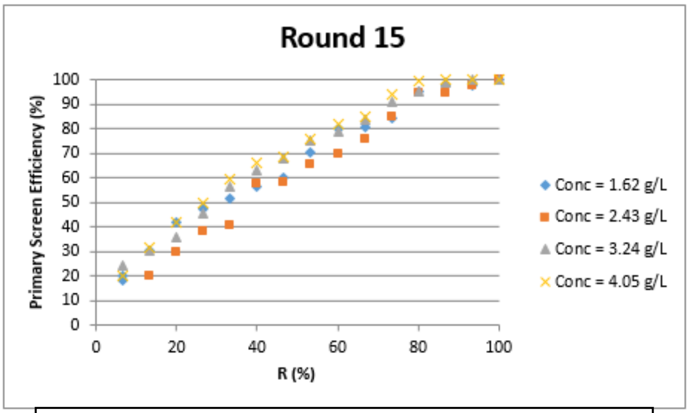


Figure 48: Results for round 15 of testing

Discussion

Primary Screening Efficiency Versus Particle Ratio

The experiment showed that there was a strong positive correlation between the ratio of particle size to pore diameter size. Generally, more than half of the particles with a ratio of 40% were removed from primary screen filtration, whilst greater than 95% of particles 80% of the filter size were removed. Practically all particles that had an R value of greater than 90% were removed from the Tumblemate system.

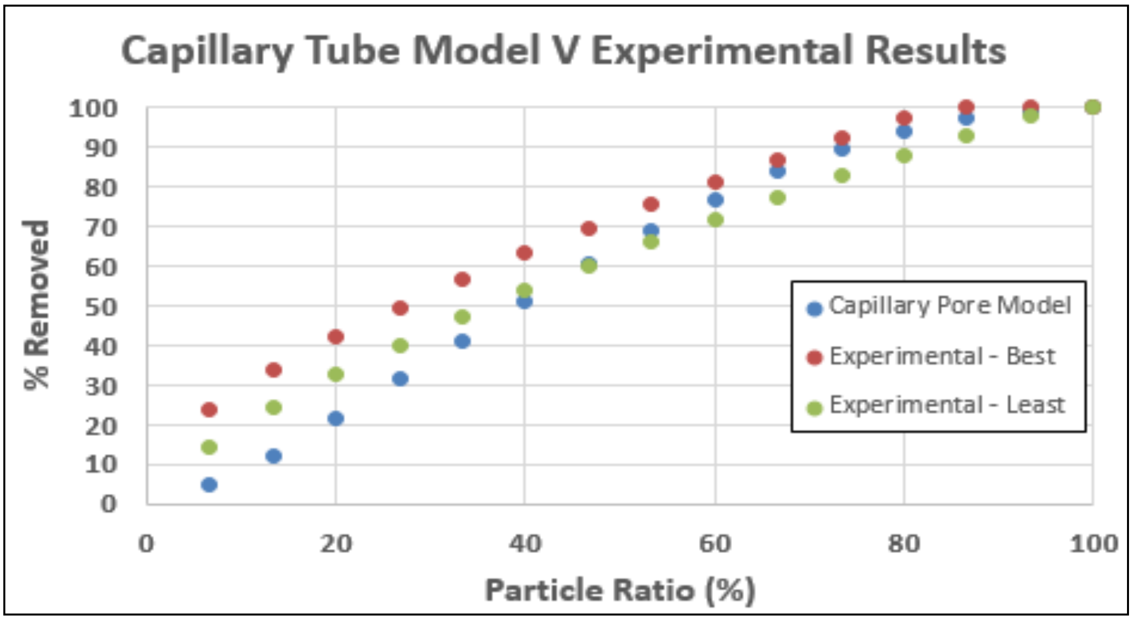


Figure 49: Comparison of the theoretical capillary tube model and experimental results

Using the capillary pore model, the ratio between the sizes of the particle relative to the mesh diameter plays a crucial role in determining the removal efficiency of a screen. Figure 49 shows the results based on equation 12 assuming a sticking efficiency of 100%, however this could be as low as 33% (Logan, 1993). With a sticking coefficient of unity the results reflect those derived in the experiment, with larger particles close to the mesh aperture being removed with a high efficiency approaching 100%. Figure 49 shows that the theoretical model follows similar trends to that of the derived experimental model, largely due to a comparable large dependence on the particle ratio evident in equations 12 and 26. Figure 49 shows that substituting the best case scenario in the experiment, with a velocity of 0.08 m/s and a concentration of 4.05 g/L yielded results that were elevated with respect to the pore model, whilst the worst case scenario with a velocity of 0.18 m/s and the lowest concentration of 1.64 g/L showed mixed results relative the model with heavier particles estimated to be removed with higher efficiency for the pore model.

For both experimental graph outputs, particles with a lower 'R' value were predicted to be removed with greater efficiency than that of the capillary pore model. This could be a consequence of the mechanism of the Tumblemate system, with a circular fluid motion created by the oil screens which initially sent particles to the bottom of Compartment 1, which could potentially remove these fines before they were subject to primary screening, thereby increasing the efficiency relative to the capillary pore model.

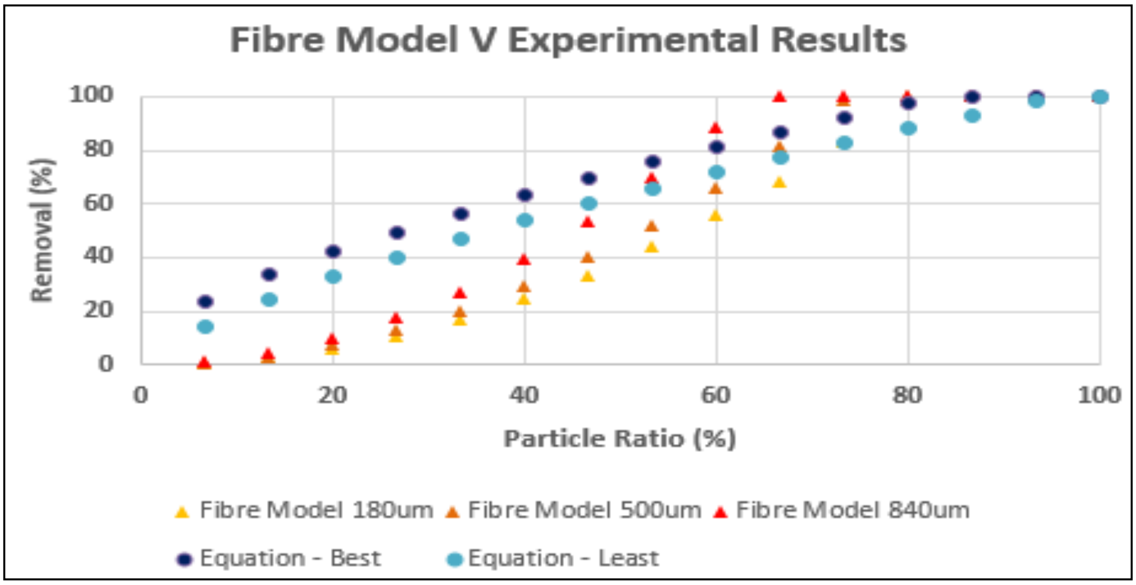


Figure 50: Comparison of different mesh sizes for the primary screen efficiency for the theoretical Yao single collector model

The Yao model for single collector efficiency varies greatly for removal efficiencies for each particular screen size (Figure 50) – as its efficiency depends on the ratio between particle size and the pore size (equation 2), but rather the particle size and width of the fibre – which for the experiment was 1mm. The advantage of this method is that the gravitational component of equation 3 predicts that for the same R value for different screens, the larger screen size will have a greater removal efficiency as larger particles will tend to settle out quicker in suspension and therefore be more likely to be removed by primary screen filtration.

Particle Removal Efficiency Versus Velocity

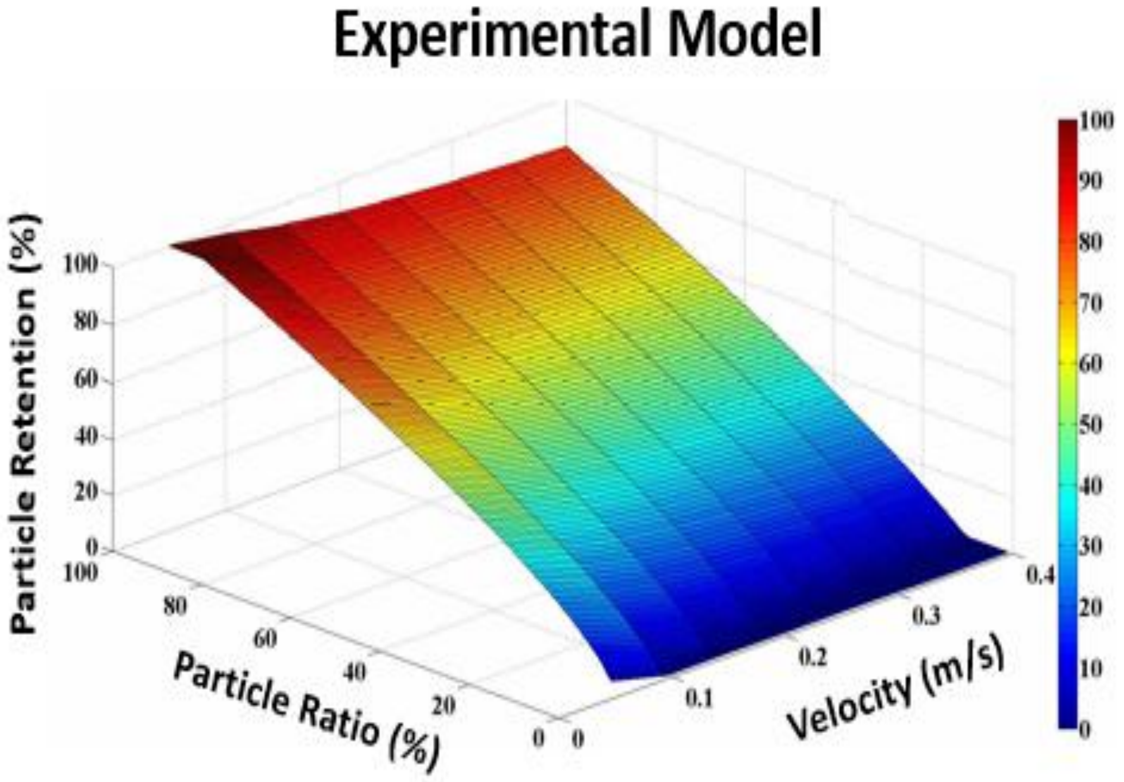


Figure 51: Graphical representation of the equation derived from the experiment showing the influence of velocity and particle ration of primary screening efficiency.

The results showed that there was a negative correlation between velocity and particle removal. As seen in Figure 51, particle removal efficiency continually declines until a velocity of 0.25 m/s is reached in which a relatively constant value is achieved.

The interception mechanism in the capillary pore model does not take into account velocity which is only present in the diffusion term as seen in equation 11. As the soil mass distribution was mostly larger than the 35 micron, diffusion was considered to have minimal effect as this generally impacts on particles of a size of 1 micron or less, thereby negating any impact that velocity would have according to the capillary pore model.

Two of the three parameters for the fibre model are dependent on velocity, namely diffusion and gravitation (equation 1 and 3 respectively). Similarly, diffusion for the pore model was disregarded in theoretical calculations, however gravitation effects are relatively important, with an increase in water velocity compared to the particle settling velocity creating a significant decline in particle removal velocity evident in Figure 52.

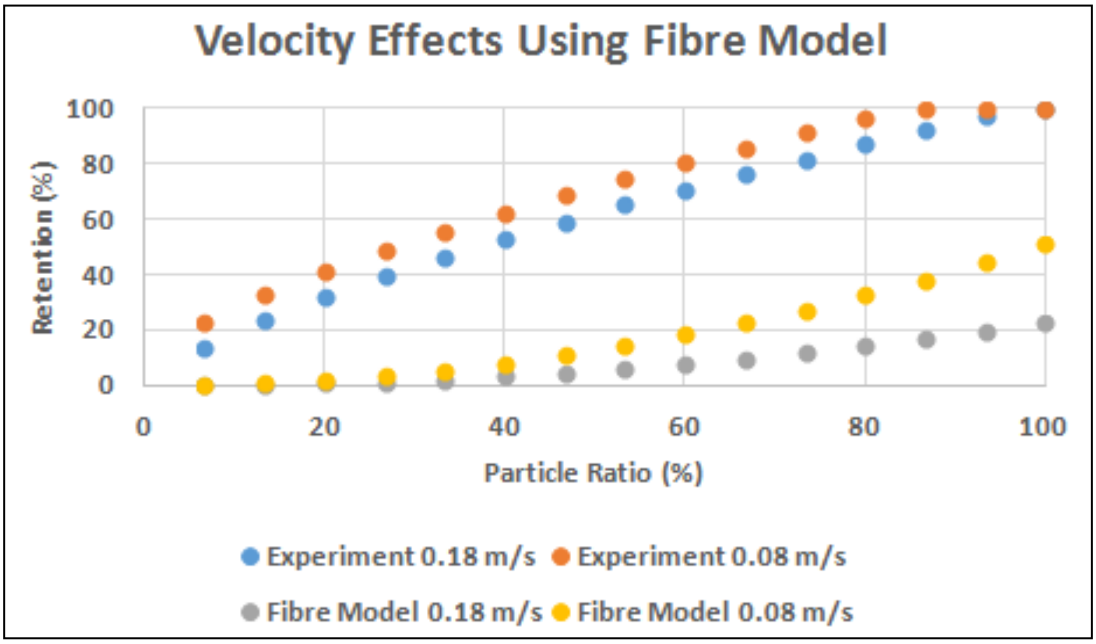


Figure 52: Impact of velocity on gravitation deposition mechanism for the fibre model compared to experimental results for velocities of 0.08 m/s and 0.18 m/s.

Whilst the pore model cannot be used for mesh screens as it is only a single collector measure of efficiency, the notion that velocity plays a part in particle removal needs to be extended in any equation that defines how particles move through a screen. It is intuitive that slower velocities will allow the deposition of particles at a higher rate than faster flowing fluids and therefore using the capillary pore model alone would be an invalid way to describe the Tumblemate system.

Particle Removal Efficiency Versus Concentration

Concentration was shown to be the least important parameter out of the three that were tested in this experiment.

The general trend showed that an increase in the concentration for a certain particle size would increase the efficiency for that particle to be removed, however the impact that this increase would have is minimal as seen in Figure 53. This depicts the highest and lowest stormwater concentration that was used in the test that would be predicted by the equation that was derived (equation 26) using a flow velocity of 0.12 m/s.

Neither the fibre or pore models directly use concentration in their removal efficiency equations which form parallels with the experimental results in that concentration does not significantly play an important role. However, if a significant TSS concentration was present (upwards of 10 g/L), then this may cause a sufficient increase in the dynamic viscosity of the water. For the fibre model, this is incorporated in the diameter for gravitation, and therefore an increase in the viscosity will lead to a decrease in total removal efficiency, as it would become harder for particle to settle onto the fibre thereby going against the experimental results.

As TSS concentrations only ranged between 1.62 - 4.05 g/L this effect could not be definitively proven. Testing above 4.05 g/L caused an issue with the ball valve which would continually get clogged and compromised the accuracy of the experiment. In future, a method to test the impacts of concentration on removal should be tested by using a tenfold increase to the base concentration so clear results can be established.

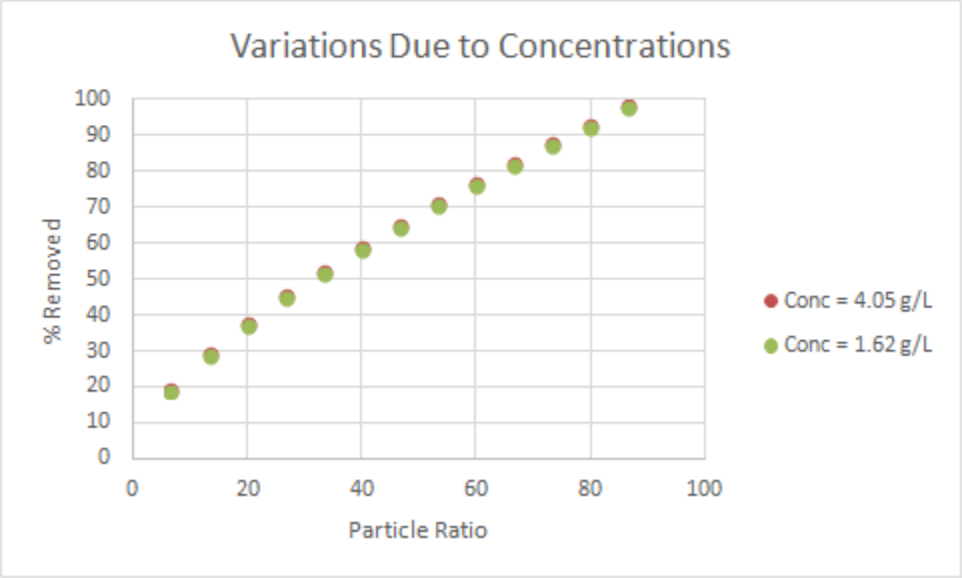


Figure 53: Graphical representation of the equation derived from the experiment showing the influence of concentration

It must be noted that besides diffusion, equations describing particle removal were derived solely for the fate of one particle with no regard for others in the solution that may affect its removal potential. For example, the gravitation deposition in the fibre model only considers the falling velocity of a single particle, and does not include the statistical possibility that a larger particle will create a faster settling velocity of a smaller particle through differential settling. This means that theoretical models can only be used as an indicator to particle removal, however the actual retention efficiency is better described the by experimental model developed in this research thesis.

Error

Numerous sources of error were present throughout the experimental procedure which may have impacted on the quality of results.

Firstly, the clogging of the filter may have impeded the true capacity for primary filtration. This effect was more notable for the 180 micron mesh with the smaller pore sizes allowing fine particles to lock into open mesh spaces and impede water flow. This can have two potential impacts on the results of the experiment:

1. The reduction in open pore space effectively creates a filter with mesh sizes smaller than the original filter mesh, easily capturing smaller particles at a greater efficiency then what would otherwise occur.
2. Too many particles fill the mesh spaces and cause a substantial hindrance to the flow, effectively plugging the system. Under this mechanism, water from the header and mixing chambers will then bypass the screens on the sides of the Tumblemate device. This could compromise the experiment as particles contained within this flow are not subject to primary filtration which will cause a lower efficiency to be recorded. To account for this, if a sufficient amount of water was found to be bypassing the system the experiment was restarted to ensure accurate and reliable results.

The next source of error is in regards to testing the Blackwattle Bay material. As minimal particles passed through the screens for each test, a round (four individual tests) of testing was undertaken before particles that passed through the screens were taken out and weighed. Similarly, this could have two implications for experimental results:

1. Some particles that initially passed through the screen may be sent back through the Tumblemate system and be captured, thereby elevating the efficiency of the screen. To alleviate this problem, the chamber under the table was divided into two separate

chambers so that particles had time to settle in the first part when water flowed over the top into Chamber 2.

2. When all the material that was classed as ‘missing’ was collected and analysed at the conclusion of each round, there was only one size distribution that could be calculated, which was an average of all four size distributions rather than individual distribution for each test. However, this error was expected to be minimal due to the homogeneity of the Blackwattle bay material.

The method used to calculate size distributions could also potentially have error. Soil samples were dried until no visible moisture content was apparent and then analysed under the microscope to determine individual particle sizes. However, due to time constraints, only 300 particles for Blackwattle Bay and 700 particles for the Tumblemate material could be analysed for each compartment for every test which possibly lead to slight inaccuracies for size distributions. To ensure this error was kept to a minimum particles were continually analysed until:

1. A sensible particle and mass distribution was present in each compartment
2. There was an increasing trend in capture efficiency for each of the 15 particle size classes

Despite the drill creating a near uniform concentration, at certain times the true concentration deviated from the average concentration. In particular, the time at which the cup of material entered the mixing chamber created an initial high flux of particles, as the heavier particles settled quicker and hence passed through the ball valve quickly rather over the entire minute as intended.

Similarly, flow rates may have been altered slightly throughout the duration of the experiment due to two reasons:

1. Clogging of the ball valve; when larger particles were present there was a tendency for the ball valve to clog up and not release water; thereby reducing the overall velocity. Once this valve was opened to allow water to pass through, velocities would have temporally exceeded the velocity for the specific test.
2. At the start of the minute interval when the 5 litres were added to the mixing chamber, water velocities would have been higher than the average due to the greater hydraulic

head available to force the water through the ball valve. Conversely, towards the end of the minute interval water velocities would have reduced.

Finally, there may have been some error in estimating the ratio between the relatively dry material weight before entering the Tumblemate system and the fully saturated weight of material once it was retrieved from its respective compartment. To minimise this, tests were carried out before each round, and if a round was not concluded by the close of a day a new test would be carried out the next morning to determine if the dry material had lost any moisture.

Further Research

Further research should be based on other factors that can impact on particle removal from stormwater.

For example, hydrocarbons in stormwater that are derived from impervious surfaces such as roads and industrial precincts can attach to particles, reducing the overall density thus making them more buoyant. This can elevate the TSS concentrations, which will reduce the overall efficiency of the Tumblemate as the particles that initially settle out in the first stage of Compartment 1 will remain in suspension and be subject to primary screening rather than being immediately deposited.

Another possible factor is to determine how density of the particle impacts on the removal efficiency. From literature in Section 1 of this report it is evident that an increase in the particle density will increase the efficiency due to increased deposition rates, however, the extent of this could be determined by analysing the degree at which this parameter would influence final results.

The pH in stormwater can vary between 6 and 9 depending on the sources of stormwater pollution, and therefore it is worth considering how this may impact on particle removal efficiencies.

Summary of Experimental and Theoretical Results

Experimental results showed that the particle ratio was largely the driving factor for particle removal, accounting for approximately 90% of the predicted result given values for the three parameters analysed. Velocity showed some significant impact, with faster velocities leading to a reduction in particle retention. The effect of concentration was shown to be minimal, with only slight positive correlation being detected.

The lowest particle ratio analysed (6.67%) was shown to have a corresponding removal efficiency of approximately 20%. Half the particles were found to be removed at a ratio of approximately 40%, with most being retained by the filter for a 'R' value of 80%. Generally all particles with a ratio of greater than 95% were removed.

As particles analysed in the experiment were generally greater than 10 microns, the diffusion mechanisms in both fibre and capillary pore theoretical models were neglected. The consequence of this was that concentration was shown to have no direct impact on particle removal efficiency based on theoretical equations.

The fibre model showed that despite having a slightly different definition, the particle ratio, that is the size of the particle relative to the fibre size, was the governing factor in particle removal. Similarly to experimental results, faster velocities caused a reduction in retention efficiency, as this increase in velocity would reduce the amount of particle settling on the fibre as these would be retained in suspension.

The capillary pore model ignores the impact of velocity and describes particle removal solely in terms of particle ratio. At low particle ratios (<50%) , this model underestimates the particle retention of the Tumblemate system be approximately 5-10%, however as the R value exceeds 50% this theoretical model generates results similar to those found experimentally.

Conclusion

By analysing three parameters that could influence particle removal in stormwater it was found the most influential parameter in determining the removal efficiency is the ratio between the particle size and the screen aperture 'R' which showed a positive correlation. The smallest R value of 6.67% had an experimental removal efficiency of approximately 20%, with half the particles being removed at a ratio of 40% and all particles removed when a ratio of 95% was achieved. Velocity was demonstrated to have the next greatest impact, however this was much lower than that of the 'R' value and showed a negative correlation. This is because faster velocities keep particles in suspension and do not allow them to settle at the chamber bottom or on the mesh screen. The total suspended solid concentration (TSS) demonstrated very little impact, with only a small increase in particle retention efficiency between a concentration of 1.62 g/L and 4.06 g/L. The theoretical fibre model was shown to agree with trends derived from experimental results in that the particle ratio largely governed particle removal and that faster velocities would reduce retention efficiency whilst concentration for particles with a size of greater than 10 microns would have negligible impact. However, the model described particle removal by a single fibre and not a mesh screen and had the inability to account for a large range of velocities and particle sizes which meant that the model had to be used with caution with output results being unreliable. The second model to be analysed, the capillary pore model showed that particle retention was independent of velocity and concentration and was solely dependent on the particle ratio. Whilst this underestimated the effects for values of R less than 50%, the model was relatively accurate in describing experimental results for larger particle ratios (> 50%). However, experimental results showed that velocity still had a significant impact on final retention efficiencies and therefore the capillary pore model was not the best method to describe the Tumblemate system. The fact that the equation derived in this thesis has an R adjusted value of 0.945 and accounted for parameters that were present within both theoretical models proves that the experimental model is the best method to describe particle removal for a mesh screen for the Tumblemate stormwater device.

Acknowledgements

I would firstly like to thank my academic mentor Federico Maggi who has offered much professional advice throughout this thesis year in relation to experimental design and theoretical understanding of material which allowed me to gain an in depth knowledge base in the area of study.

Secondly I would like thank Leo Crasti, CEO of Water Decontamination Technologies for the experimental design and set up of the Tumblemate prototype that was used to be tested in this thesis. Leo also provided funding and other materials that were required throughout the duration of the project which allowed me to direct more time towards research and analysis of results.

Finally, I would like the Australian Mathematical Sciences Institute that allowed Federico, Leo and myself to work together on this project which allowed me to attain a detailed grasp of both industry and academic experience that will assist in my development as a professional engineer.

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