Scaling relations for manufactured stormwater BMPs

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Manufactured stormwater best management practices (BMPs) generally apply one or both of two unit operations to remove particles from stormwater runoff: hydrodynamic separation and filtration. Hydrodynamic separation is best used to remove sand particles, while filtration is used to remove organic particles as well as silt and clay. Many manufactured stormwater BMPs also have a chamber designed to remove floatables, or particles that are lighter than water. The numerous designs and multiple sizes of these manufactured stormwater BMPs suggest the need for scaling criteria to size and apply designs in the field. This paper reviews the scaling criteria research that has been completed, the research that may be adopted from other areas, and the needs for developing scaling criteria in manufactured stormwater BMPs.

Introduction

Most manufactured stormwater BMPs (M-BMPs) function as either hydrodynamic separators or filters. Hydrodynamic separators utilize the difference in density to settle suspended solids into the bottom of the device and to retain floatables, such as hydrocarbons at the surface of the device, while the effluent flows through an intermediate elevation. Filters use a media to retain particles of a given size while the effluent flows through the filter. These devices are generally placed below ground, and therefore are suited for high density locations and retrofits to existing infrastructure. There is a great need for these underground devices, and manufacturers have responded to this need. M-BMP units supplied by each vendor are manufactured with specific capacity/size categories, such as sewer pipes. There is little room to exactly follow the scaling ratios which might have been tested under laboratory conditions. However, an industry-wide, uniform methodology to scale and size these devices does not currently exist. This paper will review the need for scaling criteria in M-BMPs, the scaling criteria that have been developed and the possibilities for adapting scaling relations from other areas of research.

Need for Scaling Relations

Because of interaction with a complex flow field, the need for scaling criteria is probably greatest in hydrodynamic separators. The vertical velocity relative to water causes separation while the turbulence of the flow field tends to mix the media that is being separated back into the water. There are three issues that need to be addressed: 1) settling of heavier-than-water particles out of the flow, 2) rise of lighter-than-water compounds such as oils and trash out of the flow field, and 3) the tendency to entrain both after separation has been accomplished in high flow. Experimental tests are possible on model-scale or full-scale devices, but these tests will need to be scaled to another size of device in order to meet demand. In addition, if an accurate scaling procedure can be developed and verified, it will be possible to perform smaller-scale model studies on each device which can be scaled to full device size with a known accuracy.

A filter media can be tested through column studies. However, the parameters that need to be controlled (e.g., grain size versus column diameter) and scale-up to full scale filters needs to be documented. In addition, many filters are partially self-cleaning, utilizing turbulence in the flow field to remove caked material from the filter. The scaling relations developed in item 3) above may be sufficiently general to apply to this case as well. Tests would still be required on the devices to demonstrate and measure the self-cleaning properties. To apply the results of such tests to a multiple of device sizes would require scaling criteria.

Dimensionless Numbers and Scale Effects

One goal of scaling is to have one dimensionless number that represents the important processes of the device. This is not generally possible at all scales, so criteria are developed on the appropriate model scale. These criteria include a critical Reynolds number value that must be exceeded to assure that turbulent flow occurs:

$$\mathbf{Re} = \frac{Q}{\nu d} \geq \mathbf{Re_C} \tag{1}$$

and a critical Weber number that must be exceeded to assure that surface tension does not alter the flow field:

$$\mathbf{We} = \frac{\rho Q^2}{\sigma d^3} \geq We_C \tag{2}$$

where Q is discharge through the device, ν is kinematic viscosity, ρ is density of the liquid, σ is liquid surface tension, g is the acceleration of gravity, and d is the smaller of the important length scales in the flow field, such as the diameter of the device or depth of water. It is also common practice to enhance the wall roughness in a physically-scaled model to result in a similar relationship of wall shear stress to flow velocity (similar friction factor or drag coefficient) as in the full scale.

Fenner and Tyack (1997) reviewed the scaling criteria for removal efficiency and head loss of hydrodynamic separators and, in addition to geometric similarity, came up with the following dimensionless similarity criteria:

Removal Efficiency: Hazen number = $\mathbf{Ha} = \frac{Q}{AV_s}$ (3)

Froude number = $\mathbf{Fr} = \frac{Q}{\sqrt{gd^5}}$ (4)

Pressure loss: Euler number = $\mathbf{Eu} = \frac{\Delta P d^4}{\rho Q^2}$ (5)

$$\text{Friction factor} = \mathbf{f} = \frac{u_*}{V} \qquad (6)$$

where A is the plan area of the separator, V_s is the settling velocity of the particles, g is the acceleration of gravity ΔP is pressure drop, ρ is the density of the fluid, and $u_* = (\tau_{wall}/\rho)^{1/2}$ is the shear velocity at the walls. The Hazen number is designed for similarity of settling in a quiescent flow field, Froude number similarity is required for fluid flow driven by gravity, Euler number similarity will appropriately scale up pressure loss and friction factor similarity is required for the influence of turbulence in the flow field. Friction factor similarity would also be important for removal efficiency, because of the impact of turbulence on particle settling.

Scaling of Removal Efficiency for Hydrodynamic Separators

Fenner and Tyack (1997) investigated the performance of a 1.6 m and 0.3 m diameter hydrodynamic separators with plastic beads of specific gravity equal to 1.04. They found that Froude scaling was most accurate at low removal efficiencies and Hazen scaling was more successful at higher removal efficiencies. They proposed a hybrid scaling formula which incorporates the impact of each dimensionless number:

$$\frac{Q_{prototype}}{Q_{model}} = \eta_m L_r^{\ 2} + (1-\eta_m) L_r^{\ 2.5} + \frac{d_p}{3}(1-\eta_m) L_r^{\ 2.5} \qquad (7)$$

Where η_m is the fraction of removal in the model, d_p is the mean particle diameter and L_r is the length ratio (prototype/model). To be used in practice, Eq. (7) should be adjusted for the specific gravity of the particles, which typically will differ from those used in Fenner and Tyack's experiments.

Based upon previous experience with settling of suspended sediments in lakes (Dhamotharan, et al. 1981), the Peclet number ($\mathbf{Pe} = V_s L / D_t$) and a dimensionless time, are appropriate and sufficient dimensionless scaling parameters to explain sediment deposition rates. In the definition of the Peclet number V_s is particle settling velocity in quiescent water, L is settling depth, and D_t is a vertical turbulent diffusion coefficient. Peclet number is defined as the ratio of convection to diffusion: in this case the convective, settling process is opposed by turbulent diffusion in the system tending to keep solids in suspension. Similar to the approach taken for lakes and reservoirs, Wilson, et al. (2007, 2008) scaled convection with the settling velocity (V_s), used the settling depth (h) as a vertical length scale L, and a flow velocity times a length scale for the vertical diffusion coefficient (D_t). When the diameter is the shortest dimension of the flow, $D_t \sim Ud,$ and by continuity $D_t \sim Qd/A.$ In most hydrodynamic separators, flow enters the chamber from above and turbulence is stronger where plunging occurs. Therefore, if A is taken as the horizontal projection of the chamber (the cross-sectional area of mixing) which is proportional to d^2, then $D_t \sim Qd/d^2 = Q/d$. The Peclet number for the stormwater treatment device therefore becomes;

$$\mathbf{Pe} = V_s\, h\, d/Q \qquad (8)$$

If the smallest dimension of the device is its height, or settling distance, as is the case for detention ponds, then inflow is relatively horizontal and thus A becomes the cross-section of the pond, hd. Therefore $D_t \sim Qh/dh = Q/d$ and $\mathbf{Pe} = V_s\, h\, d/Q$. In both cases, one obtains the same equation for the Peclet number. The resulting Peclet number resembles the Hazen number, $V_s\, d^2/Q$, which is the ratio of settling velocity to overflow rate and was not developed to scale turbulent diffusion.

All that remains is to choose an appropriate relationship for settling velocity. Based on the conclusions drawn by Fentie et al. (2004) in a study comparing multiple soil particle settling formulae versus measured settling data, settling velocity was assumed to follow an equation fit to drag coefficient by Cheng (1997):

$$V_s = \frac{\nu}{d_p}\left(\sqrt{25 + 1.2\left(d_p\left(\frac{g\,\frac{\rho_s - \rho}{\rho}}{\nu^2}\right)^{1/3}\right)^2} - 5\right)^{1.5} \tag{9}$$

where ν is kinematic viscosity of the fluid, d_p is particle diameter, g is the gravitational constant, ρ_s is particle density, and ρ is fluid density. Equation (4) was shown to outperform other settling models, and is an explicit relationship for settling of natural sand particles derived from the particle Reynolds number (Re) and a dimensionless particle parameter. It is applicable to a wide range of Re, from the Stokes flow to turbulent regimes, and becomes Stokes law at small particle diameters.

Sample results of using Eq. (8) to scale hydrodynamic separators are given in Fig. 1 for a range of discharges and particle size. Sand was sieved to create three discrete fractions with median sizes of 107 μm (ranging from 89 μm to 125 μm), 303 μm (ranging from 251 μm to 355 μm), and 545 μm (ranging from 500 μm to 589 μm). In addition, two experiments were performed with silt-sized particles. These samples were comprised of a commercially available silica gradation with a median particle diameter of approximately 45 μm. Discharges of 25%, 50%, 75% and 100% of design were utilized in triplicate experiments to result in a graph of removal efficiency versus Peclet number. A high Peclet number represents a low discharge and high settling velocity (larger particles) and a low Peclet number represents high discharge and low settling velocity (smaller or less dense particles). The importance of knowing particle size distribution (PSD) and organic content of the inflow is apparent in Eqs. (3) and (8) and Fig. 1. Without PSD, Fig. 1 cannot be used, or must be used with substantial assumptions.

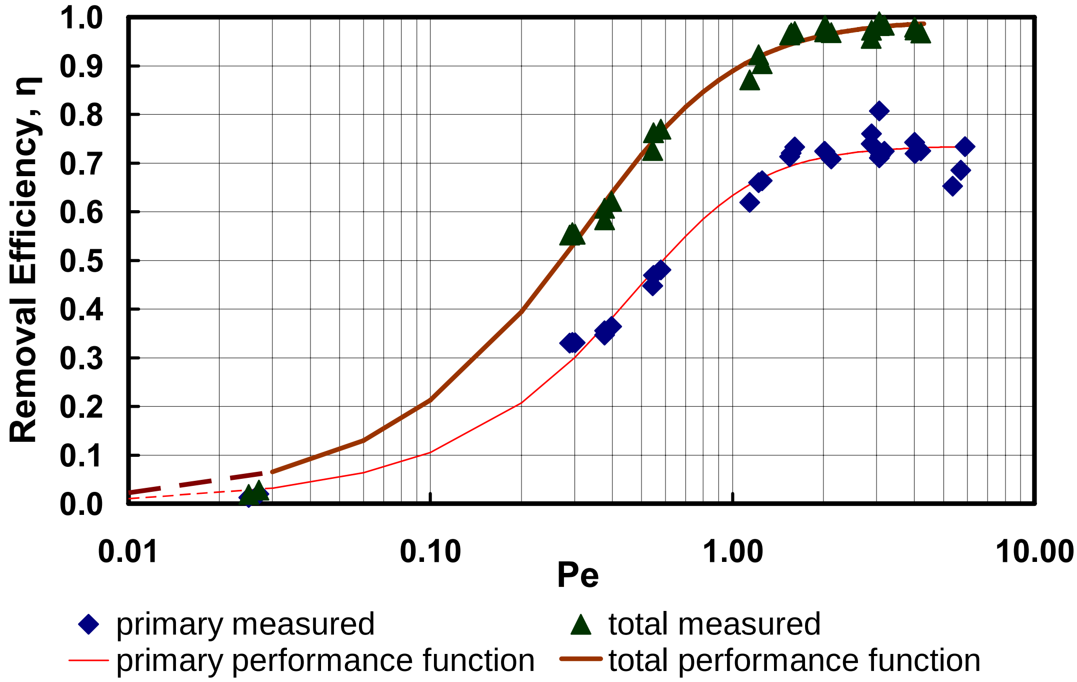

Figure 1: Removal efficiency of settling particles versus Pe for the V2B1 Model 4, reflecting removal by: (1) solely the primary settling chamber, and (2) total removal by the combination of the settling chamber and floatables trap (Wilson et al. 2007, 2008).

Scaling Needs: Hydrodynamic Separators

The development of Eq. (7) from experiments is empirical, and only as good as the data that it is based upon. One drawback that deserves consideration is the impact of particle density on Eq. (7). The data given by Fenner and Tyack (1997) will prove valuable in combination with similar experiments with silica-based particles in attempts to bring particle density into the similitude criteria. The derivation of Eq. (8) is also limited. It makes assumptions about the flow field that have not been fully tested. The result of reducing the diameter by 50% and depth by 20% did not change **Pe** sufficiently to constitute verification of the scaling analysis (Wilson et al. 2008). The results were within the scatter. In addition, the scaling of floatable retention and high flow scour will likely require a separate analysis. There is much research to be completed in the scaling of hydrodynamic separator experiments. Due to the yet-unknown scaling law, the draft Wisconsin lab-testing protocol (WDC and WDNR 2007) calls for testing of at least two sizes of a hydrodynamic separator to confirm any suggested scaling formulation.

Scaling Needs: Removal Efficiency for Filters

The particle trapping of a filter is a local phenomenon, dependent upon the characteristics of the media and the particle size distribution of the suspended solids. This can be relatively well simulated with a bench-top column test, where the media filtration efficiency is tested with the PSD of interest. The scaling parameters of most interest are the media Reynolds number,

$$\boldsymbol{Re} = \frac{Q}{\varepsilon^{1/3} A^{1/2} \nu} \qquad (10)$$

and the suspended solid-media size ratio:

$$L_s = \frac{d_p}{d_{med}} \qquad (11)$$

Where ε is the porosity of the filter media and d_{med} is the equivalent spherical diameter of the media.

The scaling of one PSD to another, and scaling with filter flow rate is of interest because it would reduce the required filtration tests. In addition, filters are often placed in the turbulent flow field of the device, resulting in differential pressure drop across the filter that varies spatially.

In the application of filters, one needs to also consider the fouling that will occur at the filter surface. Fouling will increase the frequency of cleaning and could reduce the filter life. The cleaning of particle cake which has accumulated on the surface of the filter, however, cannot be simulated with column tests because cleaning is often provided by turbulence generated in the chamber of the filter device. This would require a scaling analysis similar to high flow scour, since both are based upon the resuspension of collected material.

Conclusions

1. M-BMP units supplied by each vendor are manufactured with specific capacity/size categories, such as sewer pipes. There is little room to exactly follow the scaling ratios which might have been tested under laboratory conditions.
2. There are three issues that need to be addressed: 1) settling of heavier-than-water particles out of the flow, 2) rise of lighter-than-water compounds such as oils and trash out of the flow field, and 3) the tendency to entrain both after separation has been accomplished in high flow.
3. Flow and particle sizes vary greatly throughout and among storm events. One will have to establish the representative Q, d and V_s. A different approach is to use the scaling to establish performance parameters that can be put into a runoff model. The performance of the device will then vary throughout a storm.
4. The scaling relation of Fenner and Tyack should be adjusted for the specific gravity of the particles, which typically will differ from those used in their experiments. The data given, however, will prove valuable in combination with similar experiments with silica-based particles in attempts to bring particle density into the similitude criteria.
5. The derivation of Wilson, et al. makes assumptions about the flow field that have not been fully tested. The result of reducing the diameter by 50% and depth by 20% did not change **Pe** sufficiently to constitute verification of the scaling analysis.
6. The scaling of floatable retention and high flow scour in hydrodynamic separators will likely require a separate analysis, with appropriate experimental data.

7. Filters are often placed in the turbulent flow field of the M-BMP, resulting in differential pressure drop across the filter and fouling that varies spatially. From this point of view, filters need a protocol developed that can perform model-prototype and prototype-prototype scaling.

The ability to scale the performance of manufactured stormwater BMPs through similitude relationships will help size and design these products for municipalities. In addition, it will focus the research and experiments on items that are truly essential to performance. The result will be more focused research, improved quality of tests, and better manufactured stormwater BMPs. Although there is much work to be completed in improving scaling relations for these devices the committee believes that the benefits will greatly outweigh the costs.

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