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FIELD MEASUREMENT OF PARTICLE SETTLING VELOCITY

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ABSTRACT

Many stormwater management practices depend on sedimentation as their primary removal mechanism, but the settling velocity distribution of particles in runoff from a specific watershed is rarely known. A simple and effective method to characterize settling velocity distribution is needed to improve the design of stormwater management practices. Elutriation devices have been used to characterize the settling velocity distribution of river sediments (Walling and Woodward 1993) and combined sewer overflows (Krishnappan et al. 2004). The elutriation device has been modified and tested to determine its effectiveness in measuring the settling velocity distribution of particles in urban runoff. The device has a series columns with increasing diameters. Stormwater is pumped vertically through the columns, and the upward velocity through each of the columns can be calculated. Particles with settling velocities greater than the upward velocity settle in the column, and particles with settling velocities less than the upward velocity are flushed through the column. Initial experiments have shown particles can be predictably separated with the elutriation device. Using different materials and methods, an elutriation device to measure particle size distribution in the field and laboratory is being developed and tested. The application of the elutriation device will provide practitioners with a new tool to better design stormwater management practices.

1. INTRODUCTION

Pollutants such as heavy metals, phosphorus, and polycyclic aromatic hydrocarbons (PAHs) adsorb to the surface of particles, and the pollutant-carrying particles can be transported with stormwater runoff (Sansalone et al. 1997, Bathi et al. 2009). Particles alone can act as pollutants because they increase the turbidity of the receiving water body and disturb spawning grounds for aquatic life. If particles in urban runoff are not removed before entering receiving water bodies, they can contribute to the degradation of water quality. To mitigate the negative impacts of runoff, stormwater treatment practices are often implemented. In many of these practices, such as ponds and underground separators, settling of particles is used as the primary mechanism for pollutant removal.

A primary factor in particle settling is particle size. Recent research has primarily focused on measuring particle size distribution (PSD) of particles in runoff. When using PSD to calculate a settling velocity distribution and to design removal from stormwater treatment practices, practitioners must make assumptions about other particle properties. As an alternative to measuring PSD, methods to directly measure the settling velocity distribution of particles are available. Methods include both settling columns and elutriation devices. Settling columns allow a suspension of particles to settle over time, and elutriation devices separate finer, lighter particles from coarser, heavier particles by means of an upward stream of fluid. The development and application of a water elutriation devices to measure particle settling velocity distribution of stormwater runoff is discussed in this paper.

2. PARTICLE SIZE AND SETTLING VELOCITY

When predicting the particle removal for unit operations, practitioners must use a settling velocity distribution for particles in runoff. The settling velocity distribution can be measured directly, calculated from a particle size distribution, or assumed using previous research. A commonly used, assumed distribution is the settling velocity distribution measured during the Nationwide Urban Runoff Program (NURP). The NURP settling velocity distribution was developed using settling velocity measurements

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from 46 different samples from 13 unique sites (USEPA 1986). Some guidelines recommend practitioners use the NURP distribution, and the NURP distribution is also used as the default distribution in modeling software such as the P8 Urban Catchment Model.

The NURP distribution, however, may not be representative of actual settling velocity distributions in urban runoff suspended solids. PSD, a major factor in settling velocity, varies based on land-use, site location, and storm intensity (Goonetilleke et al. 2005, Egodawatta et al. 2007). Recent studies from Sansalone et al. (1998), and Li et al. (2005), and Kim and Sansalone (2008) have demonstrated the particles characterized in the NURP distribution may be finer than the particle size distributions found in urban watersheds, especially in the higher-intensity design storms. Figure 1 shows the variation in particle size distribution for both the NURP distribution and other PSDs found in more recent runoff studies.

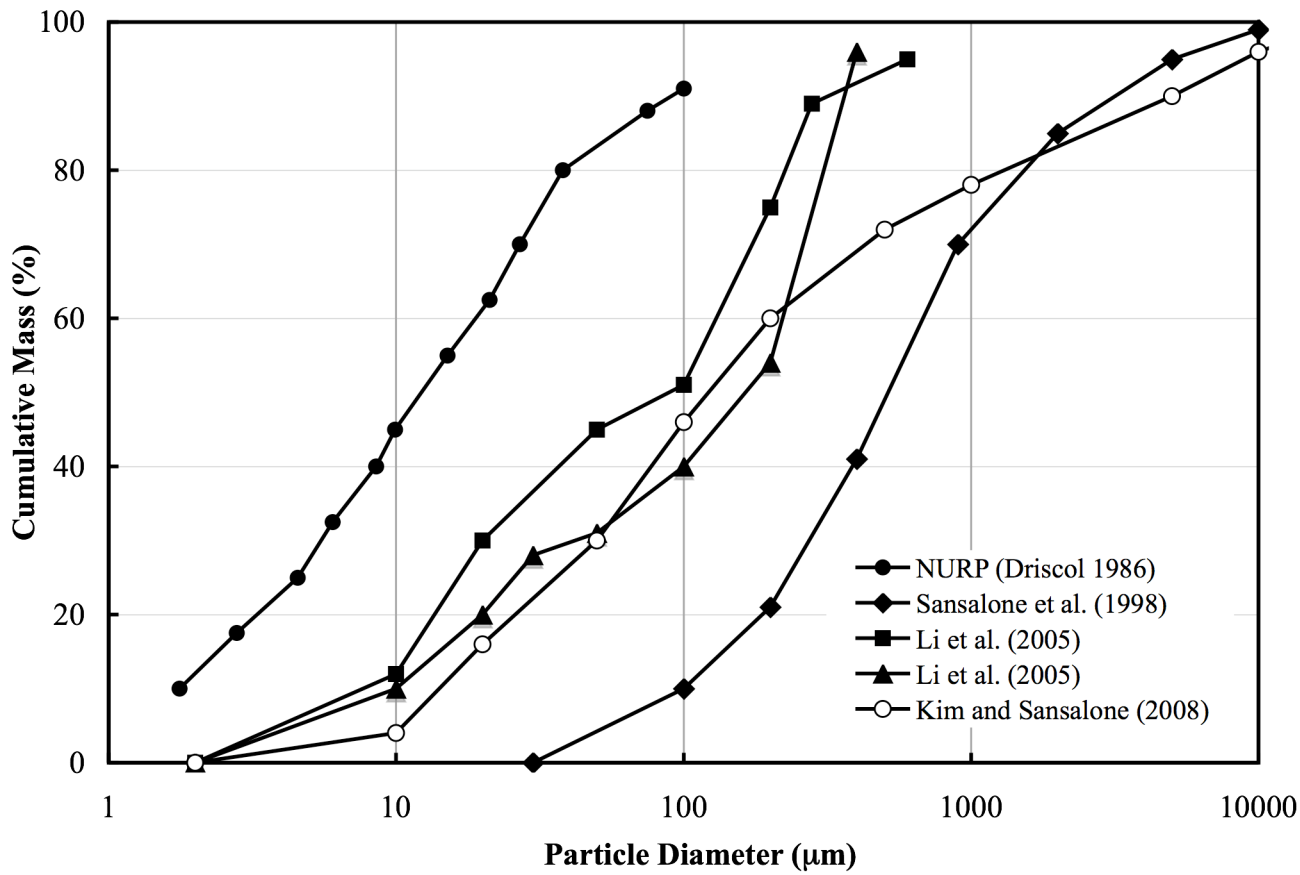

Figure 1. Comparison of particle size distributions

While the recent studies primarily focus on particle size, settling velocity also depends on particle specific gravity, particle shape, and particle texture (Dietrich 1982). For design purposes, stormwater particles are typically assumed to have a certain size distribution and be smooth spheres with a specific gravity equal to sand. Actual stormwater particles, however, are rough, are non-spherical, and have varying specific gravity. Inaccurate assumptions about particle properties can lead to improper characterization of settling velocity distribution and ultimately have an impact on stormwater unit operation design and performance.

To overcome the inaccuracies associated with converting particle size distribution to settling velocity distribution, the settling velocity distribution of particles in stormwater may be directly measured.

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Common measurement methods include the USEPA column, the Umwelt- und Fluid- Technik (UFT), the CERGRENE protocol, the Aston column, and the Camp protocol (USEPA 1986, Lucas-Aiguier et al. 1998). While the methods provide a direct measurement of settling velocity, they have some drawbacks when compared to particle sizing techniques. First, the various settling techniques require a larger sample volume than most particle sizing techniques. Additionally, the time required for analysis of the settling devices is on the order of hours to days compared with a few minutes for the more sophisticated particle counting devices. Whether particle size distribution or settling velocity of particles are measured, the various factors affecting settling velocity should be considered.

3. ELUTRIATION DEVICE

A device to measure particle settling velocity known as an elutriation device has been used in previous studies to measure the settling velocity of particles in the field. In elutriation, a suspension of particles is pumped upward through a series of columns with increasing diameters. The flow rate and the cross-sectional area of the columns are known so an upward velocity through the column can be calculated. If a particle has a settling velocity larger than the upward velocity in the column, it will settle in the column. If a particle has a settling velocity smaller than the upward velocity in the column, it will be flushed through to the next column. When the entire sample has been pumped through the device, the mass of particles retained in each column and in the effluent is then measured. The mass distribution can be combined with knowledge about the upward velocity in the columns to provide a particle settling velocity distribution.

Walling and Woodward (1993) used an elutriation device made from four custom-built glass columns to measure the settling velocity distribution of particles in a stream. In the experimental setup, an intake was placed in a stream and connected to a series of four columns. The four columns were then attached to a peristaltic pump that pulled river water through the four columns and into a collection tank. The system was calibrated so particles with equivalent diameters greater than 63 μm were retained in the first column, particles between 32 and 63 μm were retained in the second column, particles between 16 and 32 μm were retained in the third column, and particles between 8 and 16 μm were retained in the fourth column. Other researchers have used a similar setup with up to seven columns to determine the settling velocity distribution of suspended solids in combined sewer overflows, or CSOs (Krishnappan et al. 2004, Marsalek et al. 2006). The device in the CSO studies was not deployed in the filed. Instead, a 65-liter sample of combined sewer overflow was collected and transported, and the sample was passed through the elutriation device at another facility.

Elutriation devices have benefits when compared to settling columns, which also directly measure particle settling velocity. First, regular settling columns operate under quiescent conditions, which does not mimic the conditions of most unit operations utilizing settling. Studies have shown turbulence can have an impact on settling velocity (Doroodchi et al. 2008), and the dynamic nature found in elutriation devices incorporates the effect of turbulence. Second, operation of the device is relatively passive because it only requires the operator to turn on a mixer and pump. Finally, the device separates particles into distinct settling velocity ranges, and the particles in each settling range can be analyzed for metals and other pollutants.

Modifications have been made to the original elutriation device setup to make the device more widely available and more appropriate for field implementation for stormwater runoff. First, the columns are changed from glass to plastic. The change makes the device lighter, cheaper, and less fragile. Second, the mechanism of entry for the suspension is changed. In the original device, particles are introduced to the bottom of the column through a tube that extended from the top to the bottom of the column. To avoid the possibility of particles being trapped at the bottom of the column without having a chance to

be suspended in the column, the updated device introduces particles directly from the bottom of the column. Third, the pump is moved from the downstream end of the device to the upstream end of the device. The pump operating at the downstream end of the device utilizes suction to pull water through the device so airtight seals must be maintained throughout operation of the device. If a seal becomes loose, the device fills with air and stops operating properly. This concern is mitigated by pushing water through the device rather than relying on suction. Finally, four screens are placed normal to the flow field in each column to provide head loss that will spread the flow so that the columns can be shortened. The shorter columns reduce the amount of time and the volume of sample required to operate the device. A schematic of the modified elutriation device is shown in Figure 2.

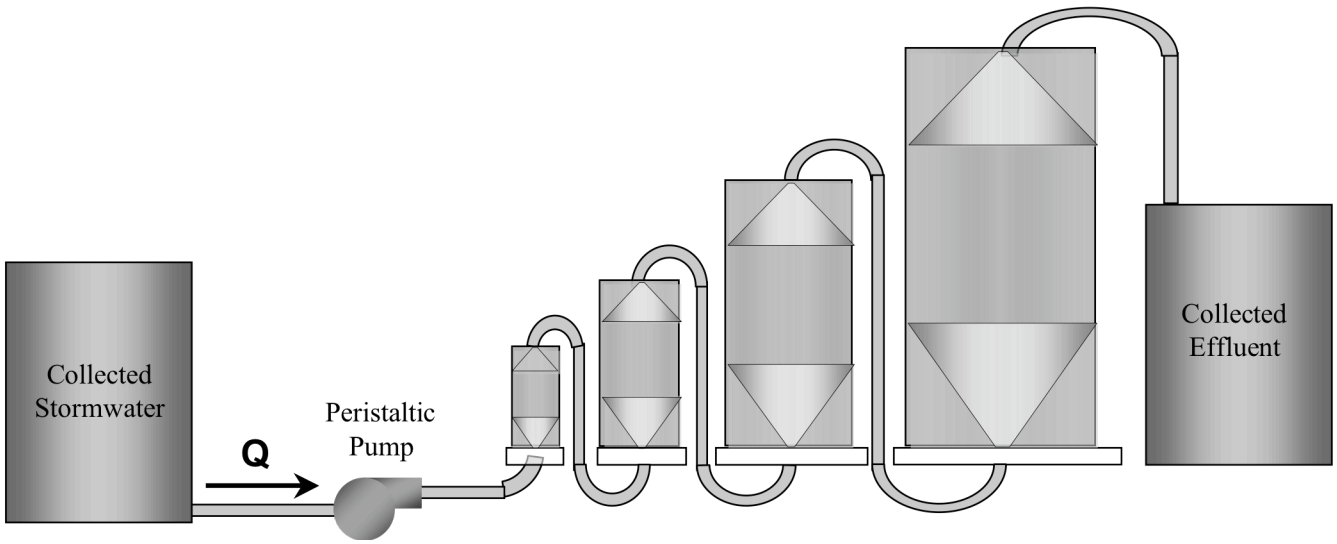

Figure 2. Modified elutriation device

4. EXPERIMENTAL RESULTS

The modified elutriation device has been tested in a laboratory setting to evaluate its accuracy. Suspensions of particles with known particle size distribution and density were introduced to a single column. The suspension was pumped through the device, and the particles retained in the column and flushed through the column were collected. Both the mass and the particle size distribution of the particles were measured and compared to theoretical expectations. Typical results are given in Figure 3, which indicates that the experimental results do not match theoretical results if a uniform flow profile in the column is assumed. Instead, the experimental results closely represent theoretical results if a laminar flow profile is assumed. Since the results are closest to the theoretical expectations assuming laminar flow, a computer program to convert the results from the elutriation device to the actual settling velocity distribution of particles in the initial suspension has been developed and utilized.

The modified elutriation device can be used either in a laboratory setting or in the field. If it is to be used in a lab, a 10 to 20-liter stormwater sample must be collected in the field, transported to the lab, and pumped through the device. The device can also be implemented in the field to directly measure settling velocity distribution of particles in runoff from a storm. To implement in the field, someone must operate the device during a storm, or the device must be connected to a pump that can be autonomously operated. For the latter setup, the pump connected to the elutriation device must be turned on when depth or flow-rate in a stormwater pipe outfall reaches a pre-programmed value. Whether the device is operated by a person during a storm or operated by an automated system, the entire volume of effluent pumped through the device must be collected so the mass of particles in the

effluent can be estimated.

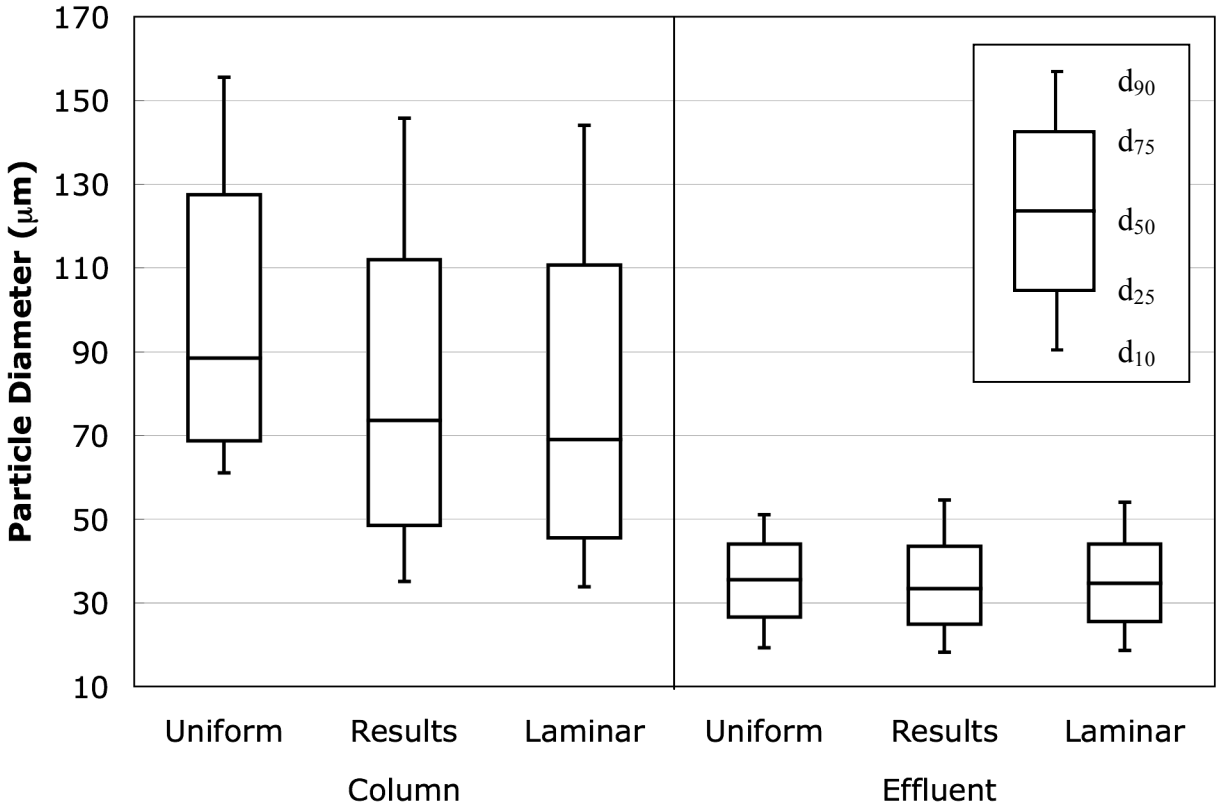

Figure 3. Results from test of modified elutriation device, compared with two theoretical velocity profiles(uniform and laminar) in the columns. The predicted and measured effluent particle diameter is to the right, and that retained in the column is on the left.

5. CONCLUSIONS

Stormwater treatment devices utilizing sedimentation as a primary treatment mechanism can improve water quality of receiving waters, and the effectiveness of the devices can be evaluated if the settling velocity distribution of particles in runoff is known. Settling velocity distribution can be effectively measured using an elutriation device. Researchers have used elutriation devices to characterize settling velocity in rivers and combined sewer overflows. The original design of the devices has been modified for simple, wide-scale implementation with urban stormwater runoff, and tests have shown the modified device can predictably determine the settling velocity distribution of a suspension of particles. The modified device can not only be used in a laboratory setting with a collected stormwater sample, but it can also be implemented in the field at stormwater outfalls.

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