BASICS OF GRAVITY SEPARATION DEVICES

A TECHNICAL SERIES ON UNDERSTANDING COMMON STORMWATER TREATMENT METHODS

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Basics of Gravity Separation Devices

Introduction

Gravity separation is one of the most widely deployed pollutant removal mechanisms in stormwater treatment systems. It is one of the primary unit processes used in various stormwater control measures (SCMs) such as wet or dry sedimentation basins, baffle boxes, and hydrodynamic separators. Flow-through SCMs that rely on gravity separation can be used in stand-alone treatment applications, or as pretreatment to other SCMs depending on local stormwater regulations and treatment goals. Gravity separation devices primarily target the removal of particulate solids with high specific gravities (silt, sand, and gravel) by promoting sedimentation to separate the solids from the stormwater. Depending on the type of device, sedimentation may be enhanced by swirl concentration, screening, and/or baffling. The removal of suspended solids from stormwater is important because these solids are one of the most common contaminants found in urban stormwater runoff. An increased presence of suspended solids often results in environmental degradation by way of elevated levels of turbidity, habitat-altering sediment deposition, and the transport and release of other harmful pollutants including nutrients and metals which are often attached to solid particles.

When it comes to evaluating the performance of an SCM's ability to remove suspended particulate solids, the Stormwater Equipment Manufacturers Association (SWEMA) supports standardized, industry-wide accepted testing protocols. Examples of such protocols are the New Jersey Department of Environmental Protection's (NJDEP) MTD Certification Protocols and the State of Washington Department of Ecology Technology Assessment Protocol – Ecology (TAPE) and the Canadian Procedure for Laboratory Testing of Oil-Grit Separators. Additionally, ASTM Committee E64 is creating standards around SCM test methods and specifications with the first two programs as foundational building blocks. The standards developed by ASTM E64 will help establish the framework and test protocols for a national testing and verification program: Stormwater Testing and Evaluation for Products and Practices (STEPP).

End users of SCMs should be wary of performance claims for practices and technologies that do not have performance verification or approvals from well-established testing protocols and programs. Evaluating an SCM's performance relative to the removal of pollutants in compliance with industry-wide standards ensures that test data is collected under consistent conditions and reported with consistent and complete metrics, thereby producing data and reported results that can be viewed with higher degrees of confidence and better comparability.

This Basics of Gravity Separation Devices series of technical papers will guide the reader through the fundamentals of gravity separation SCMs. Each of the four papers in this series can be independently valuable resources; however, reading the collection together may provide the reader with a more comprehensive understanding of the overarching topic due to the interconnectedness of each part. These papers will focus on the operation and performance of manufactured gravity separation devices, with the goal of creating a greater understanding of the treatment mechanisms at work and the engineering principles behind their design relative to the industry-wide standards currently accepted for these practices.

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Part 1: Principles of Sedimentation

Sedimentation

Gravity separation in stormwater treatment is often called sedimentation – the process by which solids are removed from water by settling. Because most solids in stormwater are denser than water, they will settle out of suspension due to the effect of gravity. Manufactured SCMs that use sedimentation as a treatment mechanism are engineered with two major principles in mind: the settling velocity of particles and the maximization of residence time.

Settleable solids are generally defined as those that settle in the bottom of an Imhoff cone within a certain amount of time, usually an hour (see Figure 1). Relative to stormwater treatment, this definition is not quite sufficient. SCMs with long residence/ detention times, like ponds, would contain far more settleable solids, in particular finer particles with long settling times, than would be expected based on the results of an Imhoff cone analysis. Instead, because of the longer hydraulic residence times present in stormwater treatment SCMs, silt, sand, and gravel particle size ranges are recognized to be settleable, while clay particle sizes are not.

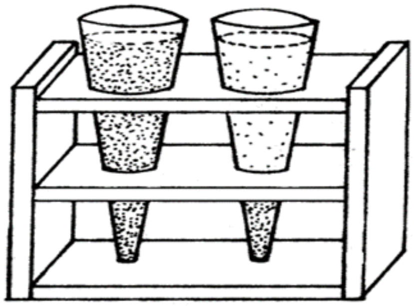

Figure 1 - Imhoff Cone Settling

There are many factors that impact how well a particle settles, including: size, shape, specific gravity, and water temperature. Each of these factors impacts the rate at which a particle will fall out of suspension, also called the settling velocity. When the particle size is known, the settling velocity can be estimated by Stokes' Law with two major assumptions: the particle is a sphere and the flow around the particle is laminar. With these two assumptions, the equation can be simplified as shown in Figure 2.

$$V = \frac{g\,(\rho_s - \rho)\,d^2}{18\,\mu}$$

where:
V = settling velocity of a particle
g = standard acceleration of gravity
ρ_s = mass density of the solid
ρ = mass density of the fluid
d = diameter of the solid (assumed sphere)
μ = dynamic viscosity of the fluid

Figure 2 - Stokes' Law Equation

In this equation, for particles of the same specific gravity (density), shape (assumed sphere), and in water of the same temperature (same viscosity), the size of the particle (diameter) is left as the only dynamic variable. Because the size of the particle contributes exponentially to the settling velocity, it is evident that larger particles will have higher settling velocities than smaller particles, resulting in a reduced settling time for the same settling distance. Under this simplified understanding of particle settling velocity, gravity separation devices must be designed to simulate longer settling distances by promoting longer hydraulic residence times in order to effectively capture smaller particles.

Manufactured gravitational separation devices operate as flow-through treatment systems where the settling of particulate solids occurs primarily during the storm event. This is referred to as dynamic settling. The design parameter that best predicts the removal efficiency of a target particle size in a dynamic settling process is the hydraulic loading rate (HLR) of the treatment device. HLR is defined as the rate of flow through the system divided by the treatment surface area of the system. When removing a blend of multiple particle sizes, the smallest particle that is likely to be retained at a given HLR (also called the critical particle size) is a function of hydraulic residence time (HRT). HRT is defined as the volume of the system divided by the flow rate through the basin. Understanding that HRT is equal to the time required to settle the design particle, which is a function of the settling velocity, it can be derived that the HLR is equal to the settling velocity of the design particle.

If $HLR = \frac{Q}{A}$ and $HRT = \frac{V}{Q} = \frac{A \times D}{Q}$ and $t = \frac{D}{v}$

When $HRT = t$, then $\frac{A \times D}{Q} = \frac{D}{v}$ and $v = \frac{Q}{A} = HLR$

Where:

HLR = hydraulic loading rage
HRT = hydraulic residence time
Q = flow rate (cfs)
A = basin area (ft^2)
V = basin volume (ft^3)
D = basin depth (ft)
t = settling time (s)
v = settling velocity (ft/s)

Figure 3 - HLR and settling velocity derivation

This derivation indicates that basin depth and area are crucial factors in removal efficiency. For basins of the same volume, those with shallower depths and greater surface areas would have lower HLR, and therefore effectively target particles with lower settling velocities. Consequently, targeting particle sizes with lower settling velocities corresponds with higher overall removal efficiencies for an SCM as it will more effectively settle out a greater portion of the smaller particle sizes. This relationship shows that HLR, rather than HRT, is the critical variable when designing SCMs. Increasing depth to maximize the volume of a basin has diminishing returns if the basin's surface area does not also increase.

Innovations in stormwater treatment have led to the development of manufactured gravity separation devices that capitalize on this relationship. Internal components such as swirl concentrators, flow controls, and baffles are added to constructed basins to organize flow into complex flow patterns that promote increased residence times for the water passing through the system. Each of these modifications enhance the overall removal efficiency of the SCM and reduce the size of the system bringing it closer to its theoretical limit. Manufactured gravity separation devices can settle a greater range of particle sizes with higher HLRs than that of comparable settling basins without modifications, however they do not all provide the same efficiency of suspended solids removal.

Baffle Dissipators

One innovative technology in gravity separation is the use of baffles in sumped manholes to promote the capture of large particles and prevent the scour and subsequent resuspension of previously captured material. Typically, basic manholes are not used for any form of treatment. They are primarily used in the conveyance of stormwater to provide junctions for multiple pipe connections, change the direction of a storm sewer network pipe, or provide maintenance access to a storm sewer network. In some areas, it is acceptable to set the elevation of the bottom of a manhole several feet below the invert of the storm pipes, creating a sump. These sumped manholes act as small sedimentation basins and are effective at capturing large particles that do not typically stay suspended in stormwater. This is beneficial to the storm sewer network because it provides a centralized maintenance access point to remove the solids that have settled in the sump.

However, resuspension and washout of the settled solids is a concern in standard sumped manholes. During high intensity rainfall events, the velocity of water through the storm sewer network may scour the previously captured sediment in these sumps, causing the previously captured solids to be washed out downstream. To reduce the potential for scour, baffle dissipators can be added to sumped manholes. These baffles can reduce the formation of circular eddies that can scour and resuspend the previously captured sediment.

Gravity separation devices that use baffle dissipators and sumps to capture sediment are best used for applications that target large particle sizes. Since typical manholes do not have a large surface area, their HLR is generally quite high compared to other practices like settling basins or gravity separators designed specifically to treat stormwater. While these manholes can be deep, depth alone does not make for highly effective sediment capture, so the sumps are most effective at capturing coarse particles like sand and gravel.

Swirl Concentration (Hydrodynamic Separation)

Another prominent technology deployed in gravity separators is the use of swirl concentration, also called vortex separation or hydrodynamic separation. Internal components are added to stormwater structures to organize influent flow into concentrated vortex flow – that is a rotating motion of flow around a vertical central point, not unlike the swirl found around a tub drain. This rotational flow is not fast enough that centrifugal forces are a primary factor in the removal of solids, instead gravity remains the prominent force for settling particles. By creating a vortex, these hydrodynamic separators (HDS) condense the flow path by coiling around a central point.

Compared to a settling basin where a large area would be required to provide a settling path long enough to capture particles, the same settling path is condensed in a much smaller area for HDS (compare Figure 4 and Figure 5 for simplified diagrams of settling paths).

This organized flow generally results in the removal of smaller particles than in a basic settling basin with the same HLR. Since the HLR is controlled by the area, and the hydrodynamic separator has a reduced area compared to a settling basin, HLR for a hydrodynamic separator would be higher than that of a basic settling basin targeting the same particle size.

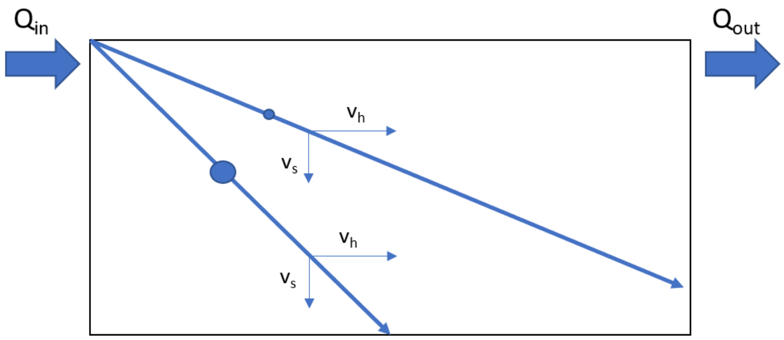

Figure 4 - Simplified diagram of particulate settling paths in a settling basin

Manufacturers of HDS systems use different vortex producing geometry and may include other treatment components such as baffles, flow controls, and screens to aid in particle separation and meeting other treatment goals (such as the containment of trash, debris, and hydrocarbons). Because the configuration of each manufactured HDS is different, the performance for each configuration differs when compared by the same HLR. The evaluation of removal efficiency for each HDS device is recommended to be performed according to industry-wide testing protocols in order to establish a performance curve specific to each unique technology.

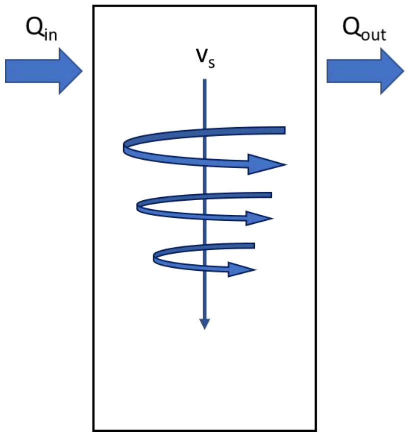

Figure 5 - Simplified diagram of HDS settling

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Basics of Gravity Separation Devices

Part 2: Particle Size Distributions and Loading Rates

Particle Size Distribution

Although many state and local stormwater programs have implemented policies that call for an 80% reduction of post construction total suspended solids (TSS) loads, estimating the composition of TSS when designing stormwater quality controls is up to local interpretation. A required "80% reduction of TSS" in one municipality will result in different treatment parameters than "80% reduction of TSS" in another municipality. This is because the particle size distribution (PSD) varies by location and land use. A particle size distribution generally identifies all the particle sizes of sediment found in a sample of stormwater runoff, categorized by size and portion of the whole sample by mass. Many stormwater control measures (SCMs) can operate across a wide range of hydraulic loading rates, which in turn greatly impacts the particle sizes they effectively capture, with finer PSDs requiring lower loading rates to achieve the same level of capture. Since most SCM performance data is based on a specific PSD, actual removal for any given project will be different because the PSD will be different. In jurisdictions that define a PSD in their TSS removal specification, it is possible to estimate actual removal; in those that don't, estimating performance requires some additional engineering judgement.

In general, PSDs can be characterized by a particle size specification, a median (d_{50}) particle size, or a specified distribution within a range. Three common examples of these are described below.

Particle Size Specification: NJDEP Test Protocol PSD

The New Jersey Department of Environmental Protection (NJDEP) has developed a laboratory protocol, in conjunction with SWEMA and other industry stakeholders, to assess the TSS removed by hydrodynamic separator (HDS) manufactured treatment devices (MTDs). The protocol involves testing across a range of operating rates and utilizing a specific broad PSD that is similar to a silt loam distribution. The PSD is based on soil gradations encountered in the field in New Jersey. Testing with a known PSD under consistent laboratory conditions allows for repeatability of the procedures and comparability of the results. For an HDS to receive NJDEP certification, the tested PSD must be consistent with or finer than the PSD shown in column 2 of Figure 1.

Table 1: Test Sediment Particle Size Distribution[1]

	TSS Removal Test PSD	Scour Test Pre-load PSD
Particle Size (Microns)	Target Minimum % Less Than[2]	Target Minimum % Less Than[2 and 3]
1,000	100	100
500	95	90
250	90	55
150	75	40
100	60	25
75	50	10
50	45	0
20	35	0
8	20	0
5	10	0
2	5	0

1. The material shall be hard, firm, and inorganic with a specific gravity of 2.65. The various particle sizes shall be uniformly distributed throughout the material prior to use.
2. A measured value may be lower than a target minimum % less than value by up to two percentage points, (e.g., at least 3% of the particles must be less than 2 microns in size [target is 5%]), provided the measured d_{50} value does not exceed 75 microns for TSS test removal efficiency PSD.
3. This distribution is to be used to pre-load the MTD's sedimentation chamber for off-line and on-line scour testing.

Figure 1 - NJDEP Specific Test Sediment PSD

Performance Goal	Influent Range	Criteria
Basic Treatment	20-100 mg/L TSS	Effluent goal < 20 mg/L TSS
	100-200 mg/L TSS	≥ 80% TSS removal
Dissolved Metals Treatment	Dissolved copper 0.005 - 0.02 mg/L	Must meet basic treatment goal and exhibit ≥ 30% dissolved copper removal
	Dissolved zinc 0.02 - 0.3 mg/L	Must meet basic treatment goal and exhibit ≥ 60% dissolved zinc removal
Phosphorus Treatment	Total phosphorus (TP) 0.1 to 0.5 mg/L	Must meet basic treatment goal and exhibit ≥ 50% TP removal
Oil Treatment	Total petroleum hydrocarbon (TPH) > 10 mg/L	1) Daily average effluent TPH concentration < 10 mg/L 2) Maximum effluent TPH concentration of 15 mg/L for a discrete (grab) sample
Pretreatment [b]	50-100 mg/L TSS	< 50 mg/L TSS
	100-200 mg/L TSS	≥ 50% TSS removal

mg/L - milligrams per liter
TP - total phosphorus
TPH - total petroleum hydrocarbons
TSS - total suspended solids

a. See TAPE Technical Guidance Manual for further details.
b. Pretreatment technologies generally apply to (1) project sites using infiltration treatment and (2) treatment systems where pretreatment is needed to ensure and extend performance of the downstream basic or dissolved metals treatment facilities.

Figure 2 - TAPE Performance Goals

Median d50 Particle Specification: Washington State Department of Ecology TAPE

The Washington State Department of Ecology Technology Assessment Protocol-Ecology (TAPE) is a comprehensive field monitoring protocol that includes a peer-reviewed verification and certification process for emerging stormwater technologies. Long duration and low intensity storms predominate in the pacific northwest (PNW) region, so stormwater often contains more fine silt and clay sized particles as compared to other regions where higher intensity rainfall mobilizes larger sand sized particles. The finer PSDs common to the PNW can make TSS removal results more modest for a given technology than would be achieved at the same loading rates in a region that tended to have coarser PSDs. TAPE monitoring is performed at a designated field site of the stormwater treatment system. With a requirement of testing where stormwater contains mostly silt sized particles (d_{50} of less than 50 µm), pretreatment technologies must demonstrate the ability to remove at least 50% of the TSS when influent TSS is 100-200 mg/L, as shown in Figure 2.

Specified Distribution Within a Range: OK-110 Silica Sand

The OK-110 PSD is not dictated by any established state level test protocols but was commonly used in other laboratory-based protocols that predate the ones previously mentioned. This material is a commercial blend of silica sand with a PSD range with 90% of the particles between 100 and 240 µm and a median particle size of about 110 µm (microns). Although OK-110 is not commercially available from US Silica any longer, an equivalent can be obtained and OK-110 is still a commonly used particle size distribution for manufacturers testing MTDs that require an 80% removal rate of TSS and is still referenced in the BMP manuals of some jurisdictions.

If a distribution is not specified, but a minimum and maximum are known, it is possible to estimate a distribution and use it for estimated performance calculations. The easiest distribution is a linear one, where all particle sizes are assumed to have the same percentage. For example: 20% between 20 µm – 50 µm, 20% between 50 µm – 100 µm, 20% between 100 µm – 200 µm, 20% between 200 µm – 500 µm, and 20% ≥ 500 µm. Other options would be to assume that the sizes are distributed normally between the minimum and maximum in a statistical bell curve, or distributed log-linearly between the minimum and maximum.

The Effect of Loading Rate and PSD on Removal Performance

When sizing a hydrodynamic separator to remove a target percentage of 80% for a specified PSD, it is important to compare the PSD to the particle size targeted for capture within the hydrodynamic separator. The definition of critical particle size is discussed in **Part 1** of this series. In summary, the critical particle size is the smallest sized particle that can be reliably removed by the separator at a given flow/hydraulic loading rate. For example, a specific hydrodynamic separator might be chosen for the capture of a critical particle size of 150 µm at a flow rate of 4 cfs. This means that the device will typically capture particles 150 µm and larger at an operating rate of 4 cfs. If the same size device was treating less than 4 cfs it would be capable of removing finer particles; conversely, increasing the flow above 4 cfs would increase the size of the critical particle that could be reliably captured.

Critical Particle Size Theory

Commercially, sediment removal data is presented as removal efficiency versus flow rate for a given test PSD (commonly, the NJDEP PSD). Another way to estimate removal for a target PSD and flow based on data from NJDEP is to use the “Critical Particle Size Theory” (CPST). The CPST is based on the theory that an HDS will capture all particles above a certain critical diameter and no particles below the critical diameter. Application of the CPST is straightforward and most easily understood by example.

Consider a system that achieved 51% removal of NJDEP PSD at the project flow rate. The critical particle size will be between 50 & 75 µm, because 51% removal falls between 50% and 55% of the PSD captured (100% - % finer) as shown in Figure 3. If more precision is desired, linear interpolation can be used between

Critical Particle Size (µm)	NJDEP PSD		OK-110 PSD	
	% finer by mass	% of PSD Captured	% finer by mass	% of PSD Captured
1000	100	0	100	0
800			100	0
500	95	5	100	0
250	90	10		
212			99.8	0.2
150	75	25	98.8	1.2
125			83.8	16.2
106			43	57
100	60	40		
88			18	82
75	50	50	3	97
50	45	55	0	100
20	35	65		
8	20	80		
5	10	90		
2	5	95		

51% capture between 75 and 50 µm

Figure 3 - Comparison of CPS for different PSDs

the two particle sizes to calculate that 70 µm corresponds to 51% removal. This critical particle size (CPS) at 1 cfs is then compared to the PSD for the project.

Relative to the OK-110 PSD, the CPS (70 µm) falls between 50 µm and 75 µm, so the removal will be somewhere between 97% and 100%. Linear interpolation between the two values gives 97.6% removal of this PSD. This means that a unit certified for 51% removal of the NJDEP PSD would be expected to achieve ~97% removal of the OK-110 PSD at the same flow rate.

Another way to illustrate Critical Particle Size Theory graphically is to plot the critical particle size against the desired PSD. This provides a visual reference for the expected removal efficiency of a system with a given critical particle size. In the example shown below in Figure 4, a system designed to target a critical particle size of 120 µm is estimated to remove 80% of the coarser PSD and 50% of the fine PSD.

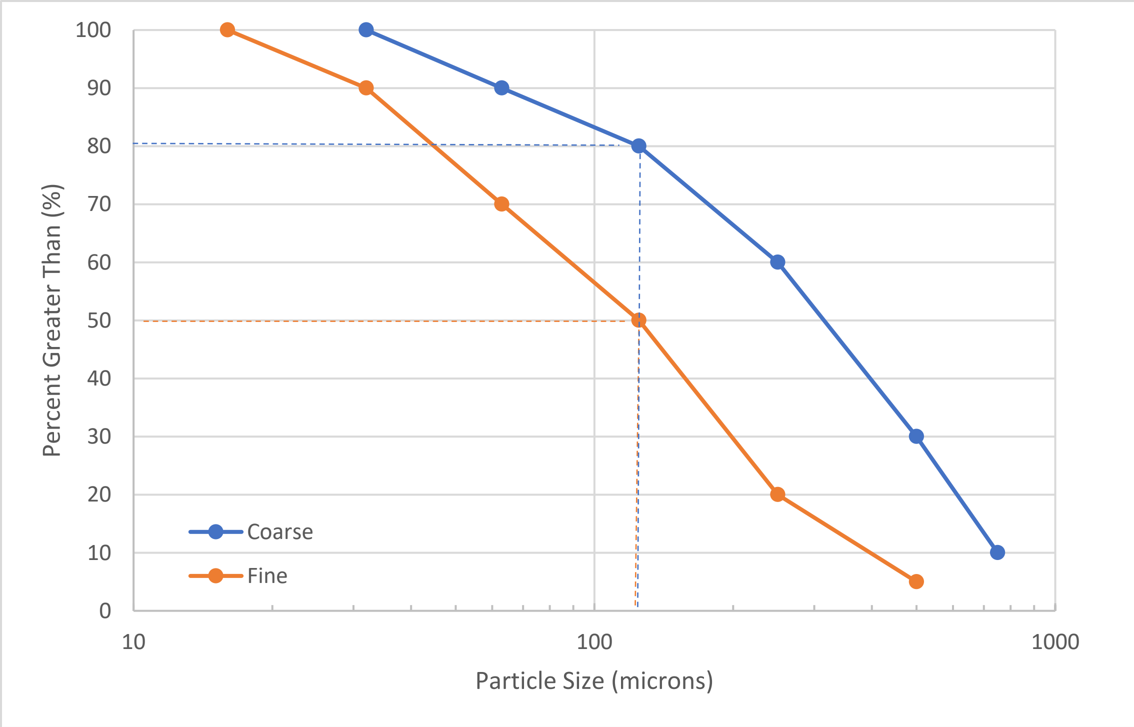

Figure 4 - Graphical plot of example coarse and fine PSDs with comparison of CPS for each

Summary

In summary, the reporting of HDS performance as a removal efficiency requires additional context in the form of a specified hydraulic loading rate and a specific PSD. As gravity separators rely directly on the gravitational settling of particles for treatment, the gradation of the PSD in relation to the system loading rate ultimately has the biggest influence on the removal efficiency. A PSD predominantly comprised of finer particles (i.e. silts and clays) will require a longer residence time in the separator than that of a coarser particle gradation to achieve the same level of removal efficiency. Subsequently, finer PSDs will require a lower hydraulic loading rate.

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Basics of Gravity Separation Devices

Part 3: Principles of Scaling

Overflow Velocity

In order for a gravity separation device to provide pollutant capture, a particle must have enough time to settle far enough that it will not reach the outlet. As noted in **Part 1**, Stokes' Law shows that smaller particles fall out of suspension more slowly. In **Part 2** it was shown that for two systems to achieve the same removal they must be able to settle out the same critical particle size. This means the two systems must have the same effective detention time.

In the stormwater industry it is more common to look at this problem in terms of velocities. If the settling velocity of a particle is greater than the critical velocity of the system, sometimes called the overflow velocity, the particle will be captured. The overflow-rate concept is most often used for settling basins, and characterized by the following:

$$\boldsymbol{V_O}(\boldsymbol{overflow\ velocity}) = \boldsymbol{Q/A} \qquad Q = influent\ flow\ rate\ (ft^3/s)$$

$$\boldsymbol{V_S}\,(\boldsymbol{particle\ settling\ velocity}) > \boldsymbol{V_O} \qquad A = surface\ area\ of\ basin\ (ft^2)$$

Scaling by Hydraulic Loading Rate

The hydraulic loading rate (HLR), as introduced in **Part 1**, is the volumetric flow rate of the fluid divided by the surface area of the separator and is often expressed in either gallons per minute per square foot (gpm/ft^2) or liters per second per square meter (lps/m^2). This is the same equation as the overflow rate, only expressed in different units. **Part 1** also describes how the performance of a hydrodynamic separator can be estimated using the hydraulic loading rate (HLR) and the critical particle settling velocity, the same way that basin performance is estimated using settling velocity and overflow velocity.

Since two systems that have the same HLR will be able to settle out the same critical particle size they are expected to have the same performance. This makes keeping HLR constant a convenient and widely accepted method to scale hydrodynamic separators to larger or smaller sizes while maintaining equivalent performance.

For example, most available removal-versus-flow data is from laboratory studies that measured the performance of a smaller HDS model size, typically around 4-ft in diameter. A unit of this size has a surface area of around 12.6 sq.ft. and if this separator achieved 80% removal of 100 µm particles at 250 gpm, then the calculated hydraulic loading rate that produced these results was:

$$250\ gpm\ /\ 12.6\ sq.ft\ or\ {\sim}20\ gpm/sq.ft.$$

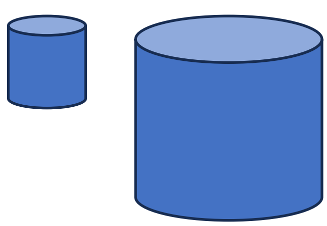
Scaling by HLR assumes that this loading rate will produce the same result of 80% removal of 100 µm particles in a larger size separator as long as the HLR is maintained at 20 gpm/sq.ft. To continue this example (see Figure 1), a 10-ft diameter separator has a surface area of 78.5 sq.ft. If this 10-ft separator was loaded at a HLR of 20 gpm/sq.ft. the flow rate through the system would be around 1570 gpm.

4-ft Diameter Vessel

Surface Area = 12.6 sq.ft.

Flow Rate = 250 gpm

HLR = 250/12.6 = **20 gpm/sq.ft**



10-ft Diameter Vessel

Surface Area = 78.5 sq.ft.

Flow Rate = 1570 gpm

HLR = 1570/78.5 = **20 gpm/sq.ft**

Figure 1 - HLR scaling assumes equivalent performance in two vessels with the same hydraulic loading rate

While HLR is the most significant factor in the scaling of a hydrodynamic separator, relying only on HLR can be an oversimplification. Two separators that have the same HLR but very different hydraulic residence times (HRT) may behave very differently. While HLR is based on the surface area of the system, the HRT is based on the volume of the system (See Figure 2). If the performance of two systems with the same surface area are studied and one is very shallow and the other is very deep, the results are unlikely to be the same due to the settling distance to the sump.

If $HLR = \frac{Q}{A}$ and $HRT = \frac{V}{Q} = \frac{A \times D}{Q}$ and $t = \frac{D}{v}$

When $HRT = t$, then $\frac{A \times D}{Q} = \frac{D}{v}$ and $v = \frac{Q}{A} = HLR$

Where:

HLR = hydraulic loading rage	V = basin volume (ft^3)
HRT = hydraulic residence time	D = basin depth (ft)
Q = flow rate (cfs)	t = settling time (s)
A = basin area (ft^2)	v = settling velocity (ft/s)

Figure 2 - HLR and settling velocity derivation

Other factors like vessel shape, ratio of length to width, inlet pipe velocity, etc. can all affect the performance of a system, but none of these factors have as much influence as HLR. Hydraulic loading rate is used as the basis for the design of stormwater detention basins as well as the design of sedimentation tanks in wastewater treatment plants. For that reason, the most widely accepted verification agencies in North America: New Jersey Center for Advanced Technology (NJCAT), Washington State Technology Assessment Protocol - Ecology (TAPE) , and Canada's Environmental Technology Verification (ETV) use HLR as their primary method of scaling hydrodynamic separators.

Geometric Similitude

NJCAT verification for testing under the NJDEP protocol ensures that there are no unintended consequences of the scaling methodology by requiring geometric similitude between system sizes. This means that when scaling a hydrodynamic separator, it should be scaled in all three dimensions to avoid any unintended increases in turbulence within the system. Additionally, the protocol uses a prescribed inlet pipe size. Removing this variable further ensures that the results from tests performed on different hydrodynamic separators are comparable.

Scaling a hydrodynamic separator using HLR and HRT is a type of hydraulic similitude – the hydraulic conditions at any point in one system is the same as the velocity at the corresponding point in the scaled system. Because hydraulic loading rate (HLR) is ultimately a form of velocity (see Figure 3 for unit analysis), the ratio of settling velocity (V_s) to hydraulic loading rate (HLR) is dimensionless. This means that it can easily be used regardless of preferred engineering units. While there have been other more dimensionless numbers proposed for scaling hydrodynamic separators - Peclet Number, Froude Number, Reynolds Number and combinations of these – V_s/HLR remains the industry standard for its simple explanation, reliability and ease of use.

$$HLR = \frac{Volume\ per\ Time}{Area} = \frac{Volume}{Time} \cdot \frac{1}{Area} = \frac{Length^3}{Time} \cdot \frac{1}{Length^2} = \frac{Length}{Time} = V_s\ (velocity)$$

Figure 3 - Unit analysis showing that HLR and velocity have the same units

Resources

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Basics of Gravity Separation Devices

Part 4: Flow Rates and Performance Based Goals

To ensure that hydrodynamic separators (HDS) perform adequately and to allow for comparisons between similar devices, standardized test protocols have been written to evaluate removal performance versus flow rate capability. Examples of current test standards are ASTM C1746-19 (Standard Test Method for Measurement of Suspended Sediment Removal Efficiency of Hydrodynamic Stormwater Separators and Underground Settling Devices) and the New Jersey Department of Environmental Protection Laboratory Protocol to Assess Total Suspended Solids Removal by a Hydrodynamic Sedimentation Manufactured Treatment Device (Jan. 1, 2021).

As described in the previous parts of this series, stormwater professionals should select a device based on their water quality goals, typically a design flow rate and the percent of sediment removal desired. The specified sediment removal performance attributed to an HDS will be influenced by many factors, the most significant being flow rate and particle size distribution. Particle size is addressed in **Part 2** of this series. This paper will discuss the different ways to calculate the impact of flow rate on performance.

Flow Rate

The hydraulic capacity and the treatment flow rate of a hydrodynamic separator are two important but distinct aspects of its performance. Hydraulic capacity is concerned with the HDS ability to handle stormwater while the treatment flow rate focuses on its ability to effectively remove pollutants. From ASTM E3318 Standard Terminology for Standards Relating to Stormwater Control Measures, the following definitions apply:

- **Maximum Hydraulic Flow Rate** (MHFR), *n*—the flow rate at which a manufactured treatment device (MTD) can convey flow without exceeding hydraulic grade line restrictions.
- **Maximum Treatment Flow Rate** (MTFR), *n*—the highest flow rate that can be conveyed through a MTD to achieve the verified performance-based claims for pollutant removal.
- **Water Quality Flow Rate** (WQFR), *n*—the design flow rate at which a MTD is sized to meet a specific water quality treatment target.

Stormwater professionals need to consider both hydraulic capacity and treatment flow rate to ensure efficient water treatment during storm events, especially when placing an HDS system in an on-line configuration and relying on the internal bypass components within the HDS to manage the full hydraulic load of the drainage system.

Calculating Removal Performance

The extent to which an HDS removes pollutants from stormwater is one of the key considerations when selecting a device. Removal performance may be calculated in two significantly different ways, **instantaneous removal** and **annualized removal**. Instantaneous removal assesses the separator's efficiency during an individual storm event at a specified flow rate. For example, a given system might be sized to provide 80% removal of a particular PSD at 1 cfs.

Annualized removal performance provides a more comprehensive view of a separator's average effectiveness over an entire year. While an HDS's instantaneous removal performance for a specified flow rate can be easily identified, the annualized removal requires an understanding of a site's average annual rainfall intensity distribution over a 12-month period.

There are multiple ways to do this calculation and it is possible to factor in climate change, but that is beyond the scope of this paper. ASTM is developing a standard for calculating the weight factors needed to determine annual removal, expected sometime in 2025. In the meantime, Appendix A of New Jersey Department of Environmental Protection Laboratory Protocol to Assess Total Suspended Solids Removal by a Hydrodynamic Sedimentation Manufactured Treatment Device (Jan. 1, 2021) provides an example of a relatively simple way to calculate annual removal for New Jersey.

The first step is to group the average rainfall intensities over a year into "buckets." New Jersey uses five buckets, but more groupings will give greater accuracy at the expense of requiring more calculations. Each intensity is then converted into a flow rate, using the rational method, for example. Each bucket is then assigned a weighting factor based on how often those flows occur in a year.

Percentage of MTFR	Testing Flow Rate (cfs)	Annual Frequency Weighting Factor
25%	0.25	0.25
50%	0.50	0.30
75%	0.75	0.20
100%	1.00	0.15
125%	1.25	0.10

Table 1 - Annualized testing flow rates based on 1 cfs MTFR

Referring to Appendix A of the protocol shows the weighting factors relative to a portion of the Maximum Treatment Flow Rate (MTFR), which may vary from one HDS to the next. This introduces some error, since the same frequency is assigned to different flows, but most HDS have an MTFR close to 1 cfs so the error is small. Table 1 uses an MTFR of 1 cfs as an example for ease of calculation. In the example below, storms that result in flows ≤ 0.25 cfs make up 25% of the storms in a typical year.

These weighting factors can then be applied to the removal versus flow data for the HDS and the annualized removal performance can be calculated as shown in Table 2.

Testing Flow Rate (cfs)	Instantaneous Removal Efficiency	Annual Frequency Weighting Factor	Contribution to Annualized Removal
0.25	69%	0.25	17.3%
0.50	58%	0.30	17.4%
0.75	47%	0.20	9.4%
1.00	36%	0.15	5.4%
1.25	25%	0.10	2.5%
Cumulative Annualized Removal Efficiency			**52.0%**

Table 2 - Calculation of annualized removal efficiency

It is important to note that the removal reported in the NJDEP protocol test results is an annualized removal performance based on the reported MTFR. This means that a device with an MTFR = 1 cfs reported to remove 52% of sediment does not remove 52% at a flow rate of 1 cfs, it removes an average of 52% over the course of a year, based on rainfall data from New Jersey. It can be seen in Table 2 that the instantaneous removal of this device at a flow rate of 1 cfs is 36%.

The example above is a simplistic presentation for the purposes of explaining annualized removal performance, the actual calculation may involve more complex statistical analysis. Data quality and the representativeness of the monitored storm events are crucial for obtaining accurate annualized removal performance values.

Summary

Hydrodynamic separators can play a crucial role in mitigating the environmental impacts of urban stormwater runoff and removal performance metrics offer valuable insights into their effectiveness. However, careful consideration of project goals, regulatory requirements, and available resources should guide the selection of the appropriate HDS device. The evaluation of hydraulic capacity, maximum treatment flow rate and removal performance for pollutants of a relevant particle size are critical to ensure that the system can handle the expected flow rates while maintaining the target pollutant removal efficiency, ensuring effective stormwater management and environmental protection.

Resources

ASTM International. 2019. "Standard Test Method for Measurement of Suspended Sediment Removal Efficiency of Hydrodynamic Stormwater Separators and Underground Settling Devices." ASTM C1746/C1746M-19. https://www.astm.org/c1746_c1746m-19.html.

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