Note on sediment removal efficiency in oil–grit separators

Yangbo Tang, David Z. Zhu and Bert van Duin

ABSTRACT

Oil–grit separators (OGSs) are one type of best management practice, designed to remove oil and grit from stormwater runoff (e.g., from parking lots and paved roads). This note examines scaling parameters for OGS removal efficiency. Three dimensionless parameters are chosen as scaling parameters: Hazen number (*Ha*), Reynolds number (*Re*) and Froude number (*Fr*). The Hazen number is a ratio of hydraulic residence time to particle settling time. The Reynolds number measures the surrounding turbulence effects on sediment removal efficiency. The Froude number represents the ratio of inertial and gravitational forces, which indicates the influence of gravity on fluid motion. The collected data from the literature on sediment removal in OGSs can be represented by a single curve when the Hazen, Reynolds, and Froude numbers are combined into a new scaling parameter ($HRF = Ha(Re/Fr)$). A general form is proposed to correlate the sediment removal efficiency with this new parameter. This generalized prediction method can be used as a preliminary performance indicator for OGS units. The obtained curve can also be used to adjust raw laboratory and field measurement data to improve the evaluation of the performance of various OGSs.

Key words | OGS, sediment removal efficiency, stormwater

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NOTATION

The following symbols are used in this note:

a, b, C_1, and C_2	coefficients;
A	horizontal cross-sectional area of water column in OGS (m^2);
d_{50}	medium size of sediment fraction (mm);
Fr	Froude number;
g	gravitational acceleration (m/s^2);
h	water depth excluding sediment storage depth (m);
Ha	Hazen number;
HRF	$Ha(Re/Fr)$ which is a combined parameter;
$Pé$	Péclet number;
Q	flow rate (L/s)
Re	Reynolds number;
T	hydraulic residence time (s);
V_M	vertically averaged flow velocity (m/s);
V_S	sediment settling velocity (m/s);
η	sediment removal efficiency;
ν	kinematic viscosity (m^2/s);
ρ_S	sediment density (kg/m^3);
ρ_W	water density (kg/m^3).

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INTRODUCTION

Stormwater runoff or snowmelt from urban impervious surfaces (e.g., parking lots and paved roads) usually contains oil and grit that can pose negative impacts on receiving water bodies. In order to minimize these negative impacts, oil–grit separators (OGSs) are commonly used to capture oil and grit (Higgins 2000). The focus of this note is only on sediment removal, which is the main characteristic used to evaluate the performance of different types of OGSs. OGSs can be divided into three types based on the different removal methods: (1) gravity action type in which sediment is captured by gravity only; (2) swirl action type in which swirling flow directs sediment toward the center of the OGS; and (3) screening action type which uses a screen to capture sediment (Malesevic *et al.* 2014). Although various OGSs have different configurations and dimensions, they all have two key aspects in common: the primary design function is to separate oil and grit from runoff, and they all rely on gravity to achieve their function. In order to properly apply OGSs, it is important to be able to quantify the removal efficiency under different catchment characteristics (e.g., for various sediment sizes, sediment concentrations, and flow rates).

In order to obtain removal efficiency data needed for sizing purposes, many laboratory evaluations of OGSs were conducted by suppliers, regulatory agencies and municipalities, each with their own specific sediment and for different flow rates. For example, Cornu *et al.* (2000) examined the removal efficiency of a Downstream Defender unit (i.e., a swirl type of OGS) and found its removal efficiency varied from 70% to 100% for relatively small flow rates decreasing from 25 L/s to 5 L/s (d_{50} of 0.3 mm sediment was used). Faram (2000) also tested the removal efficiency of a Downstream Defender unit and created a computational fluid dynamics (CFD) model to represent the flow regime within the unit. Based on their CFD model, the turbulence level was found to be strong in the unit being evaluated, which might negatively affect the sediment removal efficiency. Sturm *et al.* (2007) built a 1:2 scale model to examine the removal efficiency of the Skimpro OGS (i.e., a gravity action type). They made several modifications on the device and subsequently tested their performance. A detailed velocity field was obtained in their study, which also indicated the influence of turbulence.

In addition to laboratory investigations, numerous field studies have been conducted over the last two decades to obtain removal efficiency data of OGSs under prototype operating conditions. For instance, in 2004, two types of OGSs were monitored (i.e., a screening action OGS and a swirl type OGS) at a parking lot in Toronto, Canada (SWAMP 2004). The sediment in the runoff contained relatively small sediment with a d_{50} of 20 μm. The average removal efficiency of these OGSs was found to be about 40% to 50%, which is in good agreement with other studies. They suggested that different types of OGSs can be expected to have similar removal capabilities. However, their field data included some unexpected values, e.g., with a 1.7 L/s flow rate, the sediment removal efficiency was only around half of that with an 8.2 L/s flow rate. There was some concern that the performance results might be biased due to the uncertainty during fieldwork. A second challenge is that the field-testing only covers a fraction of the conditions that the units might be subjected to during their operation.

In order to overcome the discrepancies in both the laboratory and field investigations, several jurisdictions adopted various testing protocols in order to provide uniform testing conditions (Howie 2011; NJDEP 2013). In Canada, to provide a common procedure for testing and verifying the actual performance of treatment devices under controlled conditions, in an independent, transparent manner, a nation-wide protocol for laboratory testing was adopted under the auspices of the Canadian Environmental Technology Verification (ETV) process (Toronto and Region Conservation Authority 2014). Performance data based on the implementation of the recent ETV Canada protocols were obtained for several OGS units: a Downstream Defender Hydro unit (swirl type) (ETV 2016) as well as a Stormceptor EF4 unit (gravity type) (ETV 2017). The tested flow rates and sediment sizes cover a wide range as per the ETV Canada protocols. An identical, artificial sediment mixture was used for all experiments. The removal efficiency results for the overall sediment removal are believed to be reliable. However, the removal efficiency results for some of the individual particle size fractions appear to be unusual under certain flow rates, see Figure 1. The unusual behaviour is the result of challenges of being able to properly disintegrate the overall sediment sample retained in the OGS into the original particle size fractions used to create the mixture used in the experiments. In addition, the settled fine sediment can coagulate to relatively coarser sediment, which may significantly increase the sediment removal efficiency for one particle size fraction group while decreasing it for other particle size fractions. As a result, the findings for some of the particle size fractions may need to be adjusted, which requires a transparent, scientifically defensible procedure.

In this note, the general performance of sediment removal efficiency in OGSs is described, which can predict the sediment removal efficiency prior to OGS installation. The significance of this generalized prediction method is that it can be used as a preliminary performance indicator

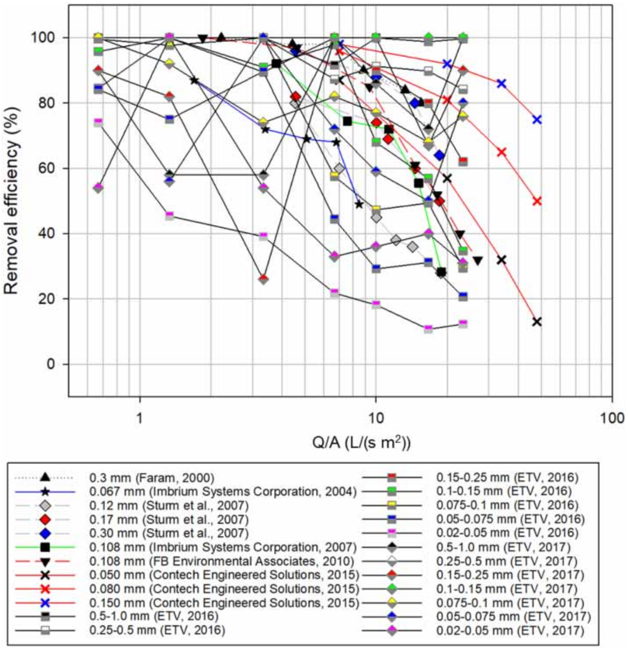

Figure 1 | Sediment removal efficiency in different OGSs.

for OGS units that have not yet been subjected to rigorous laboratory testing. In addition, this note provides useful information for the interpretation as well as, when needed, adjustment of data obtained following the ETV Canada protocols. A selection of field data as well as experimental laboratory data are compared against the outcome from the general prediction equation to demonstrate the potential use of the general prediction method.

Scaling parameters for OGS removal efficiency

Before determining scaling parameters, it is important to list all related physical parameters determining the sediment removal efficiency in OGSs. In general, there are three types of physical parameters: the sediment characteristics, fluid characteristics, and flow conditions. For the sediment characteristics, they are the sediment fractions of interest (using d_{50}: mm), the sediment density (ρ_S: kg/m^3), and the sediment settling velocity (V_S: m/s). The fluid characteristics include the water density (ρ_W: kg/m^3) as well as the kinematic viscosity (ν: m^2/s). The flow conditions can be described as the vertically averaged flow velocity (V_M: m/s), the depth of water (excluding sediment storage depth, h: m), and the horizontal cross-sectional area (A: m^2) of the water column in the OGS. The gravitational acceleration (g: m/s^2) is also important. After Pi theory was applied (e.g., Potter & Wiggert 2016), three dimensionless parameters were chosen as scaling parameters to predict the sediment removal efficiency in this note (specifically, Hazen number, Froude number and Reynolds number).

In the literature, two parameters are commonly used for hydrodynamic separators including OGS units: the Froude number ($Fr = (V_M/\sqrt{gh})$) and the Hazen number ($Ha = (V_S/V_M)$) (Fenner & Tyack 1997; Higgins 2000; Luyckx *et al.* 2005). In some studies, the Froude number was examined as a potential scaling parameter for the OGS removal efficiency since gravity plays an important role in removing sediment within OGSs (Fenner & Tyack 1997; Higgins 2000). However, Higgins (2000) found that the Froude number has limited applicability for modeling some devices since it is more relevant to free surface gravitational effects and does not strictly hold for swirl flow conditions. However, swirl flow conditions are commonly observed in many OGSs (Malesevic *et al.* 2014), which means only using the Froude number will not be sufficient. Therefore, some researchers (Fenner & Tyack 1997; Luyckx *et al.* 2005) suggest that the Hazen number has a good applicability to describe swirl action. The Hazen number can be presented as the ratio of the particle settling velocity and the vertically averaged flow velocity (Luyckx *et al.* 2005). The particle settling velocity can be calculated using the equation developed by Ferguson & Church (2004):

$$V_S = \frac{(\rho_S - \rho_W) g d_{50}^2 / \rho_W}{C_1 \nu + \left(0.75 C_2 (\rho_S - \rho_W) g d_{50}^3 / \rho_W\right)^{0.5}} \tag{1}$$

where $C_1 = 18$ and $C_2 = 1.0$. In fact, the Hazen number equals to $((Ah)V_s)/Qh$ (Q is the flow rate in the OGS), which can be treated as the ratio of the hydraulic residence time ($T = (Ah/Q)$) to the particle settling time (h/V_s). Note that the Péclet number ($Pé$) has also been used to explain sediment removal in hydrodynamic separators (Wilson *et al.* 2009; Tang *et al.* 2016). However, there is no difference between $Pé$ and Ha in terms of physical meaning (Wilson *et al.* 2009). The only difference between these two parameters is that their averaged velocities have different directions (vertical for Ha and horizontal for $Pé$). For devices with horizontal mean flow (e.g., standard sump), $Pé$ is recommended (Howard *et al.* 2012). For devices with vertical mean flow (e.g., catchbasins and OGSs), Ha is normally used (Fenner & Tyack 1997; Higgins 2000; Luyckx *et al.* 2005). Besides the Froude and Hazen numbers, the Reynolds number ($Re = ((V_M h)/\nu)$) was also considered in this note since turbulence plays a significant role in sediment removal. The turbulence caused by the interchange of eddies in a vertical direction can maintain sediment in suspension against the action of the gravitational force (Chien & Wan 1999; Verstraeten & Poesen 2000).

A combined parameter ($HRF = Ha(Re/Fr)$) is selected to develop a general prediction equation to express the removal efficiency of OGS units. The ratio of Re to Fr representing the ratio of the gravitational forces to the viscous forces has been used in many studies to describe the turbulence level as well as the hydraulic conditions (Kirkgöz & Ardiçlioğlu 1997; Belfiore 2003; Zhou & Cheng 2009). The product of Ha and the ratio of (Re/Fr) is defined as HRF and can be written as:

$$HRF = Ha\frac{Re}{Fr} = \left(\frac{V_S T}{h}\right)\frac{(V_M h)/\nu}{V_M/\sqrt{gh}} = \frac{\sqrt{g}}{\nu} V_S T \sqrt{h} \tag{2}$$

The resulting parameter is a function of the sediment settling velocity, the hydraulic residence time, and the water depth. As the settling velocity, hydraulic residence time and the water depth increase, the sediment removal efficiency increases. This tendency is physically reasonable. Note that the power of V_S, T, and h can be different from Equation (2), since Ha, Re, and Fr are dimensionless

Table 1 | Different combined parameters with R^2 and RMSE

Combined parameters	R2	RMSE
$Ha^{0.5}\ Re/Fr$	0.77	11.3%
$Ha\ Re^{0.5}/Fr$	0.83	11.2%
$Ha\ Re/Fr^{0.5}$	0.51	11.8%
$Ha\ Re/Fr$	0.93	5.8%
$Ha^2\ Re/Fr$	0.75	13.6%
$Ha\ Re^2/Fr$	0.17	24.8%
$Ha\ Re/Fr^2$	0.83	10.9%

parameters and can be of different power. However, after several trials, the combined parameter (*HRF*) was found to have the best fit in terms of R^2 and root mean square error (RMSE) (see Table 1).

Sediment removal efficiency in OGSs

Data were collected from previous studies including eight laboratory tests. The data cover a relatively wide flow rate range from 0.75 to 166.6 L/s. Different OGSs have different dimensions and designs, but their common purpose is to remove grit in storm water. All removal methods (gravity, swirl, and screening actions) are covered in this note. The sediment sizes used cover a relative wide range (d_{50}: 0.05–0.62 mm), representing very fine to coarse particles, and thus reflecting the sediment that is typically found in storm sewer systems. Table 2 summarizes key parameters of the eight laboratory studies.

Figure 1 shows the sediment removal efficiency as a function of the surface loading rate (Q/A) for the different types of OGSs. In general, the removal efficiency decreases as the surface loading rate increases and the particle size decreases. As can be seen in Figure 1, data from the Downstream Defender, Skimpro OGS, Stormceptor STC 900, Stormceptor OSR 250, CDS, and Vortech model 2000 follow this general tendency. They have approximately a 100% removal efficiency when the surface loading rate is low. When the surface loading rate increases, the sediment removal efficiency drops gently from 100% to 80%. After this period, the removal efficiency decreases rapidly all the way to around 20%. However, as mentioned before, in some instances it is hard to properly distinguish between the various particle size fractions that are part of the overall sediment sample that has been retained in the OGS. As a result, some units such as the Downstream Defender Hydro as well as the Stormceptor EF4 display unusual removal efficiency tendencies for some particle size fractions, which therefore needs adjustment. These data are therefore excluded from the data sets used to develop the general prediction model and will be adjusted afterwards.

The relationship between the developed parameter and the sediment removal efficiency is plotted in Figure 2 (log *x*-axis). All data are concentrated in an S-shape curve. In general, the sediment removal efficiency for all devices approaches 0% at low values of *HRF* and approaches 100% at high values of *HRF*. With changing values of *HRF*, the sediment removal efficiency slowly approaches 80% and 20% from 100% and 0%, respectively. When the removal efficiency approaches 50%, *HRF* equals 2.6×10^6. Note that the value of *HRF* is always large since the kinematic viscosity is the denominator. A general function is

Table 2 | Laboratory studies on different OGSs

Parameter	Downstream Defender (Faram 2000)	Stormceptor STC 900 (Imbrium Systems Corporation 2004)	Stormceptor OSR 250 (Imbrium Systems Corporation 2007)	Skimpro OGS (Sturm *et al.* 2007)	CDS (FB Environmental Associates 2010)	Vortech 2000 (Contech Engineered Solutions 2015)	Downstream Defender Hydro (ETV 2016)	Stormceptor EF4 (ETV 2017)
Type	Swirl action	Gravity action	Gravity action	Gravity action	Swirl and screening action	Gravity action	Swirl action	Gravity action
Q (L/s)	2.5–17.5	4.4–22	17.6–88.3	21–86	3.4–50	2.3–21	3.7–166.6	0.75–35.6
h (m)	1.25	1.4	1.4	1.3	1.44	1.3	1.8	1.5
A (m^2)	1.13	2.63	4.67	4.6	1.82	3.71	5.55	1.13
d_{50} (mm)	0.30	0.067	0.108	0.12, 0.17, 0.30	0.108	0.050, 0.080, 0.150	0.62[a]	0.62[a]

[a] Analyses were based on different sediment fractions instead of d_{50}.

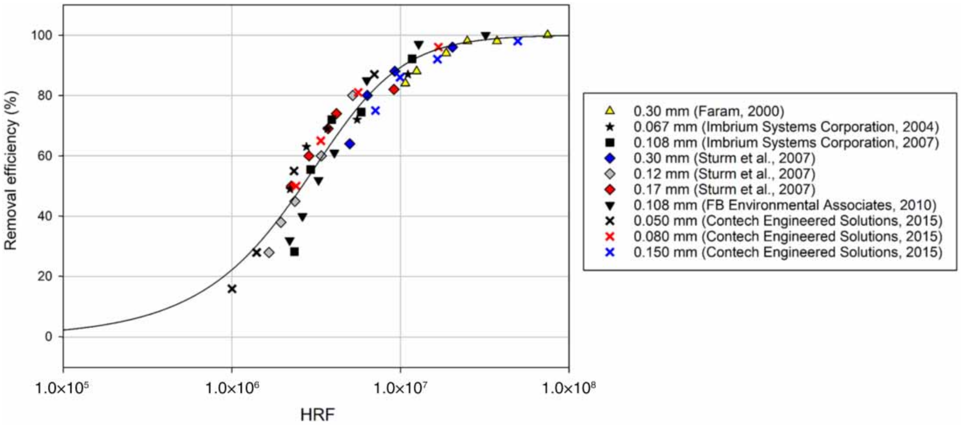

Figure 2 | Sediment removal efficiency prediction.

proposed below, which reflects the above features:

$$\eta = \left[1 + \frac{1}{a(HRF)^{b}}\right]^{-1/b} \tag{3}$$

where η is removal efficiency, and a and b are coefficients. In Figure 2, $a = 2.32 \times 10^{-7}$ and $b = 1.78$ with the R^2 value of 0.93 and the RMSE of 5.8%. The removal efficiency prediction works properly since the difference between the various experimental data and the prediction curve is only as high as 10%. This general equation can be used as a preliminary performance indicator for OGS units that have not yet been subjected to rigorous laboratory testing protocols. The values for a and b may be slightly different for each individual OGS device, reflecting the specific configuration of the unit in question. As such, where reliable experimental data exist, these should be adopted for design purposes. However, the general function can be used to evaluate whether the experimental data reflect the expected behavior and to adjust the raw data where appropriate.

Data from the Downstream Defender Hydro (ETV 2016), Stormceptor EF4 (ETV 2017), and field sampling (SWAMP 2004) were plotted together with the general prediction curve (see Figure 3). The data can be easily divided into two groups: (a) data fitting within a 20% deviation area and (b) data falling outside of this 20% deviation area. The 20% deviation is chosen since it can cover the majority of raw data, which not only represents the experimental tendency but also identifies unusual data points. The data

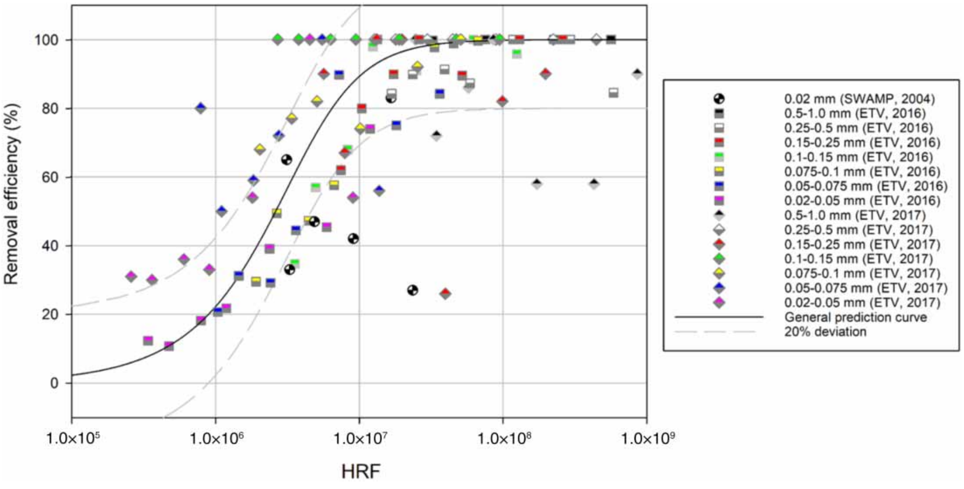

Figure 3 | Raw data and general prediction curve (SWAMP 2004; ETV 2016, 2017).

falling outside need to be adjusted to fit the general prediction curve. Specifically, for the Downstream Defender unit, the particle size fractions 0.1–0.15 and 0.02–0.05 mm data need to be adjusted, while for the Stormceptor EF4 unit, the particle size fractions 0.5–1.0, 0.15–0.25, 0.1–0.15, 0.05–0.075, and 0.02–0.05 mm data need to be adjusted. The field data need to be adjusted as well. The general prediction concept can be used as a tool to adjust the apparent scatter so that the processed data mimic the expected removal efficiency behavior. There are several factors that may bring uncertainties to the general prediction equation. Firstly, the combined parameter (*HRF*) simplifies not only the sedimentation and transport processes but also the flow conditions in OGSs. Secondly, inner structures of the OGSs (e.g., screen structures) can impact the accuracy of the equation. Moreover, various sediment size distributions, concentration and sediment composition can also affect the prediction results. Further research should be done to quantify the influence of above factors on the prediction equation. The following section describes the application of the prediction equation.

Adjustment method based on the general prediction equation

The data adjustment method based on the general prediction equation follows the flowing steps. In this note, the field data (SWAMP 2004), the laboratory data (0.1–0.15 mm from ETV (2016)) are adjusted as examples (Figure 4). First, collect all related experimental data for a particular OGS unit and transfer them into *HRF* as per Equation (2). Then, superimpose the relationship between *HRF* and the observed sediment removal efficiency on the general *HRF* curve of Figure 2. In this plot, the data points that have a deviation greater than 20% from the general curve should be adjusted, i.e., the data points outside of the dashed lines in Figure 3. Replace the observed removal efficiency data by the values on the general curve (i.e., the raw data and the adjusted data share the same value of *HRF*). Note that adjusting the data points will affect the total amount of sediment mass. For the Downstream Defender unit (ETV 2016) at the surface loading rate of 6.7 L/(s m^2) (Figure 4), the removal efficiency of 0.1–0.15 mm sediment is overestimated in the laboratory study comparing to that on the general *HRF* curve. Under the assumption of mass conservation, the removal efficiencies of other sediment fractions are underestimated. Therefore, removal efficiencies of other sediment fractions at 6.7 L/(s m^2) (in Figure 1) have been increased in this note. The comparison between the adjusted data (i.e., the solid lines) and the original raw data (i.e., the dashed gray lines) can be found in Figure 4. The adjusted removal efficiencies present a more realistic performance of the device for the particle size fraction of interest.

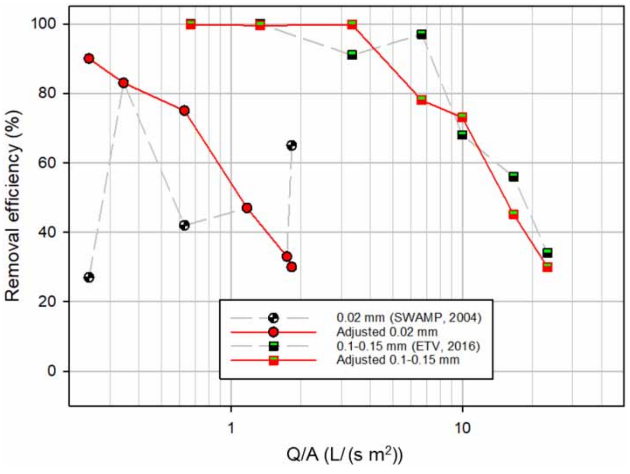

Figure 4 | Comparison between adjusted data and raw data.

SUMMARY

OGSs are commonly used to capture oil and grit from stormwater runoff or snowmelt on urban impervious surfaces. There are three different types of OGSs based on different removal methods: (1) gravity action type; (2) swirl action type; and (3) screening action type. The Hazen number, Reynolds number and Froude number are chosen as scaling parameters. A combination of these parameters expressed as *HRF* is chosen to describe the removal efficiency. This parameter is a function of the sediment settling velocity, the hydraulic residence time, and the water depth. As the settling velocity, hydraulic residence time, and water depth increase, the sediment removal efficiency increases. A general prediction form for the performance of several OGS devices was developed: $\eta = (1 + (1/(2.32 \times 10^{-7}(HRF)^{1.78})))^{-(1/1.78)}$. This form has a good fit with R^2 over 0.93 and RSME less than 5.8%. Note that a and b can be different when processing data sets from other studies. The generalized prediction method can be used as a preliminary performance indicator for OGS units that have not yet been subjected to rigorous laboratory testing. In addition, based on the general tendency of the removal efficiency, an adjustment method is developed that can be applied for test results where the results for the individual particle size fractions need adjustment.

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