Enhancing stormwater sediment settling at detention pond inlets by a bottom grid structure (BGS)

Ivan Milovanović, Vojtěch Bareš, Annelie Hedström, Inga Herrmann, Tomas Picek, Jiri Marsalek and Maria Viklander

ABSTRACT

Stormwater sediments of various sizes and densities are recognised as one of the most important stormwater quality parameters that can be conventionally controlled by settling in detention ponds. The bottom grid structure (BGS) is an innovative concept proposed in this study to enhance removal of stormwater sediments entering ponds and reduce sediment resuspension. This concept was studied in a hydraulic scale model with the objective of elucidating the effects of the BGS geometry on stormwater sediment trapping. Towards this end, the BGS cell size and depth, and the cell cross-wall angle were varied for a range of flow rates, and the sediment trapping efficiency was measured in the model. The main value of the observed sediment trapping efficiencies, in the range from 13 to 55%, was a comparative assessment of various BGS designs. In general, larger cells (footprint 10 × 10 cm) were more effective than the smaller cells (5 × 5 cm), the cell depth exerted small influence on sediment trapping, and the cells with inclined cross-walls proved more effective in sediment trapping than the vertical cross-walls. However, the BGS with inclined cross-walls would be harder to maintain. Future studies should address an optimal cell design and testing in an actual stormwater pond.

Key words | hydraulic scale modelling, sediment settling, sediment trapping efficiency, stormwater ponds

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INTRODUCTION

Progressing urbanisation leads to profound changes of the urban water cycle manifested by increased surface runoff and deterioration of runoff quality by discharges of various pollutants, including stormwater sediments (Walsh *et al.* 2005). In this context, stormwater sediments represent a broad spectrum of particle sizes, including total suspended solids (TSS) and bedload sediment, and impact both the water quality in the receiving waters and operation of drainage systems. Former impacts include TSS interference with quality processes in the water column, impairment of aquatic biota (Bilotta & Brazier 2008), and transport of attached chemicals and faecal microorganisms (USEPA 1983). Bedload sediment size classes comprising sand and fine gravel may cause blockage of conveyance elements, and reduction of water and sediment storage volumes in drainage facilities, including the ponds. Consequently, controls of runoff peaks and stormwater sediments have been among the highest priorities of stormwater management since the early 1970s. Since then, tens of thousands of stormwater detention ponds have been built worldwide for controlling runoff peaks by storage and removing stormwater sediment by settling.

Well-functioning stormwater ponds remove high quantities of incoming TSS and coarse sediment (Yousef *et al.* 1994; Pettersson 1999), which deposit and spread throughout the pond. For restoration of the pond design conditions and reduction of the risk of contaminated sediment resuspension (Bentzen 2010) and washout during high flows (Karlsson *et al.* 2010), pond sediments need to be removed and safely disposed of at time intervals as short as 16–17 years (Rishon 2013). Such a task represents one of the most

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costly items in pond maintenance (Al-Rubaei *et al.* 2017). To reduce the costs of pond sediment management, the first step was to introduce sediment forebays into pond design, with forebays occupying up to one third of the total permanent pool area (MOEE 2003). Recognizing that even the forebay cleanout is an onerous task, pre-treatment of stormwater immediately upstream of the pond, by swales or oil/grit separators, was recommended (MOEE 2003). Another way of achieving this objective would be to incorporate a sediment trap, with a small footprint, immediately downstream of the stormwater inlet into the pond.

Non-proprietary devices comprising bottom grid (or cellular) structures for enhancing settling and protecting the settled sediment against resuspension in confined waters were proposed; for example, by He & Marsalek (2014) and Simpson *et al.* (2018). Both structures enhanced suspended sediment settling by secondary currents in low velocity fields, and reduced the risk of resuspension of the settled sediment by confinement within the grid (He & Marsalek 2014). The main difference between the two structures is the cell shape: rectangular for BGS and a honeycomb in the cellular structure. The bottom grid structure (BGS) was further tested in the field, and in comparison to settling on the bare bed, it increased the sediment removal rate by a factor ranging from about 4 to 11, for various particle size ranges (He *et al.* 2014). Such promising results led to the idea of pre-treating stormwater entering the pond by a BGS device, which is easier and less expensive to manufacture than the cellular design. Thus, to reduce sediment spreading throughout the pond or forebay and lower the maintenance costs, it is proposed here to place a BGS structure downstream of the pond inlet, leading to the following benefits: (i) coarser sediment immobilization in the BGS with a small footprint, where it would be protected against washout and could be inexpensively removed by common municipal equipment, and (ii) such operations would reduce the frequency of pond dredging, which is relatively expensive and produces negative impacts on the downstream environment.

The objectives of the study reported on here were to: (i) comparatively assess the feasibility of using BGSs of various geometries to entrap and immobilize incoming stormwater sediment and (ii) suggest future research and development.

MATERIALS AND METHODS

Experiments with the BGS sediment trap were conducted in a hydraulic scale model. For model construction and testing, the following steps were taken: (i) a scale model was designed assuming a geometric scale 1:10 applied to hypothetical prototype dimensions (the inlet sewer $D = 1$ m, and BGS cells 0.5×0.5 m, 0.5 m deep), (ii) model sediment was chosen, and (iii) sediment trapping experiments were conducted in the model for selected flow rates, sediment fluxes and BGS cell designs. Further details follow.

Hydraulic scale model and model sediment

The hydraulic scale model, shown in Figure 1, was built in the Hydraulics Laboratory of the Czech Technical University in Prague and placed in an existing 1-m flume, which was fed water from the laboratory water supply system (LWSS) via an inlet tank. The discharge in the LWSS was measured using a MID flowmeter, Krohne Waterflux 300 (accuracy <1% of the measured value). Another flow measurement device, a Thompson weir (90° notch; accuracy 2–5%), was placed at the inflow to an existing 1-m wide

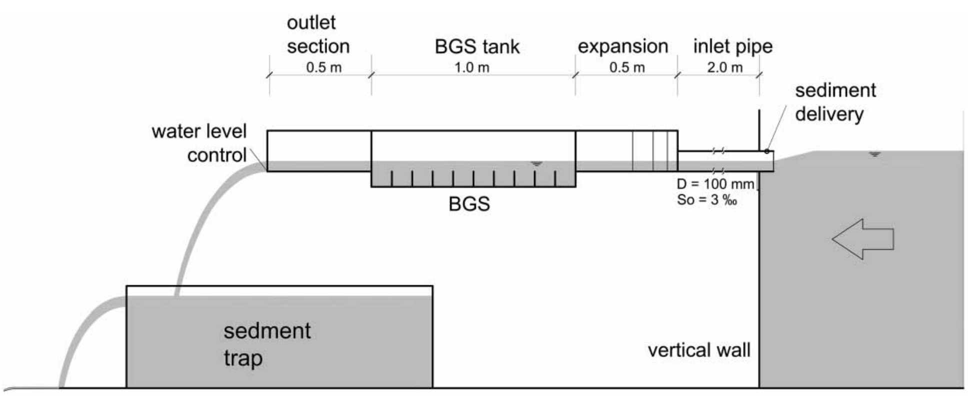

Figure 1 | Experimental setup of the BGS model.

flume. From the inlet tank, water flowed through a 100 mm PVC pipe (L = 2 m, S = 0.3 ‰) to the BGS tank (i.e. a settling tank fitted with BGS on the bottom). Two types of transition between the pipe outfall and the BGS tank were tested: (i) a sudden expansion (i.e. the inlet pipe opening was flush with the upstream BGS tank headwall) and (ii) a channel diffuser transition, 0.5 m long. The outer diffuser walls formed an angle of 40°, and insertion of three flow distribution baffles formed four flow channels with an expansion angle of ~10° (Figure 2).

The BGS tank, shown in Figure 2, was 1.0 m long and 0.5 m wide, and on its bottom rested the grid structure, with a basic cell size of 50 × 50 × 50 mm (L × W × D), subject to modifications during selected runs. The water depth in the model was controlled by a sill at the downstream end of the BGS tank, and by an inclined multiple-slots weir located at the downstream end of the outlet section, about 0.5 m downstream of the sill. Two initial runs with a depth of 5 cm indicated that a greater depth was needed for flow calming, recognizing that the BGS tank also functions as an inlet stilling basin. The addition of the BGS structure should increase the sediment trapping and protect the trapped sediment against a washout (He & Marsalek 2014). Consequently, the remaining runs were done with a constant depth of 7.5 cm.

The selection of a model sediment represents a compromise between the specifications of 'ideal' material properties (sizes in low tens of μm, density slightly exceeding that of water), the practicality of running settling experiments and retrieving the settled sediment from the model, and availability of suitable materials on the market. After such considerations, a granular PVC 'powder' NERALIT® (specific gravity = 1.32, d_{50} = 143 μm, settling velocity D_{50} = 0.0033 m/s calculated and 0.0034 m/s measured) was selected as the model sediment. The choice of model sediment concentration was governed by practicality of experimental methods, subject to two constraints: (a) working with a sufficiently large mass of material in individual experiments to ensure accuracy of measurements and, at the same time, (b) avoiding the interference of excessive suspended sediment mass with flow dynamics. The choice of 100 mg/L met such conditions (as would probably do some other concentrations as well).

During experimental runs, the model sediment was introduced into the model upstream of the inlet pipe, at a rate producing a nominal sediment concentration of 100 mg/L in the model inflow. For this purpose, a stock of water/sediment mixture was prepared, with the model sediment concentration of C = 250 g/L placed in a continuously stirred container and pumped by a peristaltic pump (ISMATEC MCP/BVP 360) at calculated rates, which would produce the inflow sediment concentration of 100 mg/L. As a mass balance check, the actual mass of sediment delivered in individual runs was verified from continuous readings of an electronic weigh scale (KERN 572, resolution of 0.05 g, representing 0.1–0.3% of the total mass of sediment used in runs with Q = 1–4 L/s) placed under the stock container.

Experimental conditions

As commonly done in comparative testing of settling structure geometries (Stovin & Saul 1994), investigations are done in a steady flow regime with constant concentrations of model sediment. Towards this end, a range of flow rates (1–4 L/s) was selected to avoid sediment settling in the inflow pipe (starting at about Q = 1 L/s) and maintain a subcritical flow regime in the model for about Q ≤ 4 L/s). For the range of model flows studied, Q = 1–4 L/s, a subcritical flow regime in the BGS tank, required the flow depth of 7.5 cm in the tank, and consequently, this depth was maintained in all runs by downstream flow controls (i.e. the sill at the downstream end of the BGS tank and the downstream weir). A

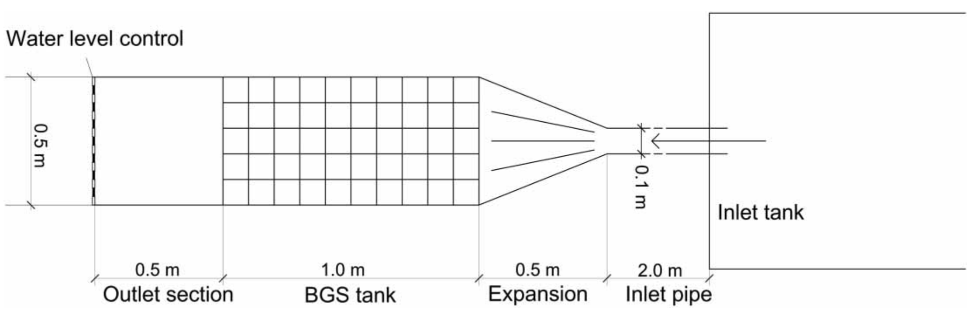

Figure 2 | Plan view of the experimental set-up of the BGS model.

laboratory protocol for model runs comprised the following steps: (a) prepare the water-model sediment mixture, (b) set up the hydraulic conditions in the model (the flow rate and depth) and start feeding in the water-sediment mixture, (c) run a preselected experimental scenario for durations of 30–50 minutes, (d) after finishing the run, retrieve the settled sediment from the BGS by a peristaltic pump, decant the water-sediment mixture, dry sediment in the oven (at 50 °C), and weigh the dry sediment, and (e) calculate the trapping efficiency $E_{tr} = M_{tr}/M_{in}$, where M_{tr} is the sediment mass trapped in the BGS and M_{in} is the mass of sediment fed into the BGS model. In total, 24 runs of the BGS model were carried out for various flow conditions (two flow depths, two transitions from the inlet pipe to the BGS tank, four flow rates), and combinations of cell widths, depths, and cross-wall angles (see Figure 3 for notation and Table 1 in the next section).

Uncertainties in trapping efficiencies E_{tr} were relatively low, because they represent values averaged over the experiment durations of 30–50 minutes. Furthermore, the total mass of sediment fed into the BGS during each run (180–720 g, for 30 minutes) was weighed accurately (0.5 g), so the uncertainty in M_{in} could be neglected. The remaining source of uncertainty was the trapped (retrieved) mass of sediment, which could be underestimated (i.e. incomplete retrieval and processing), or overestimated (should there be some sediment leftovers from previous runs, or incomplete sediment drying). M_{tr} uncertainty was conservatively estimated at 5–10%, and this estimate also represents the uncertainty in E_{tr} and its estimated magnitude was further supported by the results of repeated runs presented in the Results and Discussion section. Finally, this simplified consideration of uncertainties is acceptable in the context of study objectives constituting a comparative assessment of BGS geometries.

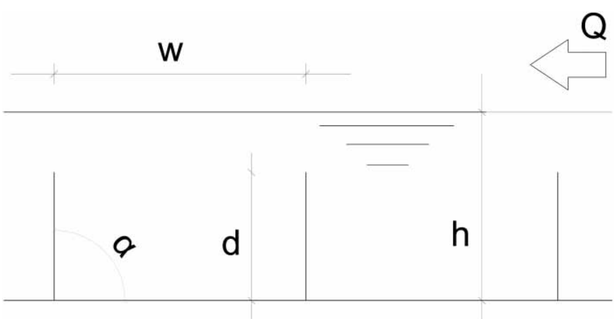

Figure 3 | BGS cells and their features varied in the experiments: cell width – w, flow depth – h, cell height – d and cross-wall angle – α.

Model similarity: flow and sediment transport

The dominant forces driving flow through the BGS model are those of gravity and inertia, for which the similarity between the model and prototype is achieved by maintaining identical Froude numbers in the model and prototype. However, the sediment transport similarity is much more challenging, because of complexities resulting from the need to reproduce not only the forces of gravity and inertia, as in the Froude similitude, but also viscous forces. For the conditions studied, this was not feasible and, consequently, the model was deemed as providing qualitative comparisons of various scenarios, but not fully quantified results.

RESULTS AND DISCUSSION

The presentation of results starts with the hydraulics of the BGS (settling) tank followed by sediment trapping. The results of all 24 experimental runs are presented in Table 1.

Initial runs of the BGS model with low flow depth (5 cm; runs 1 and 2) and a sudden transition from the inlet pipe to the BGS settling tank (runs 1–7) indicated a highly agitated flow in the tank, with a high velocity jet passing through the tank and two large backflow eddies forming on both sides of the jet. Such conditions were disruptive for effective separation of the incoming sediment from water and, consequently, the first steps were to correct this situation by: (i) ensuring subcritical flow through the facility by adjusting the flow depth to 7.5 cm and (ii) providing a hydraulically effective transition for the pipe inlet to the BGS tank by a diffuser. Such measures were fine-tuned by running the model with a smooth bottom in the BGS tank (i.e. without the BGS) in runs 6–10 and produced a quasi-uniform distribution of flow across the tank width. The testing of the BGS cell geometries followed (runs 3–5 and 11–24).

Experimental results documenting the benefits of the effective inflow transition and the presence of the BGS structure on the tank bottom are presented in Figure 4. There is a significant difference between the results with and without the diffuser transition (Figure 4(a)): for Q = 2 l/s, the diffuser proved to be 45% more effective than the sudden transition, while for Q = 4 l/s, the relative difference increased to 73%.

In general, runs with the BGS were about 25% more efficient in removing sediment from the flow than those without the BGS (Figure 4(b)), except for run 10 with the highest discharge (Q = 4 l/s), which was done with a

Table 1 | Experimental run parameter settings and the corresponding trapping efficiencies

Run	Inlet transition	Bottom arrangement[a]	Cell width w [cm]	Cell depth d [cm]	Cross-wall angle α [°]	Flow-rate Q [l/s]	Flow velocity V [m/s]	Flow depth h [cm]	Trapping efficiency E_{tr} [%]
1	Sudden[b]	BGS	5	5	90	2	0.08	5	19
2	Sudden	BGS	5	5	90	1	0.04	5	36
3	Sudden	BGS	5	5	90	1	0.03	7.5	33
4	Sudden	BGS	5	5	90	2	0.05	7.5	25
5	Sudden	BGS	5	5	90	4	0.11	7.5	13
6	Sudden	Smooth	–	–	–	1	0.03	7.5	25
7	Sudden	Smooth	–	–	–	2	0.05	7.5	20
8	Diffuser[c]	Smooth	–	–	–	2	0.05	7.5	36
9	Diffuser	Smooth	–	–	–	3	0.08	7.5	18
10	Diffuser	Smooth	–	–	–	4	0.11	7.5	26
11	Diffuser	BGS	5	5	90	2	0.05	7.5	40
12	Diffuser	BGS	5	5	90	3	0.08	7.5	24
13	Diffuser	BGS	5	5	90	4	0.11	7.5	23
14	Diffuser	BGS	5	10	90	2	0.05	7.5	34
15	Diffuser	BGS	5	10	90	3	0.08	7.5	27
16	Diffuser	BGS	5	10	90	4	0.11	7.5	20
17	Diffuser	BGS	5	10	90	1	0.03	7.5	55
18	Diffuser	BGS	10	10	90	2	0.05	7.5	43
19	Diffuser	BGS	10	10	90	3	0.08	7.5	30
20	Diffuser	BGS	10	10	90	4	0.11	7.5	20
21	Diffuser	BGS	5	10	60	2	0.05	7.5	39
22	Diffuser	BGS	5	10	120	2	0.05	7.5	40
23	Diffuser	BGS	5	10	120	3	0.08	7.5	33
24	Diffuser	BGS	5	10	60	3	0.08	7.5	32

[a]Bottom of the BGS tank.
[b]Sudden expansion – the inlet pipe was connected directly to the BGS tank.
[c]Diffuser expansion.

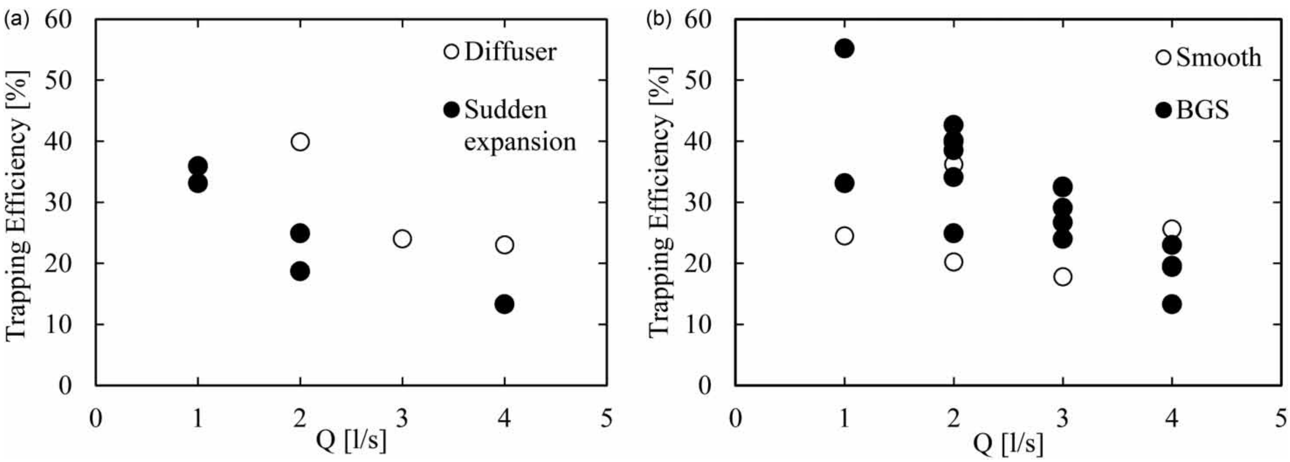

Figure 4 | (a) Sediment trapping efficiencies with and without the diffuser (cell width and depth 5 cm, cross-wall angle 90°) and (b) sediment trapping efficiencies in runs with and without BGS (smooth bottom runs).

smooth bottom and was about 11% more efficient than the best run with the BGS (i.e. run 13). Note, however, that run 10 was the only one among the routine runs in which the trapping efficiency for a particular BGS tank arrangement increased with an increasing discharge (i.e. compared to run 10, for Q = 3 l/s), which raises some doubts about the validity of this data point. One should also recognize that both variants; that is, with or without the BGS, use the same (BGS) tank promoting favourable settling conditions. The addition of the grid structure yields another benefit – protection of the deposited sediment against scouring.

Observation of flow patterns and sediment transport in the model indicated the presence of horizontal rollers in individual cells, with water moving downward along the downstream cross-wall, then in the upstream direction as a counter-current along the cell bottom, and finally upward along the upstream cross-wall and exiting from the cell. Such rollers entrained the sediment and moved it along a similar trajectory. While this flow pattern brings sediment into cells, it also tends to wash it out. Because of gravity, this pattern promotes overall particle settling, because along the downstream wall, flow and particles fall velocity act in the same direction, but along the upstream wall the particle washout is resisted by its gravity. Therefore, particles should settle near the downstream wall faster than they are being ejected by the fluid (Pedinotti *et al.* 1992). While it is conceivable that flow baffles preventing sediment washout could be fitted inside the cells, such a system would become complex and defeat the feasibility of easy maintenance and sediment removal.

Throughout all runs, the most influential factor for the sediment trapping efficiency was the discharge; that is, the streamwise flow velocity, with trapping efficiencies decreasing with increasing velocity. Figure 5 demonstrates the effect of flow velocity on the sediment trapping efficiency for a particular cell geometry (w = 5 cm, d = 10 cm, and $\alpha = 90°$).

Effects of various cell geometries on trapping efficiency were examined in runs 11–24, by changing the cell footprint size, depth, and cross-wall angle.

Cell footprint size and depth. BGS configurations with a cell size of 10 cm were on average 13% more effective in trapping sediment than the 5 cm cells (Figure 6(a)). A possible explanation of this observation may be that larger cells allowed a better development of the horizontal-axis rollers, which contributed to trapping more sediment. Within the range of the depths tested (5 and 10 cm), the cell depth did not seem to influence the efficiency of the BGS significantly (Figure 6(b)).

Cross-wall angle. Besides vertical walls, BGSs with cross-wall angle inclinations of 60° and 120° were also

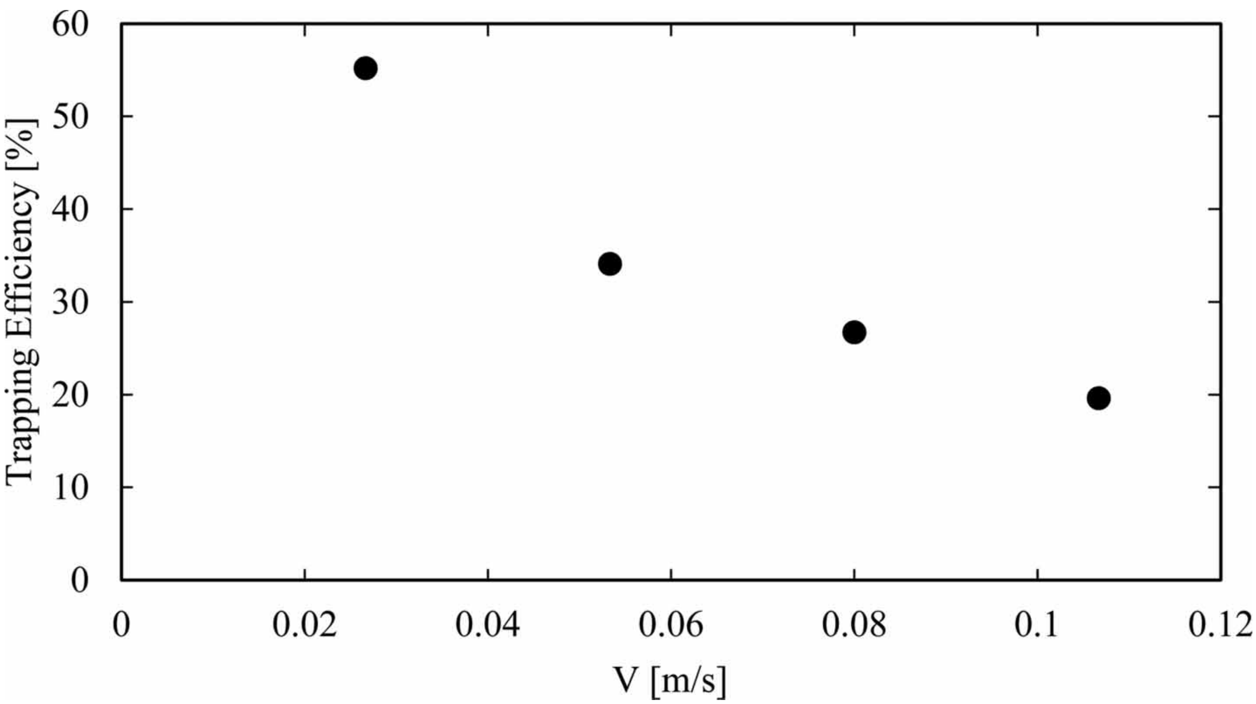

Figure 5 | Sediment trapping efficiency under various flow velocities (cell width 5 cm, cell depth 10 cm, cross-wall angle 90°).

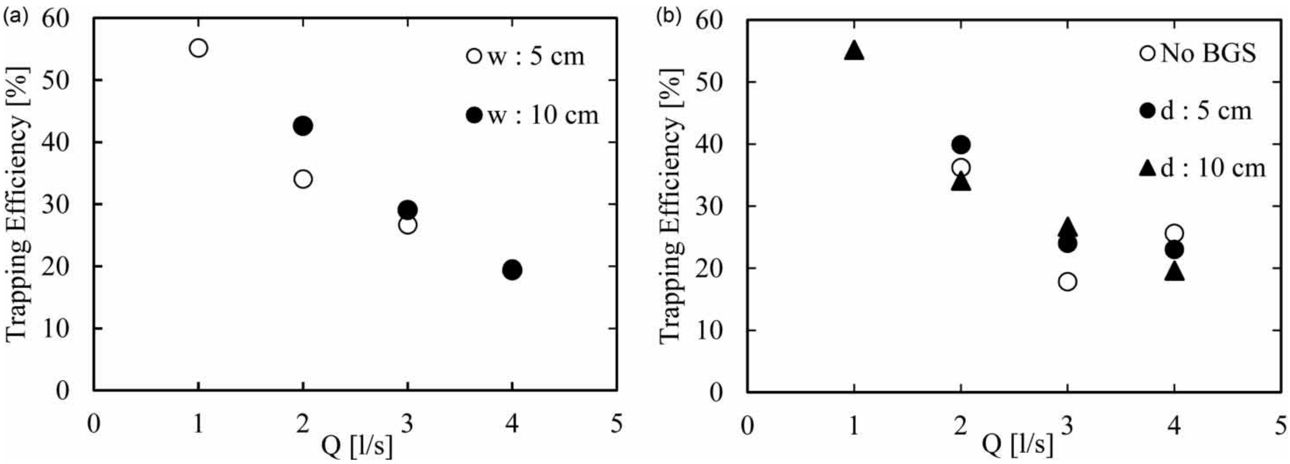

Figure 6 | (a) Sediment trapping efficiency for cell depths of 5 and 10 cm, and the cross-wall angle of 90°; (b) sediment trapping efficiency for no BGS, a cell width of 5 cm, two depths (5 and 10 cm), and a cross-wall angle of 90°.

tested, following up on the idea of settling enhancement with lamella plates. Cross-walls with both angles performed comparably and removed about 20% more sediment than those with 90° walls (Figure 7). This result was explained by the increased wall surface on which the sediment could settle. While this configuration might be beneficial for improving settling, its drawback would be the maintenance of the inclined walls, which would be more challenging compared to cells with vertical walls, particularly where the sediment removal would be done by the suction of sediment from the BGS cells.

In support of the discussion of experimental uncertainties (see Methods), a typical run with w = 5 cm, d = 10 cm, $\alpha = 90°$, and Q = 3 L/s was repeated five times. For the conditions addressed, the repeatability tests showed a very close agreement characterized by a mean trapping efficiency of 28% and a standard deviation of 0.5%. This suggests that, for the case tested, the differences in trapping efficiencies among the different experiments cannot be attributed to uncertainties in experimental techniques. However, further testing of repeatability for different conditions would be useful to examine whether the level of repeatability would remain the same.

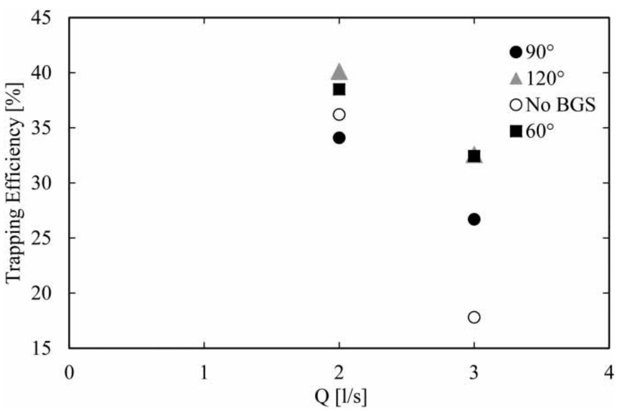

Figure 7 | Sediment removal efficiency for different cross-wall angles, a cell depth of 10 cm, and a cell width of 5 cm.

Future research. This section explores two classes of challenges encountered in studies of sediment removal by small engineering structures: (a) modelling of sediment transport in hydraulic scale models and (b) testing of small engineering structures in the field.

The experimental study reported on here expanded the knowledge of sediment settling in engineered facilities inserted into stormwater ponds, and demonstrated the challenges encountered in scale modelling of settling structures, including the attempts to attain model similitude for sediment settling in complex flow fields (i.e. as opposed to quiescent conditions in settling basins). The experience gained here was similar to the findings in the literature, best summarized by Gill & Pugh's (2009) statement that scale modelling of sediment transport in small engineering structures offers 'limited precision at best'. Consequently, the results reported herein should be understood as informative and best suited for comparisons of design alternatives, as was the case in the earlier studies of a similar nature (Stovin & Saul 1994; Dufresne *et al.* 2010; He & Marsalek 2014). Within the realm of such limitations, the study results indicate that an in-pond sediment trap (BGS) can concentrate the settling of coarser particles to a relatively small area, from which the sediments could be inexpensively removed using conventional municipal equipment (vacuum suction trucks).

In field installations, stormwater would enter the BGS facility in the form of hydrographs with varying discharges and sediment concentrations. Consequently, trapping efficiencies would vary with the varying Q, and the sediment influx and characteristics, including the particle size distributions and densities. Such conditions were tested by He *et al.* (2014) in a simplified field experiment, in which the grid structure was mimicked by batteries of open-top plastic containers ($22 \times 22 \times 11$ cm, $L \times W \times H$) attached to the pond bottom at 10 m downstream from the pond inlet. The results showed that these containers representing individual cells retained 4–11 times more sediment mass (with particle diameters $D < 250$ μm and $D < 32$ μm, respectively) than the bare pond bottom over a period of three months. The capture of very fine particles ($D < 32$ μm) was particularly surprising and could result from the settling of flocculated particles after the cessation of runoff. These findings also point out the importance of field testing of sediment trapping devices. The effect of particle sizes on sediment trapping was not addressed in our experiments using a model sediment with a single particle size. In laboratory experiments performed by He & Marsalek (2014), it was noted that the BGS trapped higher rates of larger particles than smaller ones, especially for higher flow rates. Finally, consideration of using the BGS sediment trap in new or retrofitted ponds would require a site-specific assessment of cost and benefits.

CONCLUSIONS

A scale-model study of the Bottom Grid Structure (BGS) sediment trap at the inlet of a stormwater impoundment produced information on the feasibility of such a pre-treatment of stormwater entering the impoundment, with the ultimate objective of reducing maintenance costs. At this phase of research, the following conclusions can be drawn: (a) the BGS would effectively confine coarser sediment (bedload) deposits to a small area in the pond; (b) as tested in this study, the BGS effectiveness was improved by placing it into an inlet stilling basin comprising a diffuser with wing walls, an apron and a water level control sill; and (c) concerning the settling cell geometry, larger cells (10 cm, compared to 5 cm cells) appeared more effective, increasing the efficiency by 13%; no strong influence of the cell depth was noted, and while inclined cross-walls improved settling in the model, their use might be counterproductive because of the costlier maintenance requirements. The next research phase should focus on the need for the stilling basin structure and the optimal geometry of BGS cells. Ultimately, the BGS concept should be tested in the field.

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