ENVIRONMENTAL TECHNOLOGY
https://doi.org/10.1080/09593330.2019.1694080

Taylor & Francis
Taylor & Francis Group

Evaluation of solids removal and optimisation of backwashing for an upflow stormwater filtration system utilising novel floating fibrous media

Yuhoon Hwang[a], Younggyo Seo[a], Hyowon Kim[a], Kunwan Roh[b] and Dogun Kim[c]

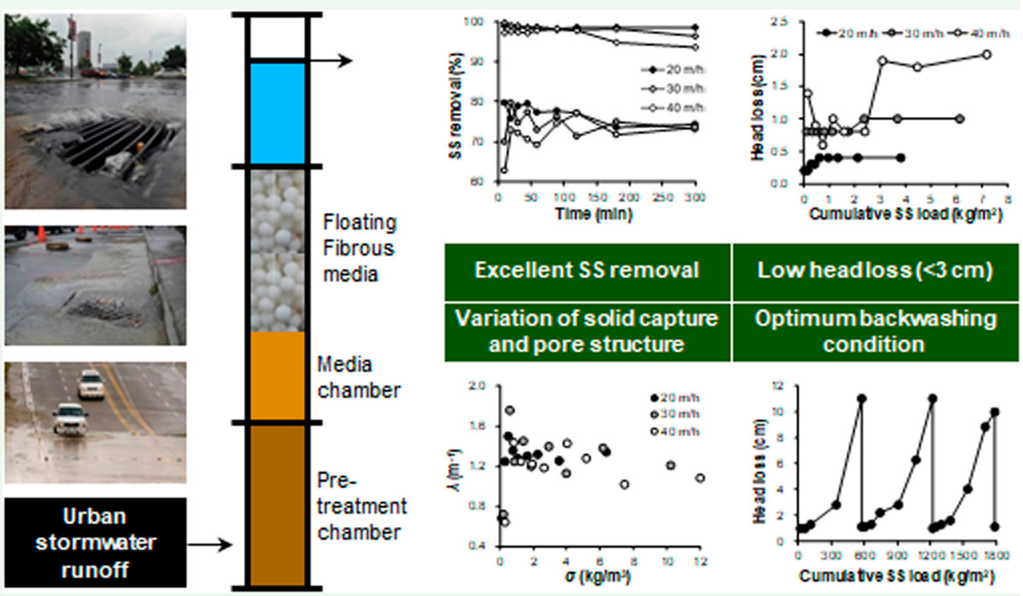
[a]Department of Environmental Engineering, Seoul National University of Science and Technology, Seoul, Republic of Korea; [b]C&C Inc., Siheung, Republic of Korea; [c]Department of Civil Engineering, Kyung Hee University, Yongin-si, Republic of Korea

ABSTRACT

Although filtration devices are already widely used for stormwater runoff treatment, there are much to be improved to ensure the required performance. Additionally, the performance of a device should be verified before on-site installation. In this context, an upflow filtration system using novel high porosity floating fibrous media formed into spherical shape was proposed and evaluated for solid capture and backwashing. At filtration velocities of 20–40 m/h, the maximum head loss was about 2 cm even under a solid load of 30 kg/m^2, and suspended solid (SS) removal efficiency was >96% throughout 300 min. A considerable amount of SS was removed in the pretreatment chamber, so the load on the media was reduced. Several models were tried to describe the solid capture in the media. The coefficients of solid attachment/detachment showed good correlations with filtration velocity. Other parameters indicated a variation of solid capture and permeability, which is unique to the media in this study. The backwashing with air and water for 1–2 min each showed good head loss recovery under the SS load up to 550–600 kg/m^2, and the SS discharge was more efficient when the stagnant water was drained before water backwashing. The results in this study suggest the high potential of the combination of fibrous media and upflow filtration system for the efficient control of the nonpoint source pollutants in stormwater runoff.

ARTICLE HISTORY
Received 15 March 2019
Accepted 10 November 2019

KEYWORDS
Backwashing; filtration; floating fibrous media; nonpoint source pollution; stormwater runoff



1. Introduction

The significance of the pollutants from nonpoint sources should never be underestimated. In the USA, nonpoint source pollutants from agriculture; atmospheric deposition; hydromodification; unspecified nonpoint sources; and urban-related runoff and stormwater adversely affected 1.9–23.1%, <31.9%, 4.1–15.1%, 2.2–10.3%, and 5.7–37.6%, respectively, to the water quality of rivers, streams, lakes, reservoirs, ponds, bays, estuaries, and coastal shorelines [1]. In Korea, the contribution of

CONTACT Dogun Kim dogun.kim@khu.ac.kr Department of Civil Engineering, Kyung Hee University, 1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do 17104, Republic of Korea

nonpoint source pollutants to biological oxygen demand (BOD) and total phosphorus (TP) emission loads is 31.7% and 58.9% as of 2012, and this is expected to increase rapidly to 72.1% and 68.6%, respectively, in 2020 [2]. In addition, the contribution of nonpoint sources to COD_{Mn} and TP of Danjiangkou reservoir in China was 68.4% and 82.9%, respectively [3]. Unlike point sources, nonpoint source pollution is irregularly generated from many diffuse sources without a specific point of discharge, therefore, it is also referred to 'diffuse pollution' [4], and it leads to the difficulty of efficient management.

Stormwater runoff is one of the most important nonpoint pollutant sources, especially in urban areas. The runoff collects and carries away natural and anthropogenic pollutants, finally depositing them into lakes, rivers, wetlands, coastal waters, and ground waters. Runoff is generated irregularly, which means that water quantity and quality fluctuate widely. The fluctuation in terms of quantity and quality makes it difficult to manage using existing water or sewage treatment processes [5]. According to U.S. Environmental Protection Agency (USEPA), urban-related runoff and stormwater significantly affected 8.4% of impaired miles of surveyed rivers and streams; 5.7% of impaired area of surveyed lakes, reservoirs, and ponds; 37.6% of impaired area of surveyed bays and estuaries; and 9.5% of impaired miles of surveyed coastal shorelines [1].

Nonpoint source pollution abatement facilities include retention ponds, buffer strips, constructed wetlands, and filtration facilities. Stormwater filtration facilities with granular media, such as sand [6], gravel [7], and perlite [8], are the most widely used. Granular media filtration is the most suitable method for sites of high impermeability and is most often used in highly urbanised areas and road areas [6]. The filtration type nonpoint source pollution abatement facility is known to exhibit excellent removal of suspended solids (SS), total phosphorus, and heavy metals in the runoff by filtration, adsorption, and microbial metabolism [9].

The pollutants reduction efficiency of filtration facilities is excellent, but the development of hydraulic head loss due to the clogging of the media layer limits the use of filtration systems via reducing treatment capacity. Clogging is the decrease in permeability of a medium due to physical/mechanical, biological, and chemical processes. Physical/mechanical clogging is induced by the accumulation of solids, which migrate into the media layer, in pores. Biofilm development can also reduce the pore spaces, i.e. biological clogging [10]. The deposition of chemical precipitates, such as calcium carbonate, gypsum, and phosphate, may lead to chemical clogging [11]. Various types of metal precipitates can also be formed in the media beds treating the runoffs with high metal concentrations from heavily trafficked areas, such as highways, which requires frequent monitoring of the content of the metals [12]. In addition, the solids trapped in the surface and inside of the media layer can be re-discharged, and SS concentration of the effluent increases at a concentrated rainfall event [13–15]. In general, physical clogging is dominant in stormwater filtration [16]. Clogging is affected by filter media, filter bed design, and operational conditions; however, filter media are of greatest importance because the ratio of pore size and solid is the critical factor which determines straining processes [7,17]. Clogging can lead to an increase in maintenance costs such as cleaning and/or replacing the filter media. Therefore, there is a growing need for media that are suitable for long-term operation with minimum clogging. In this context, various media, such as recycled glass, a foamed polymer material, potting soil, coconut fibre, compost, water sludge, mixture of pumice and woodchip, and so on, have been tried for stormwater filtration [18,19,20,21]. Out of the media, fibrous media are a potentially promising alternative in stormwater filtration due to high porosity and high surface area which can lead to high solids removal efficiency, less head loss, high filtration velocity, deep bed filtration behaviour by the migration of solids in the media layer [20,22].

Therefore, in this study, the suspended solid (SS) removal of an upflow filtration system with floating fibrous media was investigated with laboratory experiments, the solid capture was described by several models, and the backwashing efficiency was investigated under various conditions to characterise performance and to establish the optimum condition. SS removal is indicative of the removal of other pollutants in stormwater runoff such as organic compounds, nutrients, and metals because SS is the most important medium for the accumulation and transport of various pollutants in runoff [23]. For example, the transport of hydrophobic organic pollutants, such as polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and dichlorodiphenyltrichloroethane, and heavy metals is closely related to the solids transport [24]. Moreover, road-deposited sediments, which is the major source of the SS in the runoff from roads, are highly contaminated with organic matter, nutrients, and heavy metals [25]. In this regards, SS removal efficiency has been one of the standards of stormwater filtration facilities in many states in the USA [26] and Korea [27]. Also, the protocols for the evaluation of SS removal of stormwater runoff filtration devices have been established in several regions, such as New Jersey [28], United Kingdom [29], Auckland [30], and Korea [27]. Meanwhile, backwashing is recommended within 48 h of the termination of a rainfall event by the guidelines of stormwater best management practices in Korea [27] to ensure the long-term operation of a filtration system. Therefore, the optimum conditions have been studied [31], and also, backwashing systems have been developed and adopted for downflow and/or upflow stormwater filtration devices. They generally consist of a pump and a blower, and the treated water, which was temporarily stored, was used as the backwash water [32]. It does not seem that backwashing in stormwater filtration is a local issue in Korea because a filtration device incorporating backwashing has been developed and evaluated in the US [33].

2. Materials and methods

2.1. Filter media and laboratory scale equipment

Our filtration equipment consisted of an influent tank, an SS suspension tank, an inlet chamber, a pretreatment chamber, a media chamber, and an air compressor for air backwashing (Figure 1). Freshwater stored in the raw water tank flowed into the pretreatment chamber through the inlet chamber, where the high concentration SS suspension from the SS suspension tank was mixed with fresh water through a three-way valve using a peristaltic pump. The SS concentration of the twenty-seven (27) influent samples, i.e. nine (9) samples per each three (3) experiments at different filtration velocity, was 168.4 ± 4.4 mg/L, which showed the low variation of the concentration, supporting that homogeneous high SS suspension was supplied to the pretreatment chamber. In addition, no sedimentation of solids was observed in the SS suspension tank, where the suspension was agitated. The mixed influent flowing into the pretreatment chamber flowed upward into the media chamber. The length of the media chamber was 90 cm, and the media depth was 60 cm. All chambers were square, with 10 cm width. A piezometer was installed every 10 cm on the media chamber to enable hydraulic head measurement. The outlet chamber was supplemented to keep a constant difference between the hydraulic heads of the inlet and outlet.

The floating filter media used in this study was polypropylene fibres formed into spherical shape. The media had an effective diameter of about 1.2 cm and a porosity of 82.5%. It was expected that the pollutants in the water could be precipitated/adsorbed in this porous structure. It had a density of 0.934 kg/L, and a bulk density of 0.16 kg/L, which made the media float.

2.2. Influent characteristics

In this study, road sediment collected by road-sweeping vehicles was used to simulate the actual pollutants that

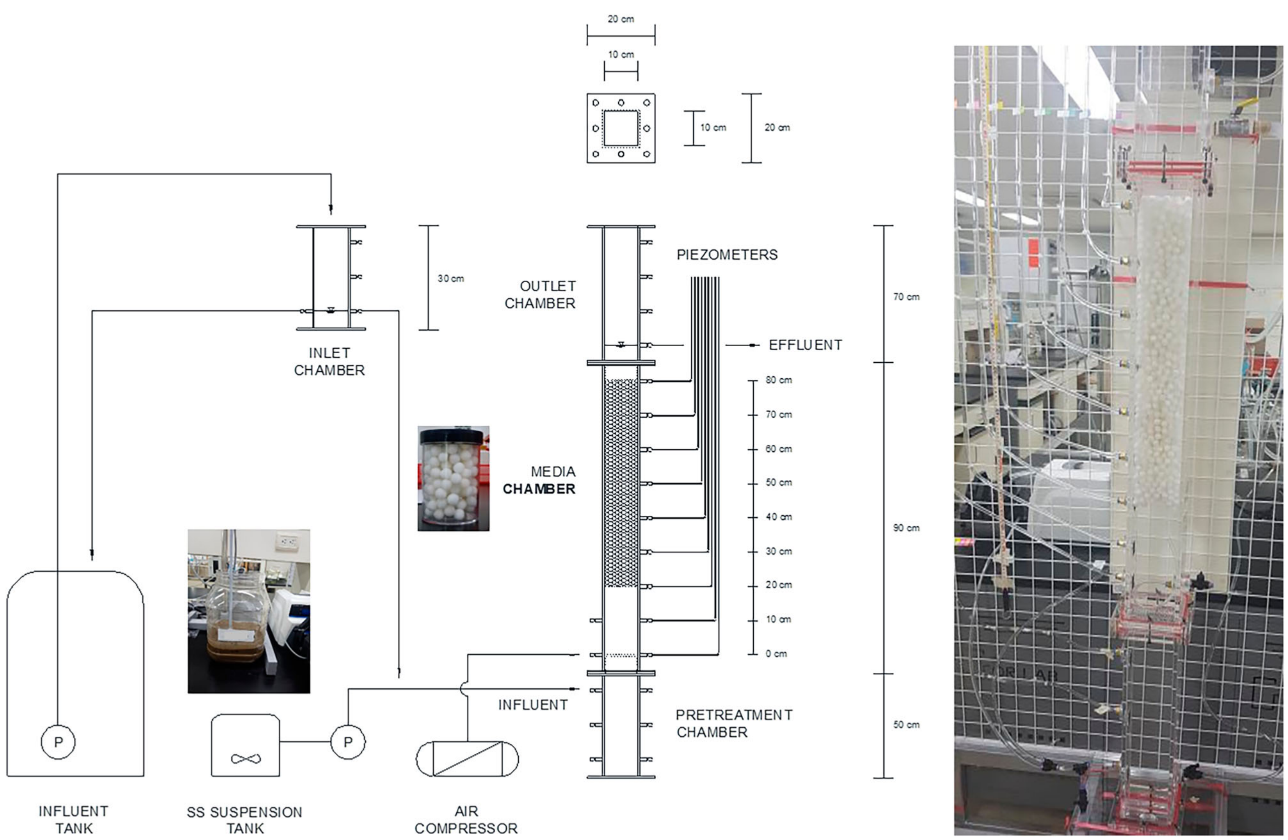


Figure 1. Schematic of filtration system (Insets are the SS suspension tank (left), media (middle) and a picture of the apparatus (right)).

could enter the filtration facility. The road sediment was collected by the Korea Expressway Corporation, and sediments of less than 200 μm were separated by sieve and used as samples. Nine (9) samples of the influent (200 mL) were collected during the filtration experiment of 300 min at a filtration velocity of 20 m/h, mixed together, and then the solids were separated by centrifugation and dried for particle size analysis (LS I3 320, Beckman Counter, USA). The value of d_{10}, d_{50}, d_{60}, and d_{90}, was 12.0, 111.2, 134.3, and 224.3 μm, respectively. The average particle size of the sediments was 125.6 μm, and the effective particle size (d_{10}) was 13.2 μm.

2.3. Filtration experiments

Head loss of the filter media itself was obtained by using only fresh water in different filtration velocities, 20, 30, and 40 m/h. Head loss in each condition was monitored more than three times, and then the arithmetic mean value was taken as the head loss of the filter media. The filtration system was operated at filtration velocities of 20, 30, and 40 m/h for 300 min, following the same and harder conditions, recommended in the protocols for the filtration devices evaluation by Korea Ministry of Environment [27]. It is recommended by the protocols that a single run of filtration until the cumulative solid load reaches 9 kg/m^2 when the influent SS concentration is in a range of 150–350 mg/L at the filtration velocity of 20 m/h or less, which corresponds to 80 (350 mg/L) to 180 (150 mg/L) minutes, to evaluate the long-term performance. Meanwhile, many authorities provide relevant protocols which differ from one another. At least ten (10) experiments with a minimum duration of 0.5 h are recommended by the New Jersey Department of Environmental Protection [28]; British Water [29] recommends to perform the tests until a minimum of ten (10) volume exchanges are reached, at 5, 10, 15, and 31.5 L/sec/ha; Auckland Council [30] recommends three (3) replicate experiments under each flowrate, i.e. 25%, 50%, 75%, 100%, and 125% of the capacity of the tested unit. A high concentration SS suspension was prepared using road sediment, and it was introduced into the inlet column together with fresh water so that the SS concentration of the influent was 166.4 ± 4.4 mg/L. The filtration velocity and the influent SS concentration were determined based on the guidelines for the design and stormwater filtration devices, provided by the Korean Ministry of Environment [27].

The water head of the media layer was continuously monitored, and the influent and effluent samples were collected to analyse SS concentration according to standard methods [34]. The SS removal rate was calculated by the following equation (1):

$$R_t = 100 \times \frac{C_0 - C_t}{C_0}, \tag{1}$$

where, R_t is the SS removal rate (%) at filtration time t, C_0 is the mean influent SS concentration (mg/L) during the filtration time, and C_t is the effluent SS concentration (mg/L) at filtration time t. The cumulative influent SS load per unit filtration area (L_s, kg/m^2) to the system with the filtration time was calculated by the following equation (2):

$$L_S = \frac{Q \times C_0 \times t}{A}, \tag{2}$$

where, Q is the influent flow rate (m^3/h), and A is the area of the media layer (m^2).

Backwashing efficiency was examined under various conditions to set optimal conditions that did not affect overall treatment efficiency. Four (4) backwashing conditions, with different backwashing durations, air/water flow velocity, and the drainage of stagnant water between air backwashing and water backwashing were investigated. Backwashing proceeded in the order of air wash, stagnant water discharge, and water wash. The recovery of head loss after backwashing and SS discharge after backwashing were examined to evaluate overall backwashing efficiency. In order to induce early clogging of the filtration system, the SS concentration of the influent was about 40 times higher than that of normal operation, i.e. 6,553.9 ± 232.2 mg/L. When the head loss reached around 10 cm, backwash was conducted. After backwashing, the filtration system was re-operated with normal SS concentration to investigate SS removal efficiency during early-stage operation.

3. Results and discussion

3.1. SS removal

The average SS concentrations of the influent and effluent, as well as SS removal, are summarised in Table 1. Figure 2 displays the SS removal efficiency and cumulative SS load with respect to time. The average SS concentration of the effluent was 2.3, 2.8, and 5.1 mg/L at filtration velocities of 20, 30, and 40 m/h, respectively. As the filtration velocity increased, the effluent SS concentration increased slightly. When converted into removal efficiency, treatment efficiency was higher than 95.0% in all cases.

In this study, particular attention was paid to the role of the pretreatment chamber. As shown in Figure 2, a

Table 1. Suspended solid concentration and removal efficiency at each filtration velocity (average ± standard deviation).

Filtration velocity (m/h)	SS (mg/L)			Removal (%)		
	Influent	Pretreatment chamber effluent	Media chamber effluent	Pretreatment chamber	Media chamber	Total
20	165.8 ± 2.8	38.0 ± 4.0	2.3 ± 0.3	77.1 ± 2.2	94.0 ± 1.0	98.6 ± 0.2
30	171.6 ± 5.1	43.9 ± 5.8	2.8 ± 1.6	74.5 ± 3.0	93.7 ± 3.3	98.4 ± 0.9
40	161.8 ± 4.6	45.8 ± 6.0	5.13 ± 2.6	71.6 ± 4.0	88.7 ± 5.8	96.8 ± 1.5

significant amount of the incoming solids were removed in the pretreatment chamber. It is thought that the decrease of the treatment efficiency as the inflow linear velocity increases is due to the relationship between the settling velocity and the fluid movement velocity. In all cases, the treatment efficiency of the pretreatment chamber itself was more than 70%. Meanwhile, the average SS removal efficiency of the media column, which was calculated based on the SS concentration of the influent and the effluent of the media column, was 94.0%, 93.7%, and 88.78%, respectively, at filtration velocities of 20, 30, and 40 m/h.

3.2. Head loss development in the media column

Figure 3(a) displays the total head loss with respect to cumulative SS load captured in the media, and Figure 3 (b) shows the total head loss of the media column with respect to time at each operation time. The initial head loss was measured as 0.2, 0.8, and 1.4 cm, respectively, when the filtration velocities were 20, 30, and 40 m/h. Head loss gradually increased, and it reached 0.4, 1.0, and 2.0 cm at 20, 30, and 40 m/h, respectively, after 300 min. Head loss increased as filtration velocity increased at the same captured SS load (Figure 3(a)), and almost linear relationships were displayed between the head loss at each operation time and the filtration velocity, except for the time of 20–90 min, when the head losses at 40 m/h were lower than those at 30 m/h (Figure 3(b)). The variation of head loss at 20–90 min at 40 m/h is attributed to the re-suspension and/or relocation of the captured solids due to turbulence at high filtration velocity [35].

The maximum head loss obtained from these experiments was measured as 2.0 cm when the cumulative SS load was 30.7 kg/m^2 at a filtration velocity of 40 m/h (Figure 3(b)). The head loss of the filtration system in this study was more than satisfactory, considering the design criterion for nonpoint pollution treatment

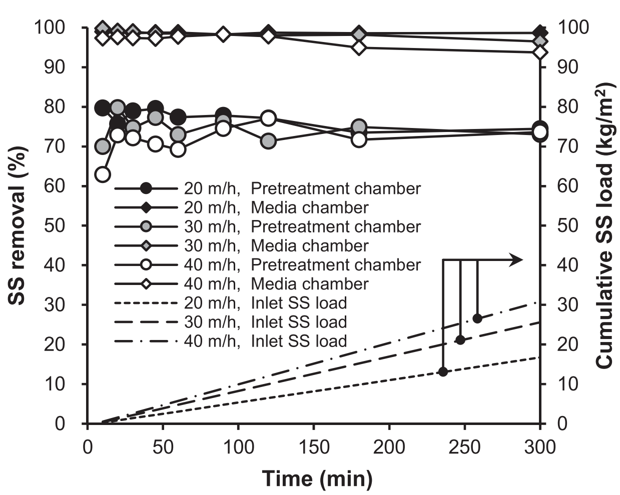


Figure 2. Cumulative SS load and SS removal with respect to time.

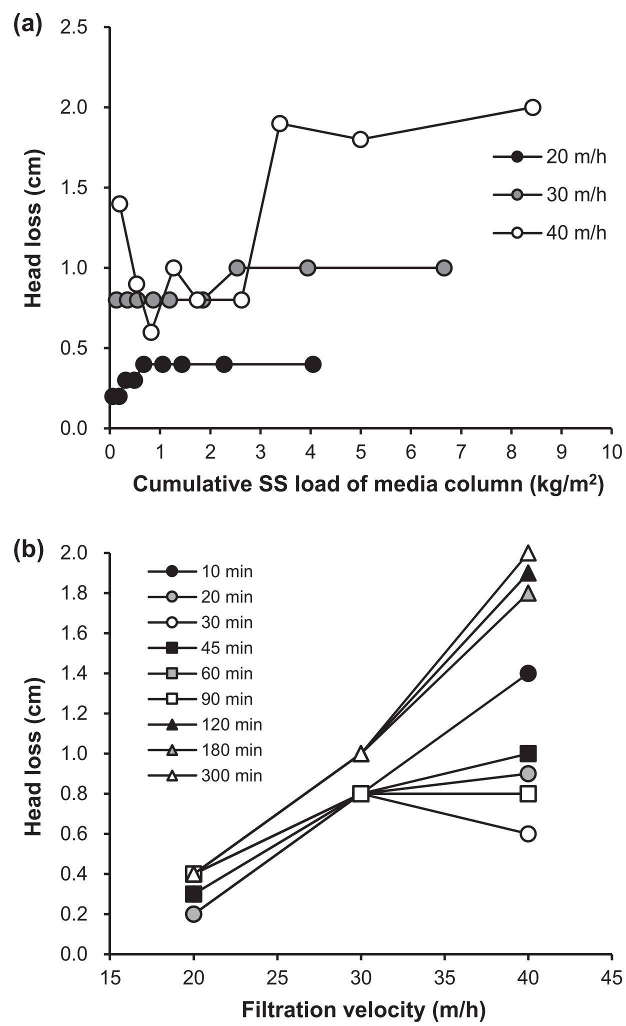


Figure 3. (a) Head loss during operation with respect to cumulative SS load captured in media, and (b) head loss with respect to filtration velocity at each operation time.

facilities of Korea that limits the total head loss to less than 10 cm at 9 kg/m^2 and 20 m/h [27]. Head loss in this study was significantly lower than that observed with granular media filters. Wang et al. [36] reported that the head loss of a sand filter was increased to around seven times the initial head loss at a solid load of around 1.8 kg/m^2. Johir et al. [37] studied the performance of an 800 mm depth filter bed filled with 1.0–1.1 mm anthracite and 0.55–0.65 mm sand with an influent of 24–35 mg/L SS. The head loss developed at 5 h of operation at 10 m/h was 10 cm. The low head loss is thought to be due to the high porosity of the fibrous media. Nakamura et al. [38] could not observe the increase of pressure drop during the filtration of 40–200 mg/L suspension of 1–50 µm kaolin and loam using a filter bed of polypropylene fibre media 2 m in depth.

Figure 4 shows the hydraulic head of the media column at different depths with respect to time. The decrease of the head was less than 0.5 cm during operation at 20 m/h. Head decreased within the bed of 30–80 cm at 30 m/h, indicating deep bed filtration. At 40 m/h, the head decreased more at 50–80 cm rather than at 0–50 cm by 90 min, indicating that solids were carried deep into the bed due to high filtration velocity and were deposited dominantly in the deeper part of the bed. Afterward, the head decreased rather uniformly throughout the media bed.

3.3. Modelling study of solid capture of the media

3.3.1. Kinetic model

The specific solid deposit (σ, kg/m^3) was described with a kinetic model [35]. It was assumed that when σ reaches a critical level, the local fluid velocity and shear stress increase due to the decrease in pore size. It causes the breakage of the deposited solid agglomerates and consequently increases the solid concentration in the liquid phase, then part of the broken solids was recaptured in the media [39]. This resulted in the decrease in overall solid capture rate due to the increase in SS in the liquid phase in pores and the discharge of captured solid out of the filter bed. The decrease in solid capture efficiency with increasing solid load was also observed in this study. The SS concentration of the effluents of the media chamber fluctuated, but it increased as the filtration continued when the filtration velocity was 30 and 40 m/h, and the increase was more significant at 40 m/h than at 30 m/h (Figure 5(a)). In addition, the total solid load carried to the media was 4.0, 6.7, and 8.4 kg/m^3; however, the reduction of it was 94.2%, 92.2%, and 85.4%, respectively, for 20, 30, and 40 m/h. Therefore, a model considering both solid attachment

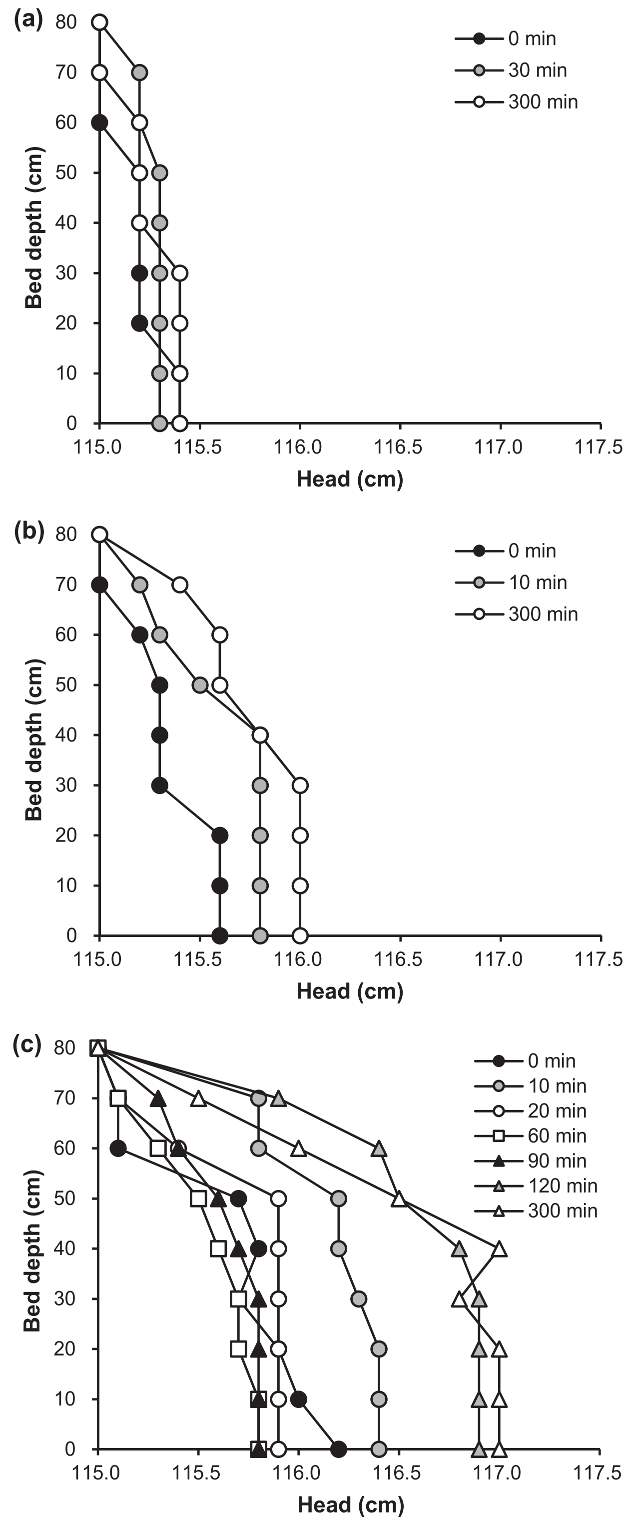


Figure 4. Hydraulic head in media column during operation at filtration velocities of (a) 20, (b) 30, and (c) 40 m/h.

to the media and the detachment from the media was used as in Eq. (3):

$$\frac{\partial \sigma_t}{\partial t} = k_a u C_0(\sigma_{\max} - \sigma_t) - k_d \sigma_t, \quad (3)$$

where σ_t is the specific solid deposit (kg/m^3) at time t (h), C_0 is the concentration of SS in influent (kg/m^3), u is the filtration velocity (m/h), σ_{max} is the maximum specific solid deposit (kg/m^3), k_a (m^2/kg) is the attachment constant, and k_d (h^{-1}) is the detachment constant.

Results showed that the model was a good fit to the experimental results with the correlation coefficient (r^2) of >0.96, and the parameters established good correlations with filtration velocity (Figure 5). It was found that k_a increased due to the increase of inlet SS load as filtration velocity increased. At the same time, k_d increased, but more significantly than the increase of k_a, probably due to the increase of shear stress and hydraulic gradient via accumulated solids [35]. The σ_{max} decreased as filtration velocity increased because the increase of detachment (k_d) was much more significant than that of attachment (k_a). This indicates that the solid captured in the media layer would be re-suspended and carried out from the filter bed at high filtration velocity.

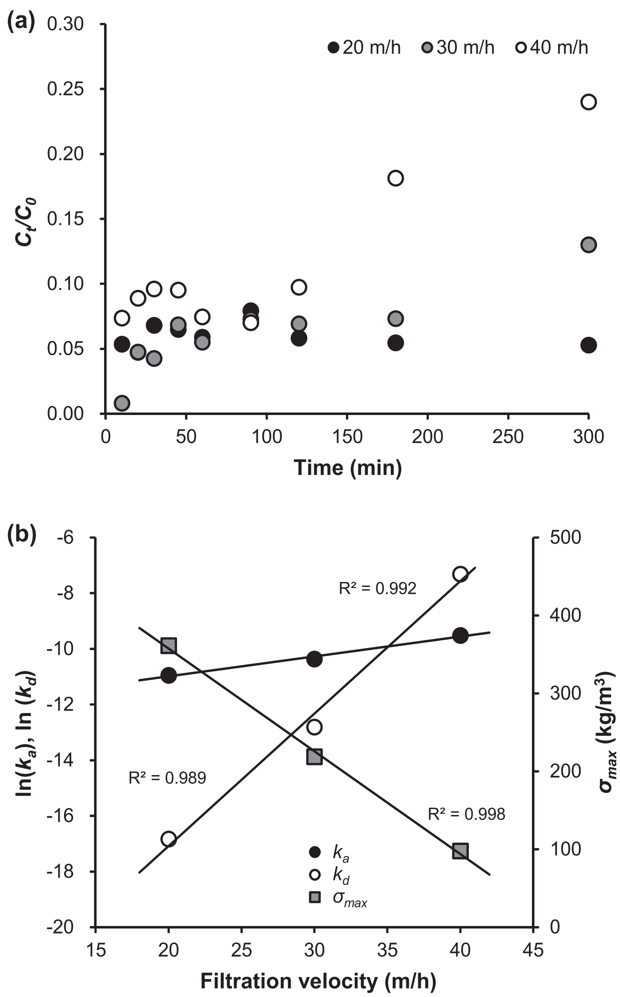


Figure 5. (a) The variation of C_t/C_0 of the media column at different filtration velocities, and (b) the correlation between filtration velocity and the parameters of kinetic model.

3.3.2. The k-C* model

A simple conceptual model, a *k-C** model, based on the first-order kinetic decay under steady-state conditions [40], was also tried to describe the overall performance of the media bed in this study. The *k-C** model has been used for the general description of the time-course of pollutant concentration of stormwater treatment devices including swales, wetlands, and gravel filters [41], and was applied to an infiltration system [7], successfully describing the performance before clogging. It is generally expressed as Eq. (4):

$$\frac{C_t - C^*}{C_0 - C^*} = e^{-kL/u}, \tag{4}$$

where, C_t is the effluent SS concentration (mg/L) at time t, C_0 is the influent SS concentration (mg/L), u is the hydraulic loading (m/h), L is the filter media depth (m), C^* is the background SS concentration (mg/L), and k is the decay rate constant (1/h). Eq. (4) can be expressed as Eq. (5), replacing C^* with A, when C^* is constant or negligible [7]:

$$\frac{C_t}{C_0} = Ae^{-kL/u}, \tag{5}$$

where, k and A represent the combined effects of many solid removal mechanisms including diffusion, interception, and sedimentation, varying with pollutant concentration and hydraulic conditions [41]. However, the time-course of SS concentration at each filtration velocity in this study could not be described by Eq. (5) due to the detachment of solids (Figure 5). Instead, C_t/C_0 was at the same operation time at each filtration velocity was correlated with filtration velocity with the linear form of Eq. (5) (Eq. (6)) to investigate the overall characteristics of the media in this study:

$$\ln\left(\frac{C_t}{C_0}\right) = \ln(A) - k\frac{L}{u}. \tag{6}$$

Only the values of C/C_0 at 120, 180, and 300 min showed correlations with filtration velocity (Figure 6(a)), indicating that the overall rate of solid capture, including attachment and detachment, was under a steady state after 120 min. The irregular performance at 0–120 min is shown in Figure 5(a), where C_t/C_0 fluctuates significantly and does not depend on filtration velocity or operation time. This can be attributed to the media property and high filtration velocity. The media in this study were not rigid nor stable in shape, but compressible with aggregated fibres, which is apt for irregular changes in shape, pore structure, and solid deposition. In addition,

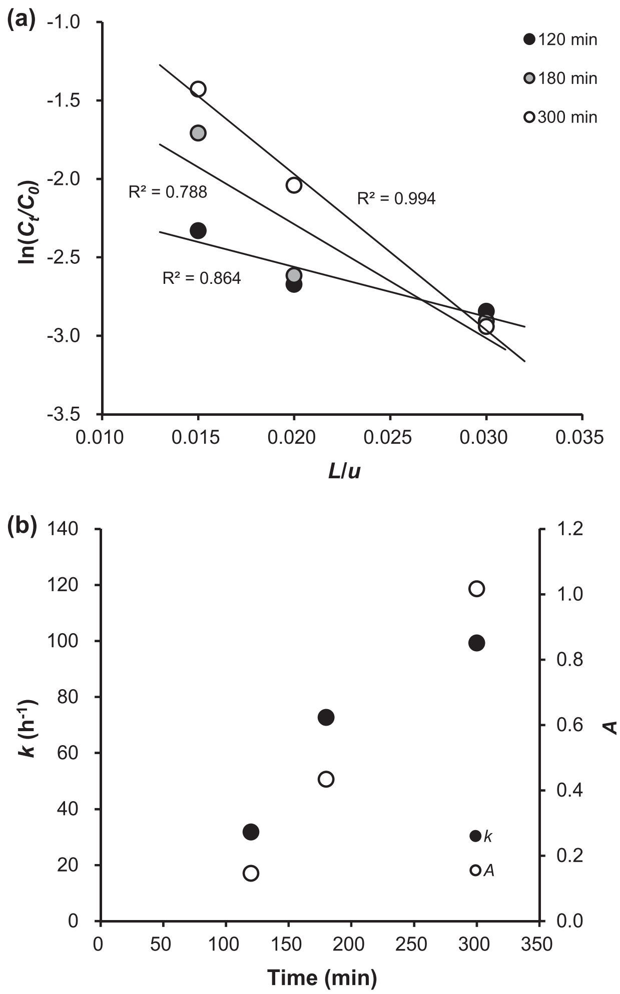


Figure 6. (a) The correlation between ln(C/C_0) and filtration velocity, and (b) the variation of the parameters of k-C model.

the high filtration velocity would induce irregular detachment of deposited solids. Sikorska et al. [35] reported that the macroscopic simulation of the solid deposit on a fibrous filter bed was difficult to predict because the breakage and re-suspension of the deposited solids occurred periodically, while the solids were supplied continuously by influent. They also suggested that the change of pore structure is due to the solid deposit on the intersections of the fibres where the momentum was reduced.

Figure 6(a) also shows that C_t/C_0 decreased, that is, SS removal was enhanced, as filtration velocity decreased, which is in agreement with the experimental results given in Figure 5(a). Both values of k and A increased from 120 to 300 min (Figure 6(b)). This indicates that the solid removal rate increased as solid deposit increased and porosity decreased. It also indicates that the dependency of C_t/C_0 to filtration velocity, that is, A, increased as solid deposit increased, which can also be shown in Figure 5(a). Though the model provides no insight into the inter-relationship between pollutant properties, hydraulic behaviour, and key treatment processes [7], it seems that the overall solids removal of fibrous media can be well described by this model when a filtration medium is stable in terms of its shape and pore structure.

3.3.3. Deep bed filtration model

The results in Figure 4 indicate the behaviour of deep bed filtration, showing the decrease of hydraulic heads as the media depth increased. Therefore, a deep bed filtration model based on solid mass balance was tried to describe solid capture in this study. The general form of mass balance of one-dimensional solid transport in a z-direction under steady-state can be expressed by Eq. (7):

$$\frac{\partial \sigma}{\partial t} + \frac{\partial \varepsilon C}{\partial t} + \frac{\partial uC}{\partial z} - \frac{\partial}{\partial z}\left(D\frac{\partial C}{\partial z}\right) = 0, \tag{7}$$

where ε is the porosity, C is the SS concentration (kg/m^3), D is the dispersion coefficient (m^2/h). Eq. (7) can be simplified to Eq. (8), assuming that the temporary changes in SS concentration in pores are negligible compared to the solid deposit and that the dispersion of solids through a fibrous filter medium is negligible [35]:

$$u\frac{\partial C}{\partial z} = -\frac{\partial \sigma}{\partial t}, \tag{8}$$

Eq. (8) was combined with the Iwasaki equation (Eq. (9)) to provide a relationship between the rate of change of σ and solid concentration, as in Eq. (10) [38]:

$$\frac{\partial C}{\partial z} = -\lambda, \tag{9}$$

$$\frac{\partial \sigma}{\partial t} = u\lambda C, \tag{10}$$

where, λ is the filtration coefficient at time t or at bed depth z, which increased as solid capture efficiency increased. Meanwhile, λ_0 is the λ of clean filter media, obtained using initial values of SS concentrations in influent and effluent. It is generally known that λ is dependent on specific deposit (σ) (Eq. (11)) [42]:

$$\lambda = \lambda_0\left(1 - \frac{\sigma}{\sigma_S}\right)^{\alpha}. \tag{11}$$

Results showed that the value of λ_0 was similar for the filtration velocity of 20–40 m/h, of which the average was 0.679 with a standard deviation of 0.038, indicating that λ_0 is not affected by filtration velocity and influent SS concentration, as reported by Nakamura et al. [38]. However, no correlation of Eq. (11) was established between λ and σ (Figure 7). The value of λ increased until σ reached 0.494, and then decreased afterward

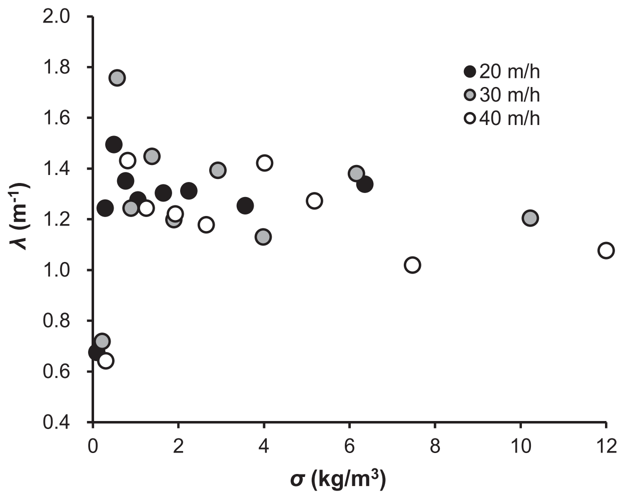


Figure 7. The value of λ at different filtration velocities.

for 20 m/h, while it increased until 0.572 kg/m^3 and decreased afterward at 30 m/h. At 40 m/h, λ fluctuated with a couple of maxima when σ was 0.816 and 4.016 kg/m^3. This might be attributed to the irregular attachment and detachment of solids, as can be seen in Figure 5(a), resulting in the variations of solid capture efficiency.

3.3.4. Steady-state, porous media capture equation

A steady-state equation was tried to describe the solid capture in this study [43]:

$$\ln\left(\frac{C_t}{C_0}\right) = -\frac{3}{2}\frac{(1-\varepsilon)}{D_C}\alpha_S \eta L, \quad (12)$$

where α_s is the sticking coefficient, D_c is the collector particle diameter, and η is the single collector collision efficiency. Eq. (12) describes the solid concentration of effluent decreasing as the porosity of the media decreased, and the media depth increased. For simplicity, α_s, D_c, and η were merged into a single coefficient X, as in Eq. (13) [19]. The increase of X indicates the decrease of permittivity and the solid concentration of effluent.

$$\ln\left(\frac{C_t}{C_0}\right) = -\frac{3}{2}X(1-\varepsilon)L. \quad (13)$$

The value of X fluctuated between 16.1 and 19.4 m^{-1} at 20 m/h. It was 30.7 m^{-1} at 10 min and decreased rapidly to 19.4 m^{-1} at 20 min, and further decreased slowly to 12.9 m^{-1} at 300 min at 30 m/h. It was 16.6 m^{-1} at 10 min and decreased to 14.9 m^{-1} at 40 min, increased to 16.9 m^{-1} at 90 min, and then decreased continuously to 9.1 m^{-1} at 300 min (Figure 8(a)). The fluctuation of X indicates the fluctuation of permissibility, as well as the solid capture efficiency, which is also shown by the

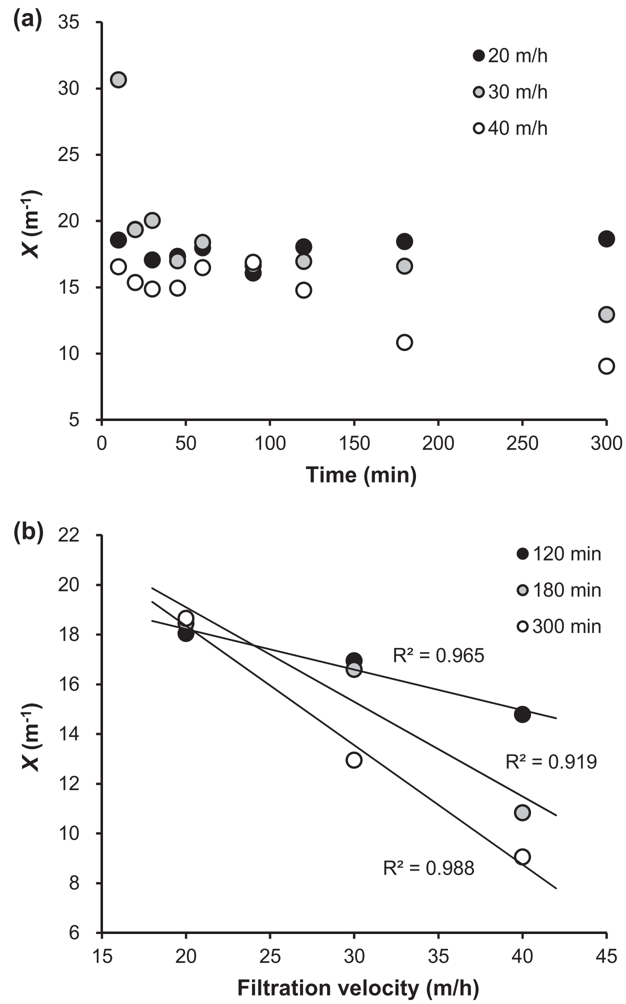


Figure 8. (a) The variation of the coefficient X of kinetic model at different filtration velocities, and (b) the correlation between filtration velocity and the coefficient X of kinetic model.

irregular variation of λ in Figure 7. After 120 min of operation, the value of X decreased; in other words, permissibility increased [19] as filtration velocity increased at the same operation time (Figure 8(b)). It is thought that this is attributed to the carryout of the deposited solids at high filtration velocity, as also indicated by the increase of detachment constant within increasing filtration velocity (Figure 5(b)).

Meanwhile, after 120 min, $\ln(C_t/C_0)$ showed stable decrease (20 m/h) or increase (30 and 40 m/h), the parameters of k-C^* model, $\ln(C_t/C_0)$ showed linear relationships with filtration velocity (Figure 6), the value of X showed stable increase (20 m/h) or decrease (30 and 40 m/h) (Figure 8(a)), and the value of X and filtration velocity were linearly correlated (Figure 8(b)). These would indicate that overall solid capture reached a stable phase with steady capture rate and re-suspension/detachment rate. The solid load at 120 min was 1.34, 2.39, and 3.11 kg/m^2, at 20, 30, and 40 m/h, respectively.

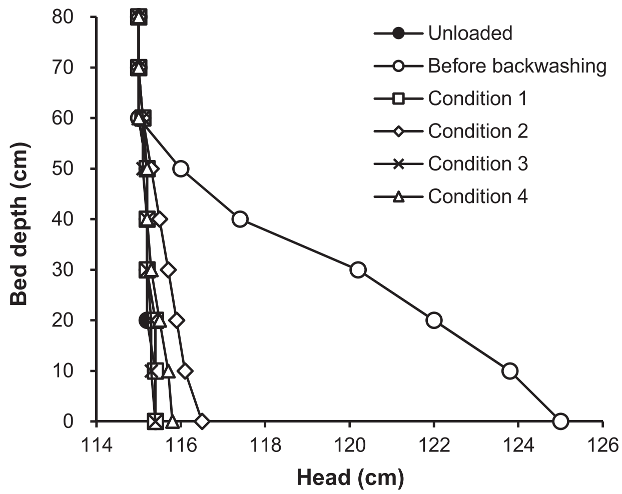


Figure 9. Recovery of head loss by different backwashing strategies (20 m/h).

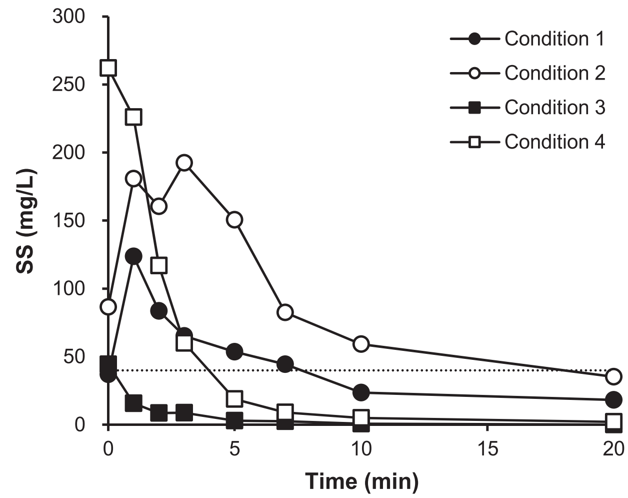


Figure 10. Effluent SS concentration in initial phase of operation after different backwashing strategies.

3.4. Optimisation of backwash conditions

The recovery of head loss is the most important objective of backwashing. Backwashing efficiency can be regarded as 100% when the head loss is recovered to that of initial operation. The initial head loss was 0.4 cm, and it was increased to >10 cm to simulate filter clogging. Under backwashing condition 1, head recovery was 100% with a head loss of 0.4 cm. Under condition 2, in which the water washing time was halved, head recovery was reduced to 88.5% as the head loss was 1.5 cm. When the stagnant water was discharged under condition 2, (condition 3), the recovery rate was restored at 100%. Under condition 4, in which the flow rate of air and water was reduced by half, the head loss was 0.8 cm, and the head recovery rate was 95.8% (Figure 9, Table 2).

These results indicate that the media was sufficiently back-washed by 2 min of 50 m/h air and 2 min of 40 m/h water, without stagnant water discharge (condition 1). Head loss recovery was adversely affected when the water backwashing time was reduced (condition 2). However, this was compensated by the drainage of stagnant water between air washing and water washing (condition 3). The significance of drainage was better verified by the results under condition 4, where head loss recovery was almost as condition 1 when the flow velocity of air and water was reduced to 50% of condition 1.

SS captured in a medium should be sufficiently removed during backwashing, otherwise, the SS in the effluent would increase to an even higher concentration than influent SS by the carryout of the residual solids, especially in operation right after backwashing. In order to examine the degree of SS washout during backwashing under the four (4) conditions, the SS concentration over 20 min of initial operation after backwashing was investigated (Figure 10). After backwashing under condition 1, the initial, maximum, and final SS concentrations were 37.0, 123.8 at 1 min, and 18.3 mg/L, respectively. It was 65.5, 180.8 at 1 min, and 35.2 mg/L, respectively, under condition 2. Under condition 3, SS concentration was initially 44.4 mg/L and then rapidly decreased to 0.1 mg/L at 20 min. Under condition 4, it was initially 262.0 mg/L, then decreased to 2 mg/L at 20 min. The average SS concentration during the initial 20 min after backwashing under the conditions of 1, 2, 3, and 4 was 56.2, 118.5, 10.5, and 87.5 mg/L, respectively.

These results indicate that SS washout during backwashing was enhanced when the air/water backwashing time was increased (conditions 1 and 2), and that it was improved when the stagnant water was drained before water backwashing (conditions 2 and 3). The improvement of solid washout during backwashing was enhanced at higher air/water flow velocity when the stagnant water was drained (conditions 3 and 4).

Table 2. Backwashing characteristics under different conditions.

Condition	Air backwashing		Drainage	Water backwashing		Recovery of head loss (%)	Average effluent SS in initial 20 min operation (mg/L)
	Duration (min)	Flow velocity (m/h)		Duration (min)	Flow velocity (m/h)		
1	2	50	No	2	40	100	56.2
2	2	50	No	1	40	88.5	118.5
3	2	50	Yes	1	40	100	10.5
4	2	25	Yes	1	20	95.8	87.5

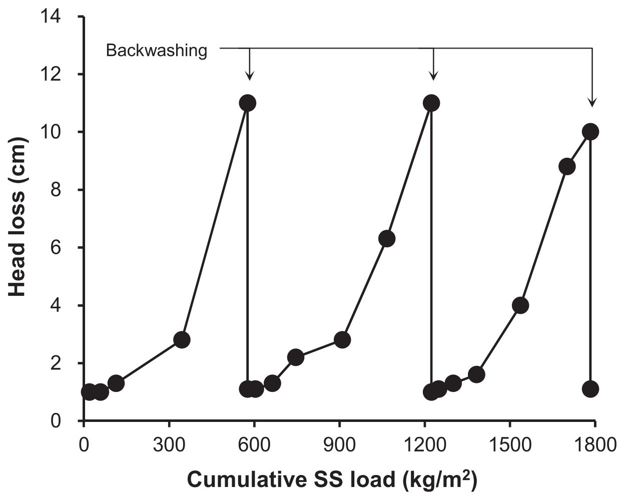


Figure 11. Variation of head loss with respect to cumulative SS load (Condition 4).

In order to verify that the floating filter media can be used in repetitive operation without significant clogging by applying backwashing, as suggested in this study, head loss during three times of repetitive operation/backwashing was investigated. Backwash condition 4 was used in this repetitive operation. When three repetitive operations/backwashing were performed, it was confirmed that the head loss after backwashing was reduced to almost the same value as the initial value (Figure 11). The cumulative SS load, which can be operated up to one occlusion, did not show any significant change at about 500–600 kg/m^2, suggesting that long-term operation using the optimal backwashing process is possible.

Meanwhile, it should be noted that more efforts are necessary to apply the results in this study to field scale backwashing. It has always been questionable, even though the scale-up of laboratory-scale results has been elaborated for a long period of time for the microscopic aspects of the role of backwashing air [44] and the prediction of bed expansion [45]. Therefore, it is thought that a field backwashing test is recommended during the commissioning to optimise the hydraulic parameters. However, It is believed that the result in this study would provide valuable information for the field backwashing optimisation, certifying the positive role of air and stagnant water discharge.

4. Conclusions

Through this study, the efficiency of treatment of non-point source pollution in an upflow filtration system using floating filter media was evaluated, and the optimal operating conditions were investigated. The upflow filtration system consisted of a bottom sedimentation tank and an upper filtration system. When it was operated at a filtration velocity of 20–40 m/h, maximum head loss was only about 2 cm, even under a total solid load of 30 kg/m^2. In the same experiment, more than 96% of the suspended solids were removed through the filtration system, and the removed solids per unit filtration area were 16.5, 25.2, and 29.6 kg/m^2 when the filtration velocity was 20, 30, and 40 m/h, respectively. Notably, it was confirmed that about 75% of SS was removed from the bottom sedimentation tank, so that suspended solids having a large particle size can be effectively removed without applying a load to the media layer.

The amount of solid matter trapped in the media layer and the head loss of the media layer were suitably represented by a series model, and the model constants showed a high linear correlation with linear velocity. In addition, the relationship between the porosity and the head loss of the filter media was also highly correlated, and future performance and life expectancy of the filtration system can, therefore, be predicted.

A kinetic model, *k-C** model, deep bed filtration model, and a steady-state equation were tried to describe the solid capture in the media. The coefficients of attachment and detachment of the solids of the kinetic model showed good correlations with filtration velocity. However, the parameters of the other models representing solid capture and permissibility varied significantly and did not show a correlation with solid load or filtration velocity, indicating an irregular change of pore structures of the media layer. However, the parameters of the *k-C** model and steady-state equation over 120–300 min of operation correlated well with filtration velocity.

In order to establish optimal backwashing conditions, the effects of air and water washing time, flow rate, and stagnant water discharge process were investigated. Under all of the experimental conditions, satisfactory recovery of head loss (>88%) and suspended solids removal efficiency (>94%) were obtained. However, in order to minimise the leaching of suspended solids immediately after backwashing, it was found that the introduction of the stagnant water discharge process between air washing and water washing processes was effective. It is confirmed that it is possible to perform a repetitive operation using the backwashing condition tested in this study, and that suspended solids load of about 550–600 kg/m^2 could be treated within one cycle.

Acknowledgments

This study was supported by the Research Program funded by the SeoulTech(Seoul National University of Science and Technology).

Disclosure statement

No potential conflict of interest was reported by the authors.

References

[1] USEPA. Polluted runoff: nonpoint source (NPS) pollution [Internet]. Available from: https://www.epa.gov/nps.

[2] Korea Office of Prime Minister, Ministry for Food, Agriculture, Forestry and Fisheries, Korea Ministry of Knowledge Economy, Korea Ministry of Environment, Korea Ministry of Infrastructure and Transport, Korea Nation fire Agency, Korea Rural Development Administration, Korea Forest Service. Second comprehensive nonpoint sources management plan, 2012.

[3] Xin X, Yin W, Li K. Estimation of non-point source pollution loads with flux method in Danjiangkou Reservoir area, China. Water Sci Eng. 2017;10:134–142.

[4] European Environment Agency (EEA). (2018). Diffuse sources [Internet]. Available from: https://www.eea.europa.eu/themes/water/water-pollution/diffuse-sources.

[5] Yi S-J, Kim Y-I. Improvement on management of non-point source pollution for reasonable implementation of TMDL - Focusing on selection of non-point source pollution management region and management of non-point source pollutant. J Korean Soc Environ Eng. 2014;36:719–723.

[6] Ahn J, Lee D, Han S, et al. Experimental study on performance of sand filter layer to remove non-point source pollutants in rainwater. Water Sci Technol-W Sup. 2017;17:1748–1763.

[7] Siriwardene NR, Deletic A, Fletcher TD. Clogging of stormwater gravel infiltration systems and filters: Insights from a laboratory study. Water Res. 2007;41:1433–1440.

[8] Gironás J, Adriasola JM, Fernández B. Experimental analysis and modeling of a stormwater perlite filter. Water Environ Res. 2008;80:524–539.

[9] Hsieh C, Davis AP. Evaluation and optimization of bioretention media for treatment of urban storm water runoff. J Environ Eng-ASCE. 2005;131:1521–1531.

[10] Stevik TK, Kari A, Ausland G, et al. Retention and removal of pathogenic bacteria in wastewater percolating through porous media: A review. Water Res. 2004;38:1355–1367.

[11] Larroque F, Franceschi M. Impact of chemical clogging on de-watering well productivity: numerical assessment. Environ Earth Sci. 2011;64:119–131.

[12] Dou Y, Klein M, Zhang TC, et al. Feasibility of developing a passive sampler for sampling heavy metals in BMPs for stormwater runoff management. Environ Technol. 2019;40:1517–1524.

[13] Boller MA, Kavanaugh MC. Particle characteristics and headloss increase in granular media filtration. Water Res. 1995;29:1139–1149.

[14] Rodgers M, Mulqueen J, Healy MG. Surface clogging in an intermittent stratified sand filter. Soil Sci Soc Am J. 2004;68:1827–1832.

[15] Kang S, Kim S, Lee S, et al. An upflow-type filtration device using expanded polypropylene media (EPM) to treat first flush of rainwater. Water Environ Res. 2016;88:195–200.

[16] Kandra HS, Deletic A, McCarthy D. Assessment of the impact of stormwater characteristics on clogging in stormwater filters. Water Resour Manage. 2015;29:1031–1048.

[17] Li H, Davis A. Urban particle capture in bioretention media. II: Theory and model development. J Environ Eng-ASCE. 2008;134:419–432.

[18] Lim HS, Lim W, Hu JY, et al. Comparison of filter media materials for heavy metal removal from urban stormwater runoff using biofiltration systems. J Environ Manage. 2015;147:24–33.

[19] Franks CA, Davis AP, Aydilek AH. Geosynthetic filters for water quality improvement of urban storm water runoff. J Environ Eng-ASCE. 2012;138:1018–1028.

[20] Shan G, Surampalli RY, Tyagi RD, et al. Nanomaterials for environmental burden reduction, waste treatment, and nonpoint source pollution control: a review. Front Environ Sci Eng China. 2009;3:249–264.

[21] Cheng J, Yuan Q, Kim Y. Long-term operational studies of lab-scale pumice-woodchip packed stormwater biofilters. Environ Technol. 2018;39:1765–1775.

[22] Lee JJ, Johir MAH, Chinu KH, et al. Novel pretreatment method for seawater reverse osmosis: fibre media filtration. Desalination. 2009;250:557–561.

[23] Przekop R, Gradón L. Dynamics of particle loading indeep-bed filter: transport, deposition and reentrainment. Chem Process Eng. 2016;37:405–417.

[24] Marsalek J, Jimenez-Cisneros BE, Karamouz M, et al. Urban water cycle processes and interactions. Boca Raton: CRC Press; 2008.

[25] Rügner H, Schwientek M, Milačič R, et al. Particle bound pollutants in rivers: results from suspended sediment sampling in Globaqua River Basins. Sci Total Environ. 2019;647:645–652.

[26] Kim D-G, Kang H-M, Ko S-O. Reduction of non-point source contaminants associated with road-deposited sediments by sweeping. Environ Sci Pollut Res. 2019;26:1192–1207.

[27] USEPA. Summary of state post construction stormwater standards. Washington (DC): U.S Environmental Protection Agency; 2016.

[28] Korea Ministry of Environment, Installation and operation manual of nonpoint pollution reduction facility, 2016.

[29] New Jersey Department of Environmental Protection (NJDEP). New Jersey Department of Environmental Protection laboratory protocol to assess total suspended solids removal by a filtration manufactured treatment device, 2013.

[30] British Water. Code of practice - assessment of manufactured treatment devices designed to treat surface water runoff, 2017.

[31] Auckland Regional Council. Proprietary devices evaluation protocol (PDEP) for stormwater quality treatment devices, Version 03, 2012.

[32] Lee J, Lee M. Stormwater runoff treatment filtration system and backwashing system. Water Sci Technol. 2019;79(4):771–778.

[33] Lee MG. Non-point pollutants removal equipments of possible back washing and possible back washing control system. Patent No. KR101764721B1, South Korea, August 7 2017.

[34] Horwatich JA, Corsi SR, Bannerman RT. Effectiveness of a pressurized stormwater filtration system in Green Bay, Wisconsin: a study for the environmental technology verification program of the U.S. Environmental Protection Agency. Scientific Investigations Report 2004–5222, U.S.

Department of the Interior and U.S. Geological Survey. 2014.

[35] APHA, AWWA, WEF. Standard methods for the examination of water and wastewater. 22nd ed. Washington, DC; 2012.

[36] Sikorska E, Gac JM, Gradó L. Performance of a depth fibrous filter at particulate loading conditions: description of temporary and local phenomena with structure development. Chem Eng Res Des. 2018;132:743–750.

[37] Wang Y, Huo M, Li Q, et al. Comparison of clogging induced by organic and inorganic suspended particles in a porous medium: implications for choosing physical clogging indicators. J Soils Sediments. 2018;18:2980–2994.

[38] Johir MAH, Vigneswaran S, Kandasamy J. Hybrid filtration method for pre-treatment of stormwater. Water Sci Technol. 2010;62:2937–2943.

[39] Nakamura K, Nakamura J, Matsumoto K. Filtration and backwashing behaviors of the deep bed filtration using long length poly-propylene fiber filter media. J Taiwan Inst Chem Eng. 2019;94:31–36.

[40] Kadlec RH, Knight RL. Treatment wetlands. Boca Raton: CRC Press; 1996.

[41] Wong THF, Fletcher TD, Duncan HP, et al. Modelling urban stormwater treatment—a unified approach. Ecol Eng. 2006;27:58–70.

[42] Bai R, Tien CA. A new correlation for the initial filter coefficient under unfavorable surface interactions. J Colloid Interf Sci. 1996;179:631–634.

[43] American Water Works Association (AWWA). Water quality and treatment. 5th ed. New York: McGraw-Hill; 1999.

[44] Amirtharajah A. Optimum backwashing of filters with air scour: a review. Water Sci Tech. 1993;27(10):195–211.

[45] Pizzolatti BS, Soares M, Romero L, et al. Comparison of backwashing with conventional cleaning methods in slow sand filters for small-scale communities. Desalin Water Treat. 2015;54(1):1–7.