Membrane and Water Treatment, *Vol. 10, No. 1 (2019) 067-074*
DOI: https://doi.org/10.12989/mwt.2019.10.1.067

Factors affecting the infiltration rate and removal of suspended solids in gravel-filled stormwater management structures

Heidi B. Guerra[a], Qingke Yuan[b] and Youngchul Kim*

Department of Environmental Engineering, Hanseo University,
46 Hanseo 1-ro, Haemi-myun, Seosan-si, Chungcheongnam-do 356-706, Republic of Korea

(Received April 27, 2018, Revised August 25, 2018, Accepted September 10, 2018)

Abstract. Apparent changes in the natural hydrologic cycle causing more frequent floods in urban areas and surface water quality impairment have led stormwater management solutions towards the use of green and sustainable practices that aims to replicate pre-urbanization hydrology. Among the widely documented applications are infiltration techniques that temporarily store rainfall runoff while promoting evapotranspiration, groundwater recharge through infiltration, and diffuse pollutant reduction. In this study, a laboratory-scale infiltration device was built to be able to observe and determine the factors affecting flow variations and corresponding solids removal through a series of experiments employing semi-synthetic stormwater runoff. Results reveal that runoff and solids reduction is greatly influenced by the infiltration capability of the underlying soil which is also affected by rainfall intensity and the available depth for water storage. For gravel-filled structures, a depth of at least 1 m and subsoil infiltration rates of not more than 200 mm/h are suggested for optimum volume reduction and pollutant removal. Moreover, it was found that the length of the structure is more critical than the depth for applications in low infiltration soils. These findings provide a contribution to existing guidelines and current understanding in design and applicability of infiltration systems.

Keywords: stormwater runoff; infiltration; design; subsoil; low-impact development

1. Introduction

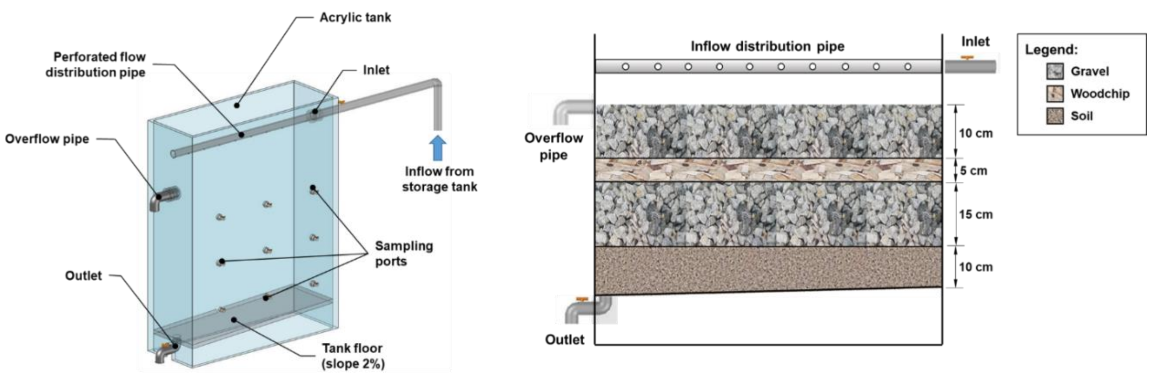
Significant changes in the natural hydrologic cycle have become increasingly apparent through more frequent flooding, declining base flows, and water quality impairment in rivers and streams. These changes are found to be the result of rapid urban development which inevitably disturbs natural landscapes and replaces them with impermeable surfaces such as roads, highways, parking lots, and building rooftops (Sharma 2017, Shuster *et al*. 2005). Conversion of surfaces from permeable to impermeable ones lead to larger stormwater runoff volume, higher peak flows, and shorter times of concentration because they do not allow rainfall to infiltrate the ground (Chahar *et al*. 2012). Instead, they contribute to surface runoff and facilitate the collection of numerous diffuse pollutants as they travel downstream to receiving water bodies through conventional drainage systems (Emerson *et al.* 2010, Fischer *et al.* 2003).

Stormwater management solutions in urban areas are now leaning towards the use of green technologies and sustainable practices that aims to replicate pre-urbanization hydrology. These are known as low impact development (LID), water sensitive urban design (WSUD), sustainable urban drainage systems (SUDS), and best management practices (BMP) that counter the effect of urbanization by controlling post-development runoff closer to the source through retention, infiltration, and evapotranspiration. Among the most commonly used are rain gardens, bioretention swales, infiltration trenches, planter boxes, etc., all of which have infiltration function. Stormwater infiltration facilities are often shallow excavations that are filled with engineered soil or gravel as filter media which provides temporary runoff storage and are selected for their pollutant reduction capabilities. As a common practice, the storage volume called the water quality volume (WQV) is targeted as the first 1 inch of rainfall or the 90th percentile of the total annual rainfall in the site, whichever is higher, since it has been reported to include the so-called first flush which contains the majority of the pollutant loads during a rainfall event (Bertrand-Krajewski *et al.* 1998). A portion of the retained stormwater becomes open for evapotranspiration while the remaining is treated by the filter media before it is gradually discharged to the underlying ground.

While numerous studies have vouched for the effectivity of this approach (Eckart *et al*. 2017, Le Coustumer and Barraud, 2007, Pitt *et al.* 1999, Welker *et al.* 2006), their applicability can be constrained by site-specific soil characteristics. For example, saturated soil infiltration rates that are deemed acceptable for infiltration trenches range between 0.52 and 8.27 in/h (13-210 mm/h) (Virginia Tech 2013). They are not recommended in areas with very high permeability and expansive soils to prevent lateral seepage and forces which can damage nearby structural foundations.

*Corresponding author, Ph.D., Professor
E-mail: ykim@hanseo.ac.kr
[a] Ph.D. student
[b] Ph.D.

ISSN: 2005-8624 (Print), 2092-7037 (Online)



(a) (b)

Fig. 1 Description of the infiltration device indicating parts and arrangement of the media

Preventive guidelines such as minimum setback distances to groundwater tables, wells, and underground utilities have also been provided to avoid contamination of groundwater and leakage to clean water distribution pipes. Nonetheless, infiltration systems can still be applied in these areas by incorporating elements such as hydraulic barriers, geotextiles, and underdrains, as well as conducting in-situ soil amendments.

Generally, sizing decisions on infiltration structures are based on the WQV to be stored for a period of time (Akan 2002). However, this goal combined with currently existing provisions such as minimum depth, surface area to catchment area ratio (SA:CA), and length to width or aspect ratio can be subjected to limitations regarding available space and minimum setback requirements. Thus, they cannot always be achieved. Also, most sizing computations assume one-dimensional flow through the bottom of the trench. However, typical designs may keep vertical flow only during small rains when the hydraulic load does not cause overflow or bypass. Heavy rains may induce dominant horizontal flow due to excessive bypass rates. This variation of flow and other hydraulic behavior during rainfall poses an impact to system performance (Sileshi *et al.* 2014, Warnaars *et al.* 1999). Therefore, it is necessary to investigate the factors affecting these variations.

In this study, the volume reduction and water quality improvement in an infiltration system over different types of underlying soil is investigated through laboratory experiments to be able to determine their implications in applicability, design, and performance. The flow during a simulated runoff inflow to the system was observed and the factors affecting it were analyzed. The study aims to provide basic design provisions and expand current understanding in terms of depth and infiltration rates for applications in Korea and other sites with similar hydrologic and geologic characteristics.

2. Material and methods

2.1 Experimental setup

A laboratory-scale infiltration device, presented in Fig. 1(a), was constructed and assembled for the experiments. It is composed of a 0.7x0.2x0.6 m (LxWxH) acrylic tank and polyvinyl chloride (PVC) pipes for the inlet and outlet. The inlet pipe is connected on one end to a pump inside a mixing tank where the inflow stormwater was stored, and on the other end to a distribution pipe inside the tank. The bottom of the tank is sloped at 2% to facilitate drainage to the outlet. An overflow pipe is connected 40 cm above the outlet pipe to release excess flow during high inflow rates. No pretreatment mechanism is included and the device is designed to prevent lateral flow thereby allowing infiltration at the bottom only.

The media were arranged inside the tank as depicted in Fig. 1 (b). The bottom is filled with 10 cm of soil (11.4 cm on the other side to account for the slope of the tank floor) which is thumped by a rod for compaction and to make an even surface. This represents the subsoil portion of the infiltration facility. The soil is then overlaid by 15 cm of gravel, followed by 5 cm of woodchip, and another 10 cm of gravel. The design of the device as well as the arrangement of the media is based on an existing infiltration trench that was also monitored for another study (Guerra *et al*. 2018) and represents a typical media setup for non-vegetated infiltration facility. The properties of these materials are summarized in Table 1. The storage volume is 0.028 m^3 which is equivalent to a 4mm runoff assuming a facility surface area to catchment area ratio (SA:CA) of 0.02 which is within the recommended ratio by design guidelines.

Two setups were used in the study, one employs a uniformly-graded sandy soil (ID-1) to represent high-infiltration subsoil while the other one employs a well-graded clayey soil (ID-2) to represent low infiltration subsoil. Standard laboratory column infiltration tests were conducted 9 times on each sample after compaction by standard proctor compaction method (ASTM 2012). The tests revealed that the average steady-state infiltration rate of sandy soil is 1400 mm/h, while that of clayey soil is 50 mm/h.

2.2 Experimental procedure

For the inflow, a semi-synthetic stormwater was prepared by mixing highway sediments with municipal tap

Table 1 Physical properties of the filter media used

Media	d_{10}[a](mm)	C_U[b]	Void ratio, e	Dry density (kg/L)
Gravel	15.0	2.2	0.47	1.4
Woodchip	11.0	1.9	0.64	0.3
Sandy soil	0.18	2.2	0.34	2.5
Clayey soil	0.01	70	0.30	3.1

[a]Effective diameter = the diameter at which 10% of the sample's mass is finer
[b]Uniformity coefficient = d_{10}/d_{60} (Indicates how well distributed the grain sizes are)

water. The sediments were collected through a highway clean-up process, taken to the laboratory, oven dried for 24 h, and sieved to remove foreign materials, stones, and other large debris. Inflow turbidity was set at 100 NTU which is equivalent to 1600 mg/L. A relationship between total suspended solids (TSS) concentration and turbidity was also established to be able to calculate TSS concentrations based on turbidity measurements during the experiments.

The semi-synthetic stormwater was fed to the infiltration device at application rates of 250, 500, and 1000 mm/h equivalent to rainfall intensities of 5, 10, and 20 mm/h over a 7 m^2 catchment area (SA:CA=0.02). Outflow and overflow rates were measured volumetrically from the start of outflow and every 5 min thereafter. The water level in the tank was also measured every 5 min. Inflow, outflow, and overflow samples were collected by time-weighted discreet sampling from the start and every 10 min thereafter for turbidity measurement and PSD analysis. Feeding was done for 1 h after which the remaining water in the tank was allowed to drain. During this drawdown period, the water level in the tank and the outflow rates were measured continuously every 10 min until all the water above the soil is drained. The drawdown time was recorded in each experiment.

Infiltration rates were computed as the instantaneous outflow rate divided by the surface area of the soil. These values were also considered as the vertical flow velocities within the infiltration device. On the other hand, horizontal flow velocities were computed as the instantaneous overflow rate divided by the cross-sectional area of the gravel layer. Average infiltration rates, as well as vertical and horizontal flow velocities, were computed as the average of instantaneous values in each experiment.

3. Results and discussion

3.1 Hydraulic response

Stormwater infiltration systems should differ in hydraulic behavior depending on the type of the underlying soil due to their differences in hydraulic conductivity, and by extension, the infiltration capacity. Fig 2 shows the variation of infiltration rates and water levels in ID-1 and ID-2. The infiltration rates observed in ID-2 were up to 10 times lower than that observed in ID-1 due to the lower hydraulic conductivity of clayey as compared to sandy soil. Average values in ID-1 showed an increasing trend of 231, 381 and 410 mm/h at application rates of 250, 500 and 1000 mm/h, respectively. This trend was much less evident in ID-2 with corresponding average infiltration rates of 39, 42, and 43 mm/h which is close to the values obtained during the initial column test. Lower infiltration rates were observed in sandy soil in the tank as compared to that obtained during the column test which can be attributed to the additional compaction caused by the weight of the gravel. Therefore, it should be noted that using soil properties obtained in initial laboratory testing can be erroneous when it comes to designing stormwater infiltration systems. On-site testing before and after installation should be conducted to avoid this type of error and ensure that the target runoff reduction or groundwater recharge during the design stage can be achieved after construction.

During the 60-min application of artificial stormwater, the infiltration rates in both systems were observed to increase rapidly within the first 15 to 30 minutes of operation. As seen in the figure, this occurred simultaneously with the rise in water level inside the infiltration device. Moreover, the rate of increase in infiltration rate and water level is directly proportional to the increase in application rate. Water accumulates faster as the application rate increases due to the limitations in the soil's hydraulic conductivity especially if the application rate is higher than the soil's infiltration capacity. As a result, the rising water level created a positive hydraulic head above the surface of the soil which induced an increase in the infiltration rate. A similar observation was reported in an experimental study conducted by Feng *et al.* (2001) on water repellent soils whose hydraulic conductivity were improved with time due to increasing pressure head induced by water ponding depth. In addition, Bouwer and Rice (1989) mentioned this phenomenon in a study of groundwater recharge basins. Thus it can be inferred that the available depth for storage within the media can influence the infiltration rates of the underlying soil.

The systems then reached a steady-state or equilibrium state upon reaching the highest water level of 40 cm due to the start of overflow. For ID-1, this equilibrium infiltration rates were about 250, 430, and 450 mm/h at application rates of 250, 500, and 1000 mm/h, respectively, while corresponding values in ID-2 were 45-47 mm/h. It can be inferred that the saturated infiltration capacity of the clayey soil used was about 45 mm/h while that of sandy soil was about 450 mm/hr. When the inflow ended, the water level started to go down and was accompanied by corresponding declines in infiltration rate. This drawdown period lasted for 30 min in ID-1 and 5 h in ID-2. The recession of infiltration rates during this period further demonstrated the influence of overlying water depth to this parameter.

3.2 Runoff volume reduction

Fig. 3(a) presents the percentage of infiltrated water volume considered as the volume reduction of ID-1 and ID-2 with respect to the applied inflow or application rates. At 250 mm/h application rate, ID-1 was able to completely capture 100% of the inflow volume which means no overflow occurred. This decreased to 79.3% and 55.2%

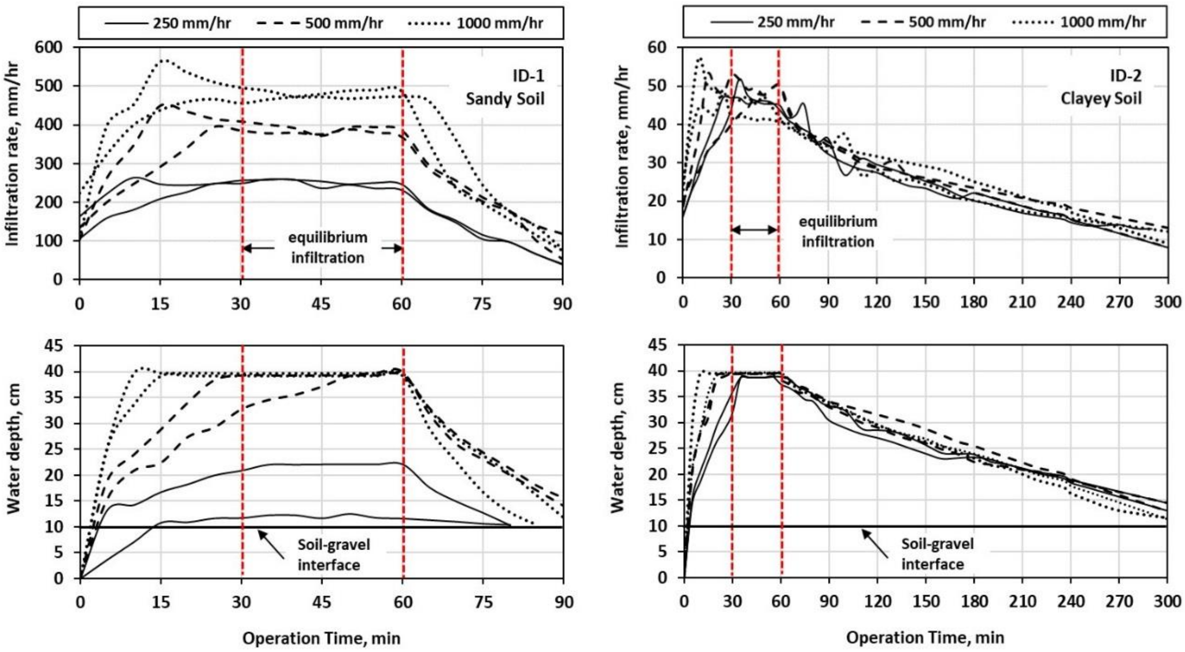


Fig. 2 Changes in infiltration rates and water depth at different application rates

when the application rate increased. On the other hand, the corresponding volume reduction in ID-2 were 59.1%, 30.9%, and 16.5%. The results clearly demonstrate the great difference in the volume reduction capability of a system as affected by the subsoil hydraulic conductivity and its implication in the sizing criteria of the design process. Take note that the two types of soil have infiltration rates that are both considered acceptable to allow for infiltration on site as per the current existing guidelines. However, considering the same surface area and catchment area for the two facilities, ID-2 requires at least twice the depth of ID-1 to provide more storage, promote greater infiltration, and achieve the same volume reduction as that of ID-1 due to the difference in subsoil type. This stresses that values used as design infiltration rates play a major role in calculating the appropriate depth for a stormwater infiltration system. Thus, the on-site infiltration capacity of the subsoil should be determined from each specific site.

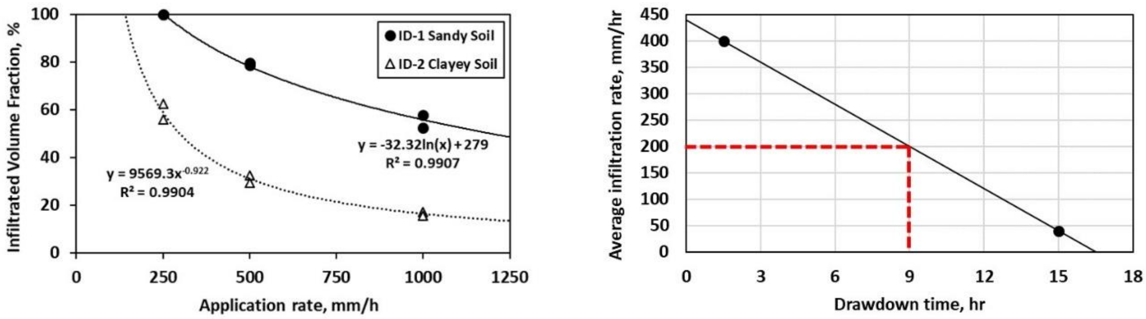
The rate of decrease of the volume reduction as the application rate increases also differed on the type of subsoil. The best fit regression line generated from ID-1 constituted a logarithmic function while the more drastic trendline in ID-2 had a power function, both with a coefficient of determination (R^2) equals 0.99. This means that the volume reduction is influenced by the rainfall intensity.

Given the volume reduction data from the two types of soils and assuming the same surface area to catchment area ratio as well as void ratio of the gravel layer, the required depth to improve the volume reduction percentage was roughly estimated through ratio and proportion. Considering a 10 mm rainfall which constitutes more than 80% of the annual rainfall in Korea (Yu *et al.* 2016), a total capture of stormwater or 100% runoff volume reduction can be achieved if the gravel layer is at least 0.97 m (3.2 ft) when the subsoil has an infiltration capacity of 40 mm/hr. This will reduce to more than 50% if the rainfall depth reached 20 mm. On the other hand, when the subsoil has an infiltration capacity as high as 400 mm/h, the minimum required depth to achieve total capture is only 0.38 m (1.3 ft) for a 10 mm rainfall and 0.54 m (1.8 ft) for a 20 mm rainfall. This is less than the minimum required depth in the US guidelines as well as in the Korean guidelines which is 0.61 m (2 ft) (LADPW 2014, Virginia Tech 2013, KEC and MOE 2013).

While a shallow facility is favorable in terms of construction cost and ease of access for maintenance and repair, a minimum depth for water quality requirements should be observed. Since most stormwater infiltration facilities have pretreatment systems that remove sediments, suspended solids are not a critical factor in determining the minimum depth. Heavy metals are also not a major factor since they are often bound to sediments (Davis *et al.* 2003, Li and Davis 2008). However, nutrients can be of concern. According to Hunt and Lord (2006), the media depth for infiltration facilities should be at least 0.61 m (24 in) for phosphorus removal, and at least 0.76 m (30 in) for nitrogen removal. Moreover, greater TKN and nitrate removal can be achieved when the infiltration rate is 25.4-50.8 mm/h (1-2 in/h) and the depth is at least 0.91 m (3 ft). Using Eq. 1 where d is the gravel media depth in m, f_d is the in-situ infiltration rate in mm/h, e is the void ratio of the gravel media, we can express these criteria in terms of the retention or drawdown time, T_R in h.

$$\mathrm{d} = \frac{f_d}{e\ x\ 1000} x T_R \quad (1)$$

Assuming the recommended minimum d=0.91 m and f_d=50.8 mm/h, the corresponding T_R that is favorable for nutrient removal is approximately 9 h. Recall that the drawdown times mentioned in the previous section was 30



(a) (b)

Fig. 3 (a) Trends of volume reduction at different infiltration rates and (b) Minimum recommended drawdown time and corresponding maximum infiltration rate

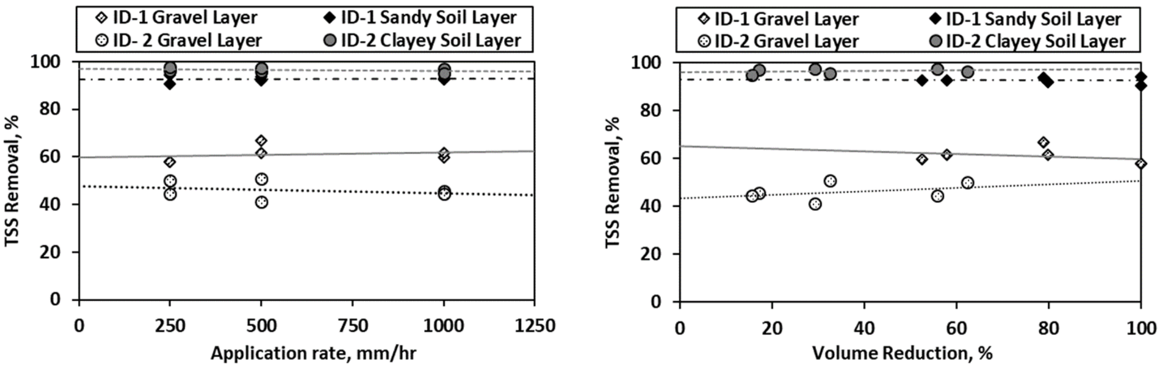


Fig. 4. Removal of suspended solids with respect to application rate and volume reduction

min in ID-1 and 5 h in ID-2 using a media depth of only 0.3 m. If the depth of the infiltration device in this study was 0.91 m, the drawdown times would have been at least 1.5 h in ID-1 and 15 h in ID-2 with a note that the infiltration rate tends to get lower with the water level above the soil-gravel interface. Thus it is apparent that the infiltration rate of 400 mm/h in ID-1 was too fast and would not provide the minimum retention time to adequately reduce nutrients.

Considering the estimated 9 h retention time to achieve preferable nutrient removal and reflecting that information on the experimental conditions of the infiltration device in this study, a drawdown time of 3 h in each experiment would be preferable. If a line is to be drawn between two data points representing the average infiltration rates and drawdown times recorded in this study as in Fig. 3(b), it can be inferred that the maximum infiltration rate recommended for the removal of nitrogen and phosphorus would be 200 mm/h. This can also be calculated through interpolation. It should be noted that this value is the maximum and the design infiltration rate used in computation for sizing should be the corrected in-situ infiltration rate with some factor of safety. If the in-situ infiltration rate is higher than 200 mm/h, it is recommended to amend a portion of the underlying soil and/or employ a geotextile at the bottom of the facility to control the exfiltration of stormwater to the surrounding ground. Other factors such as the risk to groundwater contamination, soil expansion, and damage to nearby structural foundations due to seepage should also be assessed to determine the feasibility of an infiltration facility on the specific site.

3.3 Removal of suspended solids

The removal of TSS with respect to different application rates and volume reductions from the infiltration device employing sandy soil and clayey soil is shown in Fig. 4. In all the experiments, the gravel layer was able to remove 41-67% of the solids with an average of 54±8.5%. This can be considered as high considering that no pre-treatment was used and that the depth of the gravel media is only 0.3 m. This confirms that TSS removal in an infiltration system employing gravel as the main media can be considered not critical or does not depend on the depth. Since the void ratio and hydraulic conductivity in this layer are quite high, the main solids capture mechanism would be inertial impaction and interception with some straining. Settling or sedimentation can also be a major factor especially during the period when the water accumulates above the soil and also during overflow. To improve TSS removal, avoid premature clogging, and lessen maintenance frequency, a pretreatment system should be provided before the infiltration bed. Typical pretreatment options include settling tanks or vegetated filter strips depending on space availability. No apparent trend in TSS removal with respect to application rate and volume reduction was shown indicating that these parameters did not affect the capture of solids in the infiltration device. This is possible since the flow in the gravel layer tend to stabilize as the tank is filled with water.

Majority of the solids that were not captured in the gravel layer were trapped in the soil layer giving a total of

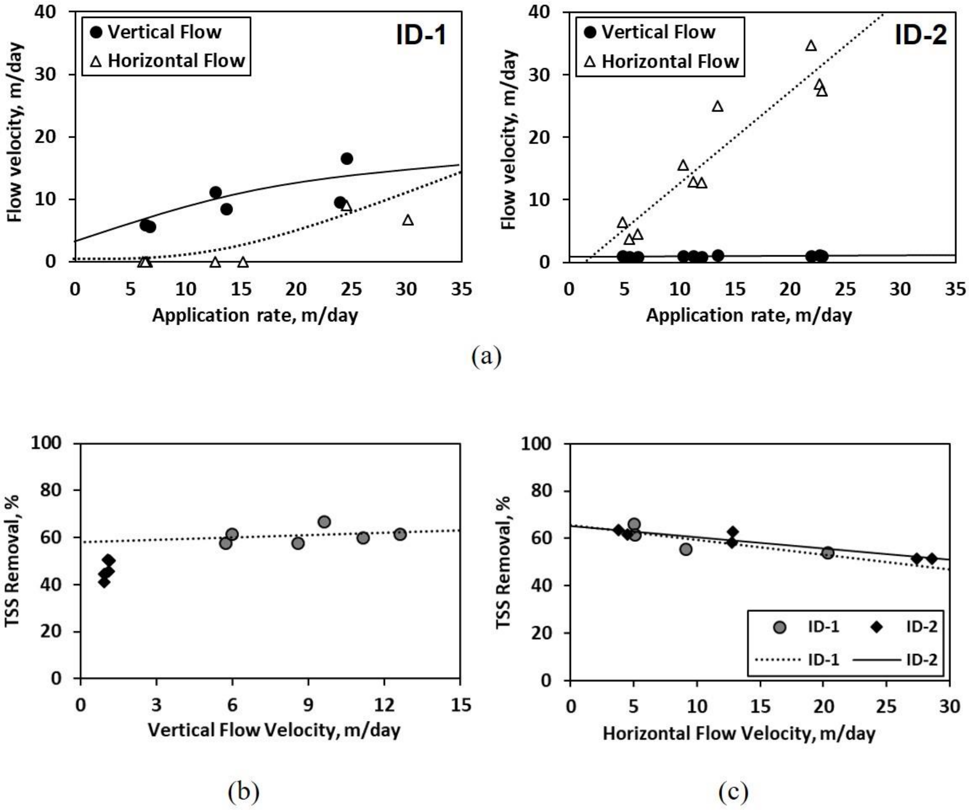


Fig. 5 (a) Changes in vertical and horizontal flow velocity with respect to application rate and (b)-(c) Effect of flow direction in the removal of suspended solids

91-94% (93±1.3%) removal in ID-1 and 95-98% (97±1.0%) in ID-2. This clearly demonstrates the great potential of the subsoil to further improve the quality of the water treated by the gravel layer and entering the ground. However, the target reduction in solids load should be aimed to be concentrated in the gravel layer to avoid clogging in the soil layer.

3.4 Effect of vertical and horizontal flows

In this study, the flow was partitioned into vertical and horizontal flow wherein the vertical flow velocity is assumed to be equivalent to the infiltration rate while the horizontal flow velocity is constituted by the overflow rate considering the cross-sectional area rather than the surface area of the gravel layer. The changes in flow velocities in both direction with respect to the application rate in m/day is shown in Fig. 5(a). It can be seen that in ID-1, both the vertical and horizontal flow increased with the application rate. This is due to the capability of the sandy soil to receive water up to its saturated infiltration rate. On the other hand, in ID-2, vertical flow remained constant due to the limited infiltration capability of clayey soil. However, the horizontal flow increased rapidly with the application rate. This indicates that although stormwater infiltration systems are usually designed and analyzed based on the assumption that water flows vertically, systems that are built above clayey soil are more susceptible to horizontal flow, especially during heavy rainfalls. Therefore, the effect of flow direction on the TSS removal was also investigated.

The variation in TSS removal in the gravel layer with respect to the direction of flow is presented in the figure. It can be seen that the flow velocity in the vertical direction did not affect the TSS removal both in ID-1 and ID-2 (Fig. 5(b)). As the water level above the gravel-soil interface rises, vertical flow tends to become stable and undisturbed. This can enhance the diffusion of small-sized particles which should otherwise be negatively affected during high-velocity flows. Moreover, sedimentation of particles was promoted in this condition. On the other hand, since the vertical flow in ID-2 remained constant, the increasing application rate resulted in a corresponding increase in the horizontal flow velocity (Fig. 5(c)). It was observed that as this velocity increases, more solids were able to come out of the infiltration device, lowering the amount of TSS retained by the system. Avoiding this phenomenon would entail increasing the depth of the gravel bed to minimize horizontal flow. However, depth is also subjected to several constraints and limitations as mentioned in the previous section. Therefore, when increasing the depth is not an option or is less favorable, the length of the system can be increased.

Considering these observations, where sites are predominantly clayey and have saturated infiltration rates less than 40 mm/h as in the one used in this study, the length of the gravel bed is an important factor for TSS load reduction. Given that the minimum depth for the removal of other pollutants are met, increasing the length of the gravel bed would minimize the escape of solid particles and particle-associated pollutants in the overflow, thereby retaining more solids to be captured by the gravel medium and also protecting the downstream water quality. This is particularly significant during heavy rainfall when the volume retention capacity of the system is surpassed and horizontal flow becomes dominant since excess stormwater is released through bypass mechanisms.

5. Conclusions

The experiments conducted at laboratory-scale confirmed that the volume reduction and TSS removal capability of a gravel-filled stormwater infiltration structure are greatly influenced by the infiltration capability of the underlying subsoil. The results also showed that after construction, this property is influenced by the depth available for stormwater storage, rainfall intensity, and inflow rates. The available depth for storage can influence the infiltration rates due to the positive hydraulic head exerted by the retained water at the soil-gravel interface. Thus, infiltration rates should be measured during operation and values before, after, and throughout the course of its lifetime should be monitored to be able to compare and analyze the changes and their contribution to the corresponding changes in performance.

Increasing inflow rates brought by more intense rainfalls were also found to reduce the volume reduction capability and that the rate of this reduction is higher for subsoils that have lower hydraulic conductivity such as clayey soil. Based on volume reduction analysis, gravel-filled stormwater infiltration systems should be at least 1 m to be able to retain, treat, and exfiltrate 100% of a 10-mm rainfall in Korea. This does not include the ponding depth and considers in-situ saturated infiltration rates of at least 40 mm/h. In terms of pollutant removal, these systems are capable of high solids reduction but the addition of a pretreatment mechanism is suggested to avoid premature clogging. In addition, it is suggested that stormwater infiltration systems be limited to sites with in-situ infiltration rates equal to or less than 200 mm/h to ensure minimum retention time to promote the reduction of nutrients. If groundwater recharge is desired in sites with higher infiltration rates, soil amendments at a certain depth below the facility or installation of geotextile fabrics to control exfiltration are suggested.

Moreover, infiltration systems built above clayey soil were found to be more susceptible to horizontal flows which allowed the escape of solids contained within the storage layer. Therefore, the length of the gravel bed is more critical than the depth in sites that are predominantly clayey and have saturated infiltration rates near 40 mm/h. In this case, increasing the length of the infiltration facility would be more beneficial when it comes to retaining solids for capture in the medium.

The findings in this study can contribute to existing guidelines in designing and monitoring stormwater infiltration systems which employ gravel or similar materials as main media. Minimum and maximum values were suggested, taking note of the premise that decisions on sizing are often met with site-specific constraints that cannot be altered. To corroborate the results, additional experiments consisting of different gravel media depths and subsoil permeabilities shall be conducted.

Acknowledgments

This research was supported by a grant (2016000200002) from Public Welfare Technology Development Program funded by the Korean Ministry of Environment.

References

Akan, A.O. (2002), “Modified rational method for sizing infiltration structures”, *Can. J. Civ. Eng.,* **29**(4), 539-542.

ASTM International (2012), “ASTM D698-12e2 Standard test methods for laboratory compaction characteristics of soil using standard effort (12 400 ft-lbf/ft^3 (600 kN-m/m^3))”, ASTM D698-12E2; ASTM International, West Conshoshocken, PA, U.S.A.

Bertrand-Krajewski, J.L., Chebbo, G. and Saget, A. (1998), “Distribution of pollutant mass vs volume in stormwater discharges and the first phenomenon”, *Water Res.*, **32**(8), 2341-2356.

Bouwer, H. and Rice, R.C. (1989), “Effect of water depth in groundwater recharge basins on infiltration”, *J. Irrig. Drain. Eng.*, **115**(4), 556-567.

Chahar, B.R., Graillot, D. and Gaur, S. (2012), “Storm-water management through infiltration trenches”, *J. Irrig. Drain. Eng.*, **138**(3), 274-281.

Davis, A.P., Shokouhian, M., Sharma, H., Minami, C. and Winogradoff, D. (2003), “Water quality improvement through bioretention: Lead, Copper and Zinc removal”, *Water Envi. Res.*, **75**(1), 73-82.

Eckart, K., McPhee, Z. and Bolisetti, T. (2017), “Performance and implementation of low impact development—A review”, *Sci. Total Environ,* **607-608**, 413-432.

Emerson, C.H., Wadzuk, B.M. and Traver, R.G. (2010), “Hydraulic evolution and total suspended solids capture of an infiltration trench”, *Hydrol. Process,* **24**(8), 1008-1014.

Feng, G.L., Letey, J. and Wu, L. (2001), “Water ponding depths affect temporal infiltration rates in a water-repellant sand”, *Soil Sci. Soc. Am. J.*, **65**(2), 315-320.

Fischer, D., Charles, E.G. and Baehr, A.L. (2003), “Effects of stormwater infiltration on quality of groundwater beneath retention and detention basins”, *J. Envi. Eng.*, **129**(5), 464-471.

Guerra, H.B., Yu, J. and Kim, Y. (2018), “Variation of flow and filtration mechanisms in an infiltration trench”, *J. Wetlands Res.*, **20**(1), 63-71.

Hunt, W.F. and Lord, W.G. (2006), *Urban Waterways AGW-588-05*, North Carolina Cooperative Extension Service, Raleigh, NC, U.S.A.

Korean Environment Corporation and Korean Ministry of Environment (KEC and MOE) (2013), *Guidelines for Low Impact Development (LID) Technology Element,* Korean Ministry of Environment, Sejong, Republic of Korea.

Le Coustumer, S. and Barraud, S. (2007), “Long-term hydraulic and pollution retention performance of infiltration systems”, *Water Sci. Technol.*, **55**(4), 235-243.

Li, H. and Davis, A.P. (2008), “Urban particle capture in bioretention media. I:Laboratory and field studies”, *J. Environ. Eng.*, **134**(6), 409-418.

Los Angeles Department of Public Works (LADPW) (2014), *Low Impact Development Standards Manual*, County of Los Angeles, California, U.S.A.

Pitt, R., Lantrip, J., Harrison, R., Henry, C.L. and Xue, D. (1999), "Infiltration through disturbed urban soils and compost-amended soil effects on runoff quality and quantity", United States Environmental Protection Agency, Washington, DC, U.S.A.

Sharma, S. (2017), "Effects of urbanization on water resources-facts and figures", *Int. J. Sci. Eng. Res*., **8**(4), 433-459.

Shuster, W.D., Bonta, J., Thurston, H., Warnemuende, E. and Smith, D.R. (2005), "Impacts of impervious surface on watershed hydrology: A review", *Urban Water J*., **2**(4), 263-275.

Sileshi, R.K., Pitt, R.E. and Clark, S.E. (2014), "Laboratory column test for predicting changes in flow with changes in various biofilter mixtures", *J. Water Manage. Model*.

Virginia Tech. (2013), *BMP Design Manual of Practice*, Virginia Department of Transportation, Richmond, VA, U.S.A.

Warnaars, E., Larsen, A.V., Jacobsen, P. and Mikkelsen, P.S. (1999), "Hydrologic behaviour of stormwater infiltration trenches in a central urban area during 2 ¾ years of operation", *Water Sci. Technol.*, **39**(2), 217-224.

Welker, A.L., Gore, M. and Traver, R. (2006), "Evaluation of the long term impacts of an infiltration BMP", *Proceedings of the 7th International Conference on Hydroscience and Engineering,* Philadelphia, PA, U.S.A.

Yu, G., Choi, J., Kang, H.M. and Kim, L.H. (2016), "Evaluation of the volume and pollutant reduction in an infiltration and filtration facility with varying rainfall conditions", *J. Korean Soc. Water Environ.*, **32**(1), 30-35.

CC