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Determination on the optimum design factors of BMP for nonpoint pollutant treatment through long-term monitoring

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ABSTRACT

Despite huge investments about point source pollution in South Korea over the past 30 years, there is no improvement in the restoration of water quality in rivers and lakes since the 1990s. The reason for this was because of the nonpoint source (NPS) pollution. Therefore, the Korean government prepared a variety of policies and systems to control NPS. The 1st comprehensive measures for NPS management were established to provide policies on the installations of test beds for NPS reduction facilities, determination of treatment efficiency through monitoring, and guidelines for planning and maintenance. The study provided a method for proper installation of the inlet screen and weir in the NPS reduction facility. In addition, the study has identified the optimal linear velocity and depth of media in a filtration facility. In the case of screens installed in closed channels, due to clogging caused by wastes, it was found out that installation of a 3-dimensional structure will be convenient for maintenance. Earth and sediment were not controlled when the weir was installed near the inlet of the facility. However, installation of the weir farther from the inlet of the facility had made improvement for the facility's removal efficiency and maintenance. Therefore, the weir should be installed 1–2 m away from the inlet of the facility to improve efficiency and to provide easier maintenance. Meanwhile, results show that a linear velocity of 25–30 m^3/h in the filtration facility is most effective for the treatment of contaminants. Also, the facility is most efficient when replacement of media takes place once a year during March. On the other hand, the media does not function normally due to blockage by particulate matters after the rainy season. Therefore, there should be surface dredging of the media once a year after heavy rainfalls. It was also found out the optimal thickness of the media in the filtration facility is more than 0.7 m according to the Total suspended solids (TSS) and Total Phosphorus (TP) treatment efficiency analysis.

Keywords: BMP guideline; Media depth; Nonpoint pollutant treatment facility; Weir

1. Introduction

For more than 30 years, Korea has invested heavily on point sources for the improvement of the water quality of rivers and lakes. As a result, the water quality of rivers and lakes has greatly improved. However, since the 1990s, Korea has experienced rapid urbanization, resulting in a failure to improve water quality above a certain level despite the continuous and significant investment with regard to point sources. The Korean government determined that the major cause behind this failure was due to the increase in nonpoint sources (NPSs), resulting from changes in various development projects and land use. Also, in 1995, the government assessed the contribution rate of NPSs in order to determine the effect of NPSs on the water quality of rivers and streams [1]. According to the results of the survey conducted by the Ministry of Environment, NPSs were responsible for approximately 22%–37% of the river and stream Biochemical

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Oxygen Demand (BOD) load in 2004, and it was estimated that this would increase to 72.1% by 2020 [2,3].

The Ministry of Environment recognized that there were limits to achieving the target water quality of rivers and streams using water quality improvement projects focused on point sources, and that efforts to reduce NPSs caused by heavy rains were also necessary. The Korean government has also developed various systems and policies to reduce NPSs in an effort to improve stream water quality. In 1998, the Korean government established the Comprehensive Measures on Water Quality Management for the Four Major Rivers in Korea which include the Han River, Gum River, Yeongsan River, and Nakdong River. This policy was the first government-scale policy related to NPSs in Korea. According to this policy, development of both sides of the rivers was limited by establishing buffering zones creating waterfront green belts and establishing a land purchase system as well as pursuing policies such as the water pollution load management system and establishment of a water system management committee and river basin environmental office [4–7]. However, this policy (Comprehensive Measures on Water Quality Management for the Four Major Rivers in Korea), which was the first to deal with NPSs, was criticized for its lack of cooperation between departments with regard to NPS management. As a result, it established the "1st comprehensive measures for nonpoint source management", initiating policies including allocation of site NPS management responsibilities, reduction of highland field mud discharge, a NPS installation declaration system, NPS management area designation system, and NPS discharge characteristics studies, involving the offices related to NPSs, such as the Ministry of Land, Transport and Maritime Affairs; Ministry of Environment; Korea Forest Service; and Ministry of Knowledge Economy [2].

In addition, this policy provided the legal foundation necessary for NPS management and included a plan to establish guidelines for managing the design and maintenance for NPS reduction facilities, by installing and monitoring NPS reduction pilot facilities. Meanwhile, the "Water and Environmental Management Plan" was established in September 2006 as a long-term plan, and as a result, NPS management per region over a wider area became possible [12].

Also, the "2nd comprehensive measures for nonpoint source management" was established and has been carried out to this day, including the improvement of NPS reduction facility installation and declaration systems, NPS facility performance certification systems, rainwater pollution fee systems, establishment and operation of NPS policy councils in related departments, expansion of animal waste facility installations, and soil erosion resistant field foundation maintenance projects, in an effort to sustain and develop upon the "1st comprehensive measures for NPS management" [3].

Among these efforts, the NPS reduction pilot facilities constructed as a part of the "1st comprehensive measures for nonpoint source management" were continuously monitored from 2006 to 2014. Through this process, optimal design parameters for NPS reduction facilities were obtained, such as the pollutant processing efficiency of each NPS reduction facility, the optimal depth and linear velocity of the filter medium, filter medium replacement period, sedimentation basin deposit dredging period, and vegetation management period, along with appropriate operation and maintenance management methods.

Meanwhile, the installation of NPS reduction facilities when developing factories and roads is obligatory, based on the regulation of water quality and hydroecological preservation. However, the NPS reduction facility design guidelines were established referencing the U.S. guidelines; thus, the guidelines do not fit the land use and rainfall events of Korea.

In order to implement NPS reduction facilities nationwide to improve the water quality of rivers and streams, NPS reduction facility design, operation, and maintenance guidelines specific for Korea were needed from the Korean government, and such guidelines were prepared for NPS reduction facilities based on the monitoring results of the NPS reduction pilot facilities carried out from 2006 to 2014.

In this study, the processing efficiencies of the facilities were improved utilizing the operation and monitoring data from NPS reduction pilot facilities obtained over a period of nine years. Aspects that NPS reduction facility designers need to consider for convenient maintenance are presented. Furthermore, this study aimed to present the optimal linear velocity and depth for the filter medium, which is one design factor of filter type facilities.

2. Materials and methods

2.1. Study sites

Following a policy to improve the water quality of rivers and streams, the Korean government began to construct NPS pilot facilities in 2005 and conducted long-term monitoring of these facilities from September 2006 to March 2014. A total of 47 NPS reduction pilot facilities were constructed in proximity to the 4 major rivers of Korea: 28 facilities near the Han River, 7 near the Gum River, 7 near the Yeongsan River, and 5 near the Nakdong River (Fig. 1). Since the management method for NPSs varies according to the source and rainfall, it is difficult to control NPSs with a single processing method. Thus, for NPSs, it is necessary to approach the problem from the perspective of BMPs (Best Management Practices) [8]. Therefore, various NPS reduction pilot facilities were constructed, including natural type facilities, such as infiltration trench, bio swale, infiltration basin, constructed wetland, tree box filter, bio pond, retention basin, and apparatus type facilities, such as filtration system, screen system, and vortex

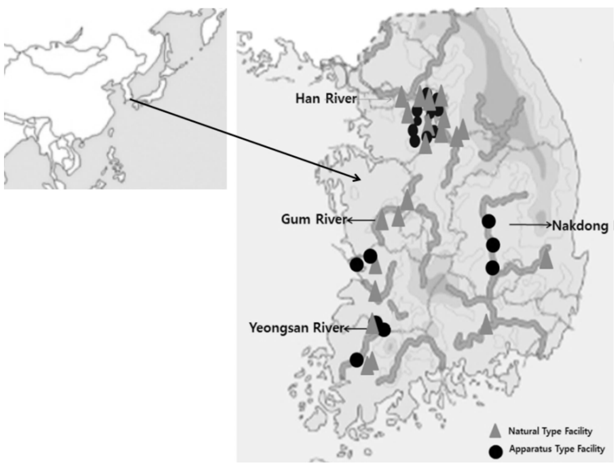

Fig. 1. Nonpoint source facility locations in Korea.

Fig. 2. Photos of nonpoint source facilities.

system. Fig. 2 shows some of the facilities installed as NPS reduction pilot facilities.

This study was carried out using the monitoring results of 13 facilities among the total 47 facilities constructed. Using the monitoring data, the inflow screen and weir structures for the facilities were analyzed, and installation solutions for optimum maintenance were presented. Also, in order to improve the efficiency of filtration facilities in terms of economic feasibility, the optimal filter medium linear velocity, depth, and replacement period were analyzed using the monitoring data from 9 filtration facilities.

Table 1 shows the specifications of the facilities used in the analysis of this study. BMP-A to BMP-D were used for the analysis of the inflow screen and weir structure analysis, and BMP-F to BMP-M were used to analyze the optimal filter medium linear velocity and depth. The drainage forms in the areas where the facilities are installed include land uses such as roads, residential areas, and farming areas. Throughout this study, maintenance activities including vegetation management, deposit dredging, filter medium replacement, garbage removal, residual water removal, and deposit depth measurement were constantly conducted in order to maintain the optimum efficiency of each facility. Moreover, various improvements were made to the facilities, including a modification to the inlet screen, to prevent the influx of various types of trash which would cause the facility efficiency to decrease, inlet structure improvement for enhanced inflow of rainwater runoff into the NPS reduction facility, and other modifications for efficiency enhancements.

3. Results and discussion

3.1. Inflow screen installation structure

A screen is a preprocessing installation that prevents the inflow of various types of garbage into the processing facility, to protect the downstream processes and maintain the processing efficiency of the facility. However, blockage of the screen by various types of garbage occurs frequently and is the cause of increased maintenance costs. In this chapter, the screens installed in the NPS reduction pilot facilities for the four major rivers are introduced, with the purpose of expanding the selection possibilities of appropriate screens selected by designers when designing the inlets of NPS reduction facilities. The pilot facilities of the four major rivers revealed that screen blockages occurred with every rainfall for screens installed near bus stops, areas with large amounts of fallen leaves, commercial areas, and residential areas (Fig. 3).

Fig. 4 below shows the screens installed in the inlets of filtration and basin facilities. The BMP-A facility has rainwater

Table 1
Data of monitored BMP facilities

Code name	Facility type	Catchment area (m^2)	Land use type of catchment area	Volume (m^3)	Media depth
BMP-A	Constructed wetland	60.00	Rural area	3,542	–
BMP-B	Filtration system	160	Residential area	17,280	–
BMP-C	Retention system	177.30	Residential area	9,162	–
BMP-D	Filtration system	0.65	Road	2	0.3
BMP-E	Infiltration retention	9.13	Road	517	–
BMP-F	Filtration system	0.121	Road	10.2	0.5
BMP-G	Filtration system	0.267	Road	5	0.7
BMP-H	Filtration system	0.36	Road	10	0.9
BMP-I	Filtration system	0.50	Road	40	1
BMP-J	Filtration system	0.99	Road	11	1.1
BMP-K	Filtration system	1.07	Road	18	1.3
BMP-L	Filtration system	3.556	Road	24	1.5
BMP-M	Filtration system	0.77	Road	44	1.9

Fig. 3. Clogging of inflow screen.

runoff flow from the outside to the inside, while BMP-C facilities have rainwater runoff flow outward from closed waterways. These facilities have screens in a plane form to filter garbage at the inlet. While this configuration has no difficulty in processing the garbage from the outside in BMP-A, this configuration is difficult and not appropriate for BMP-C in terms of maintenance, since the trash is filtered on the inner sides of the closed waterways. Therefore, when the inlet is of this structure type, it was examined to determine whether installing a nonplanar screen or a 3-dimensional structure would offer greater convenience for maintenance (Fig. 4). Since the cost of installing a 3-dimensional screen will not be significantly different compared with the installation of a planar screen, the advantages in maintenance convenience was determined to be the significant factor.

Fig. 5 shows the screen installed in the inlet of an infiltration basin. This screen was installed to prevent the inflow of garbage into the infiltration basin, but severe blockage of the screen was produced by wastewater from the surrounding drainage area. Also, it was observed that for such screen structures, when the blockage was caused by garbage, the rainwater runoff rose upward along the screen sides and did not enter the inlet but escaped on either side. Thus, screens of this type are not appropriate for areas where large amounts of garbage are produced.

3.2. Inflow weir installation method

The initial rainfall runoff should be managed carefully because the initial runoff contains a high concentration of pollutants. However, many facilities have off-line structure inlets, and weirs are installed to induce rainwater runoff toward the inlet. Due to the first flush effect of the rainwater runoff, interception of clean rainwater runoff in the middle and latter parts of the rainfall increases the facility maintenance cost. Thus, there is a need to adjust the height of the weir appropriately in order to control the amount of rainwater runoff at interception.

The weir height was designed taking into consideration the average rainfall intensity, facility capacity, and inlet size, and there were a number of designers who considered the distance to the inlet. Fig. 6 shows the installed inlet and weir of the BMP-E facility. Fig. 6(a) shows the sedimentation in the rainwater runoff flowing into the NPS reduction facility being blocked by the weir, when the inlet and weir were placed close to each other. When a large amount of sedimentation enters the NPS reduction facility, the facility fails to operate normally, and its processing capacity is degraded. Also, since the sedimentation that accumulates in the facility needs to be removed after each rainfall, the maintenance cost increases.

When the distance between the weir and the inlet is set to around 1~2 m as shown in Fig. 6(b), it was found that sedimentation flowing into the facility can be prevented. In this case, it was determined that the facility processing efficiency could be maintained and the maintenance cost could be

BMP-A (Before) BMP-C (Before)

BMP- A(After) BMP-C (After)

Fig. 4. Changes in the structure of the inflow screen (before and after).

Fig. 5. Inflow screen installation error.

reduced. When the weir and inlet were placed right next to each other, the average event mean concentration (EMC) for the Total suspended solids (TSS), COD_{cr}, and Total Phosphorus (TP) were 82.8, 31.2, and 3.8 mg/L, while the concentrations for when the inlet was installed 1~2 m away were 75.9, 2.9, and 3.1 mg/L, respectively. Accordingly, it was found that the inlet water concentration decreased more when the weir was moved (Table 2).

Additionally, analysis of the processing efficiencies for the TSS, COD_{cr}, and TP before and after moving the weir revealed that the TSS processing efficiency increased from 74% to 75.6%, while the processing efficiencies for the COD_{cr} and TP decreased from 63.1% and 71% to 54.5% and 64.5%, respectively (Table 3). This decrease in the processing efficiencies for COD_{cr} and TP after moving the weir was due to the reduced concentration of the inlet water, and it was determined that the final runoff after the weir was moved had a lower concentration value than before it was moved, even though the processing efficiency decreased (Table 4).

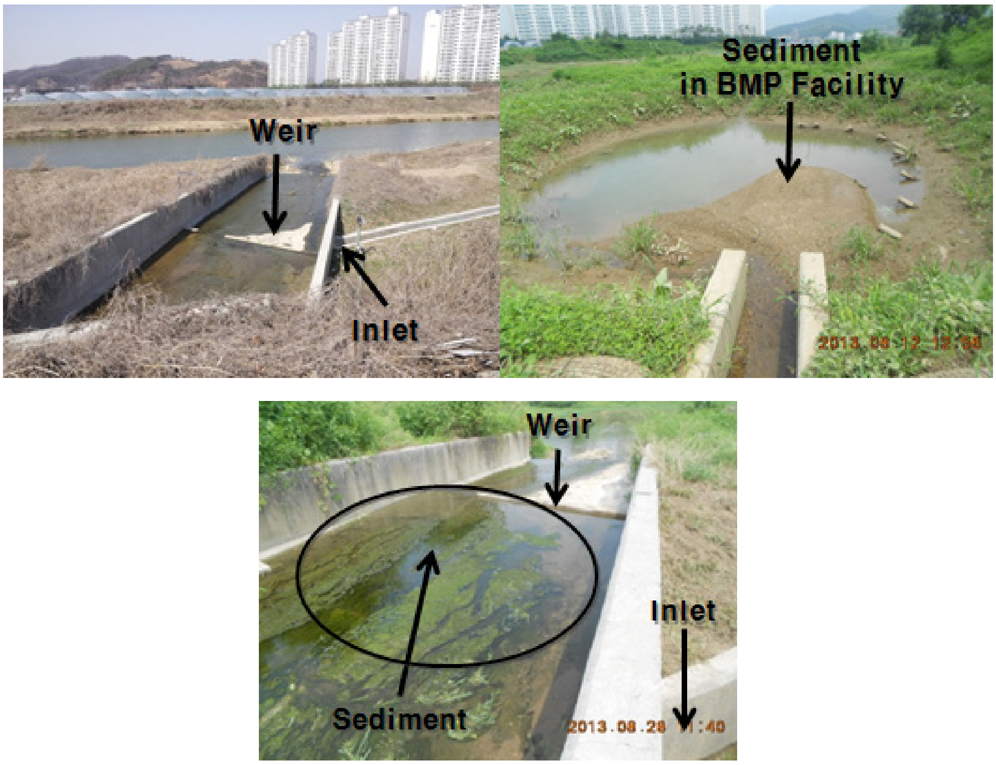

Fig. 6. Sediment accumulation: (a) before weir movement and (b) after weir movement.

Table 2
Average inflow pollutant concentration before/after weir movement in BMP-E

Parameter		TSS	COD_{cr}	TP
Min.	Before weir movement	61.5	17.5	1.2
	After weir movement	59.1	15.3	2.1
Max.	Before weir movement	101.8	45.1	5.9
	After weir movement	83.9	36.8	5.1
Mean	Before weir movement	82.8	31.2	3.8
	After weir movement	75.9	22.9	3.1
SD	Before weir movement	14.1	9.5	1.3
	After weir movement	7.1	6.4	1.0

Table 3
Average pollutant treatment efficiency before/after weir movement in BMP-E

Parameter	TSS	COD_{cr}	TP
Before maintenance	74.0	63.1	71.0
After maintenance	75.6	54.5	64.5

Table 4
Average pollutants outflow concentration before/after weir movement in BMP-E

Parameter	TSS	COD_{cr}	TP
Before maintenance	21.5	11.5	1.1
After maintenance	18.5	10.4	1.1

Therefore, it was determined that installing the weir approximately 1~2 m from the inlet was desired in an off-line structure in a location where sedimentation is significant.

However, while this measure is effective for an inlet which is an open waterway, this measure can cause the deposition of sedimentation in a closed waterway, resulting in maintenance difficulties, so a different solution may be needed in that case. On the other hand, when the weir and inlet are spaced too far apart, proper interception of the initial runoff is not possible, so follow-up studies on the appropriate weir installation distance according to the facility capacity or drainage area are necessary.

3.3. Optimum linear velocity of filtration system

The linear velocity of media was based on the results of monitoring from nine filtration facilities. In order to apply the same conditions to all the facilities, the filter media of all the facilities were replaced before beginning the monitoring. In Korea, the average precipitation over 10 years was 1400 mm. 20% of the total precipitation, or 300 mm, occurred from March to June, and most of the annual average or 950 mm occurred from July to September. 101 mm of precipitation occurred from October to November while December to February had recorded snowfall rather than precipitation. The filter medium was replaced on March 10, before the beginning of the full-fledged rainfall period. After the replacement, the initial filter medium linear velocity was found to be in the range of around 14~39.2 m/h with the high linear velocity average of 32.8 m/h. This linear velocity level continued until June 10, before the beginning of heavy rainfall.

However, as heavy rainfall began, this linear velocity began to rapidly decrease, and the average filter linear velocity in August after the heavy rainfall ended had been reduced to 3.7 m/h (Fig. 7). This was approximately 140 d after the filter medium replacement, and the accumulated rainfall was 1050 mm. The reason behind the linear velocity decrease was thought to be due to the clogging of the filter medium surface by the significant influx of large and small sand grains, soil, and clay particles from the heavy rainfall rather than overall clogging of the filter medium. Thus, maintenance was carried out to remove the sand and soil particles accumulated on the surface of the filter medium. The fact that the linear velocity increased back after performing this maintenance showed that the linear velocity decrease was caused by this surface clogging phenomenon.

However, the average filter medium velocity after this maintenance was 24 m/h, in comparison to the high linear velocity right after the filter medium replacement. Meanwhile, the increased linear velocity after the surface dredging maintenance began to decrease again as the accumulated precipitation increased. Even though the accumulated precipitation was less than before the first maintenance operation, the linear velocity was found to decrease at a higher rate. In Korea, snow falls after December, so continuous monitoring was not possible. In the monitoring conducted in February of the following year, the linear velocity was found to have been reduced to 9.1 m/h, so surface dredging was conducted. But the linear velocity did not increase as much as observed for the first dredging. Hence, replacement of the filter medium was determined to be necessary.

Meanwhile, in this study, analyses of the linear velocity and the TSS reduction efficiency were conducted. The TSS reduction efficiency was 78.2% right after the filter medium replacement, and the processing efficiency increased to 84.1% after rainfall of approximately 250 mm precipitation. This result was thought to be due to the accumulated granular material including sand and soil on the surface and inside the filter medium further decreasing the pores of the filter medium. However, after the initiation of heavy rainfall, sand and soil particles accumulated on the filter medium surface, causing the linear velocity to decrease sharply. As a result, the rainwater runoff could not flow into the facility, and overflow was observed.

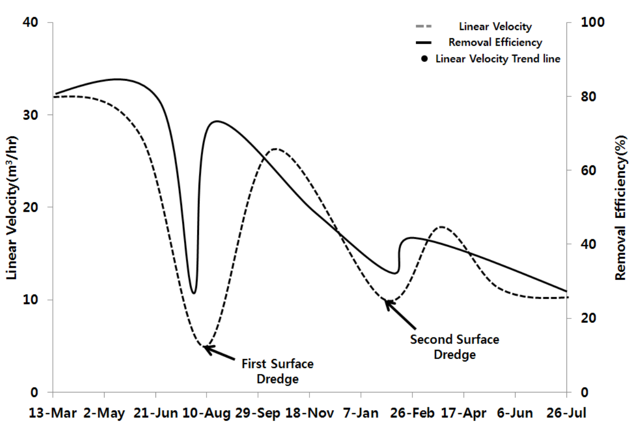

Fig. 7. Variations in the linear velocity and TSS treatment efficiency.

In addition, the processing efficiency at this time was around 20%, a very low value, so it was determined that the filter medium could not operate normally. After performing the first surface dredging, the TSS reduction efficiency recovered back to 76% with a linear velocity of around 24 mm/h, but it was found that the contaminant removal efficiency swiftly degraded, like the linear velocity, as the accumulated precipitation increased. After the second surface dredging, the TSS reduction efficiency did not increase as much as it had after the first surface dredging, and the value was approximately 41% lower. This result showed that the apparatus style facility in Korea requires replacement of the filter medium in February or March before the beginning of the full-fledged rainfall season, and filter medium replacement and surface dredging are necessary after July or August when heavy rainfall occurs. At this point in time, the accumulated precipitation after filter medium replacement was analyzed to be approximately 1050 mm.

In order to analyze the optimal linear velocity, the range of measured linear velocities was categorized into intervals of 15–20, 20–25, 25–30, 30–35, and 35–40 m^3/h. The TSS reduction efficiency was analyzed according to the linear velocity using the monitoring results before accumulated precipitation of 400 mm, after replacing the filter medium, which is before the filter medium clogging phenomenon occurred (Fig. 8). The analysis results revealed that the TSS reduction efficiency was 68.9% for a linear velocity of 15–20 m^3/h, 77.6% for 20–25 m^3/h, and 80.2% for 25–30 m^3/h. Also, the TSS reduction efficiency was 74.2% for 30–35 m^3/h and 73% for 35–40 m^3/h, so the processing efficiency for each linear velocity interval in decreasing order was 25~30 m^3/h > 20~25 m^3/h > 30~35 m^3/h > 35~40 m^3/h > 15~20 m^3/h.

The NPS reduction facility installation and management manual of Korea limits the linear velocity of filtration system to 20 m/h. Based on the results of this study, it was determined that increasing the linear velocity to 30 m/h resulted in processing of greater flux and higher processing efficiency than the current design standard.

3.4. Optimum media depth of filtration system

It is a necessity for a filtration facility to have filter media for the reduction of contaminants, and the depth of the filter media has a big effect on the removal efficiency of contaminants. It is not cost-effective if the filtration facility is to be deeply filled with filter media. Also, heavy filter media causes

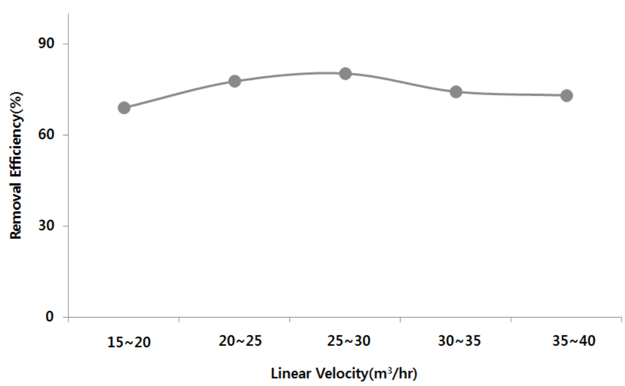

Fig. 8. TSS treatment efficiency with respect to linear velocity.

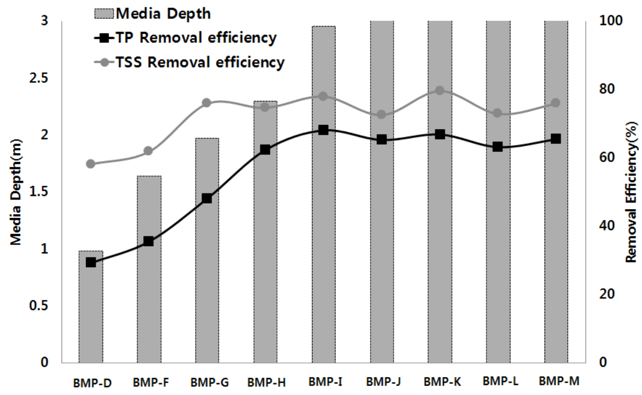

Fig. 9. TP and TSS treatment efficiency variations with respect to media depth.

a more complex maintenance. Hence, a normal depth for filter media is cost-effective. Generally, in Korea, 0.4–2 m of filter media depth is being adapted [9–11]. The study was conducted to identify the optimal depth of filter media for filtration facilities installed within the range of 0.3–1.9 m. In order to determine the optimal media depth, the removal efficiencies of TSS and TP in accordance with media depths were analyzed (Fig. 9). It was analyzed that more than 25 m/h linear velocity of filter media should be used because there seems to be a big difference in treatment efficiencies depending on degree of clogging of the filter media. There was less 60% low treatment efficiency for TSS in BMP-D and BMP-F with 0.3 and 0.5 m of filter media depths, respectively. However, TSS treatment efficiency escalated into 80.1% with 0.7 m of filter media. For higher depths, similar to 0.7 m of filter media, treatment was 73.4%–80.9% efficient. Meanwhile, a low TP processing efficiency, below 50%, was found for 0.3–0.7 m, and the processing efficiency rapidly increased to 60.8% for 0.9 m. Moreover, although the processing efficiency increased more, to 64.1% for 1 m, it was found that the processing efficiencies for depths above 0.9 m were similar to each other. In the NPS reduction facility installation and management manual of Korea, the filter medium for the filtration type facility is to be designed with a depth below 0.6 m. However, according to the results of this study, it was determined that the optimal filter medium thickness for filtration type facilities was above 0.7 m and that the filter medium depth has to be filled above approximately 0.9 m for areas to dominantly remove TP.

4. Conclusion

In this research, long-term monitoring was conducted in a NPS pollution reduction facility for the improvement and rehabilitation of the water quality of lakes in Korea. The results of the research presented which details the designers need to consider in designing NPS reduction facilities to increase the treatment efficiency and maintenance convenience. A screen was installed at the facility to prevent rainfall wastes or any litters from entering the facility. In order to have a convenient maintenance of screens, it has been found out that it is useful to install a 3-dimensional screen in cases of inflow from closed channels. In addition, a weir is installed in the facility to keep the stormwater runoff flowing into the facility. However, it was analyzed that if a weir was installed close to facility, the efficiency of the facility declined, and maintenance cost increased. Therefore, the weir should be installed 1–2 m away from the facility to optimize the efficiency and ease of maintenance. Meanwhile, the optimum linear velocity analyzed in the filtration-type facility was around 25–30 m^3/h. Replacement of filter media is desirable every year during March. Dredging of the surface of the filter media is necessary because there was clogging due to particulate matters during huge storm events during the summer season. After replacement of media, 1050 mm of cumulative rainfall is needed for dredging of filter media. Furthermore, an analysis to identify the optimum thickness of filter media in the filtration type facility was conducted, and it was found out that more than 0.7 m of thickness of filter media is preferable. The results of the research serve as important guidelines or basis whenever designing an NPS facility. In line with this, this will contribute to the cost-effectiveness and enhancement of treatment facility of future NPS facilities.

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