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Full-scale evaluation of organic matter removal in riverbank filtration in Korea

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ABSTRACT

Since 1998, both small-scale and full-scale riverbank filtration (RBF) has been introduced in South Korea to secure a stable supply of water. From 2015, a full-scale RBF plant has been in operation with a collector well capacity of 44,900 m^3/d, which is the largest in South Korea and one of the largest RBF facilities in the world. From the analysis, 58%~59% of the natural organic matter (NOM) was removed from the river water through the RBF process and the hydrophobic organic carbon content was increased from 3%–5% to 11%–17%. Aromatic compounds, building blocks, and neutral components with a molecular weight of 350–1,000 g/mol were not removed as efficiently as those with lower molecular weight. Therefore, if there is a high content of those components, the removal rate of NOM during the RBF process could decrease. There was not a significant difference in NOM removal in the laterals to depth. The results of this study are in accordance with previous research. The removal of NOM generally occurs during the first several meters on the boundary of the river/aquifer. The total organic carbon (TOC) concentration in the filtrated water fluctuates with the TOC in the river water. This resource is judged to be "groundwater under the direct influence of surface water", and additional water treatment is mandatory after RBF to ensure the safety for potable use.

Keywords: Riverbank filtration; NOM; Organic carbon; BOD; COD

1. Introduction

Riverbank filtration (RBF) is used worldwide to supply water for potable and non-potable uses and has a relatively low environmental impact and low cost [1–3]. By 2015, there were 515 water treatment plants in South Korea, of which 35 are advanced water treatment plants currently in operation and 6 are under construction. Facilities with advanced water treatment are installed at river systems which have taste and odor problems and evidence of organic micro pollutants, although there is some debate about the effectiveness of RBF systems in these conditions. There are disputes around continuous or intermittent operation and there are no standard operational criteria. Regardless, there is an increasing demand for new water treatment systems that are economical and capable of continuous operation. Also, water treatment systems are required to treat emerging contaminants. There is a demand for water treatment systems that can shorten the water treatment process and curtail treatment costs. There is a growing interest in a novel

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technology called managed aquifer recharge. Since 1998, both small-scale and full-scale RBF was introduced in South Korea to secure a stable supply of water. From 2015, a full-scale RBF plant has been in operation with a collector well capacity of 44,900 m^3/d, which is the largest in South Korea and one of the largest RBF facilities in the world. RBF water includes a combination of river water and groundwater. The flow contribution rate is determined by the hydrogeological characteristics of the study area, hydrological properties of the river, and design of the RBF facility. The effectiveness of water quality improvement of RBF depends on factors such as design, raw water quality, and aquifer properties [1,4–6]. Grischek et al. [7] showed that the removal efficiency of organic matter is influenced by a change in the prevailing redox conditions. According to Drewes and Fox [8], natural organic matter (NOM) in raw water consists of reactive organic matter, which contains a significant level of dissolved organic carbon (DOC) that influences disinfectant demand, disinfectant by-product (DBPs) formation, and coagulant demand. RBF is a low-cost technology that utilizes natural percolation processes to treat raw water from lakes, rivers, or reservoirs, and is an example of a multi-barrier water treatment process. Drewes [9] showed that easily biodegradable organic matter is effectively removed during the initial treatment phase, whereas longer travel times allow more time for attenuation of other biodegradable organic compounds. Sontheimer and Nissing [10] reported that particulate organic matter is removed efficiently in the initial stages. Also, the RBF system does not accumulate organic matter in the ground and showed steady performance in removing dissolved organic matter in river water [10]. The main subsurface removal process is DOC biodegradation. The strata are supplied with dissolved oxygen through the percolation of the water percolating under the river bed and diffusion. The consistent percolating conditions in RBF systems create a special biological activated filter layer at the interface of the water and deposits, where most of the organic matter is removed [11]. Drewes and Fox [8], Gary et al. [12] and Kivimaeki et al. [13] observed the highest rate of removal of DOC and total organic halogens in the first 1 m of percolation. Wang [14] stated that the removal of NOM predominantly occurs in the first 15 m of percolation. The average removal rate of DOC in RBF in the Rhine River in Europe is about 50. The average removal rate of DOC using RBF in the Ohio, Wabash, and Missouri rivers in the United States is reported at 50%–60% [15,16]. In Korea, river water is used as a freshwater resource and specialized additional water treatment processes are required. Should the organic matter be removed from the raw water effectively during the intake of water resources before chlorination, the formation of DBPs can be minimized. Where the organic matter content is high, and the dissolved oxygen is low, anaerobic conditions will be created during the RBF process, and iron and the manganese dissolution will occur along the RBF passage. Generally, RBF filtration lowers the DOC content, reduces contaminants in drinking water, and extends the life of the activated carbon filter bed. Moreover, RBF decreases the formation potential of the precursors to DBPs. In this study, we evaluated a full-scale RBF system in Korea by monitoring the removal efficiencies of organic matter over time and investigated the RBF attenuation mechanism of organic matter.

Table 1
Technical data of LC-OCD systems

Environment temperature	20°C~30°C (25°C recommended)
UV-Lamp zero water reactor	990 V/80 mA
UV-Lamp thin film reactor	2,000 V/40 mA
Carrier gas	Nitrogen 4.0 or 5.0, about 20 L/h
Mobile phase	Phosphate buffer 28 mmol, pH 6.58, about 2 L/24 h
Acidification solution	Phosphoric Acid pH 1.5, about 0.5 L/24 h
Measuring range TOC	10~5,000 μg/L
Detection limit TOC	2~10 μg/L
Detection limit LC-OCD	5~50 μg/L (per compound)

2. Material and methods

2.1. Location of facility

The RBF facility in this study is located in B river, in Gyeongsangnam-do Province and comprises a horizontal collector well with a capacity of 44,900 m^3/d. The diameter and the depth of the caisson are 6.0 and 37.4 m, respectively. Ten lateral wells with an internal diameter of 300 mm and a length of 80 m were installed. Laterals are structured in 3 layers: 3 laterals are at the sand layer below EL. –20.5 m, 3 layers are located in the secondary gravel layer is gravel below EL. –22 m and 4 laterals are located below EL. –23 m. Screens with an external diameter of 450 mm were installed in the 3 laterals in the sand layer and 5 laterals in the gravel layer. Laterals are oriented toward the semicircle of the stream. The laterals are installed at 7.5°–37.5° apart. There are 28 monitoring wells; 11 of these are installed in cardinal points around the horizontal collector well. Five of the monitoring wells are installed around the river bank. The operational water level is EL. –12 m based on the design capacity, and EL. –21 m based on the maximum yield capacity of 64,390 m^3/d.

2.2. Natural organic matter

2.2.1. Liquid chromatography organic carbon detection analysis

To analyze NOM, a liquid chromatography organic carbon detection (LC-OCD) system was used (Table 1). This system was manufactured by DOC-LABOR DR HUBER in Germany, model number 13. The system consists of an auto-injector, size exclusion chromatography-based column, and thin-film reactor (TFR); oxidized components are divided from the column into a UV254 detector and non-dispersive infrared (NDIR) CO_2 detector. Fig. 1 shows the schematic flow diagram and analytical conditions of the LC-OCD system. To measure organic carbon concentration, potassium hydrogen phthalate was dissolved in distilled water. Potassium peroxodisulfate (Fluka 60489) was dissolved in distilled water and phosphoric acid (H_3PO_4 85%, Fluka 79620, USA) was added to manufacture the acid solution for the removal of inorganic carbon. A 0.028 mol/L

Table 2
Subjects of analysis and analytical cycle

Sample	Analytical subjects
River water	TOC, POC, DOC, HOC, CDOC, BOD, COD, NOM (Bio-polymer, Humic substances, Aromaticity, Mol-weight, Building blocks, Neutrals, Acids), Inorganic colloid, SUVA, BDOC
Filtrated water	TOC, POC, DOC, HOC, CDOC, BOD, COD, NOM (Bio-polymer, Humic substances, Aromaticity, Mol-weight, Building blocks, Neutrals, Acids), Inorganic colloid, SUVA, BDOC
Laterals	TOC, POC, DOC, HOC, CDOC, BOD, COD, NOM (Bio-polymer, Humic substances, Aromaticity, Mol-weight, Building blocks, Neutrals, Acids), Inorganic colloid, SUVA, BDOC
Monitoring wells (Inland)	TOC, POC, DOC, HOC, CDOC, BOD, COD, NOM (Bio-polymer, Humic substances, Aromaticity, Mol-weight, Building blocks, Neutrals, Acids), Inorganic colloid, SUVA, BDOC
Monitoring wells (Forceland)	TOC, POC, DOC, HOC, CDOC, BOD, COD, NOM (Bio-polymer, Humic substances, Aromaticity, Mol-weight, Building blocks, Neutrals, Acids)

phosphate buffer was produced by dissolving KH_2PO_4 (Merck 1.04873, USA) and $Na_2HPO_4{\cdot}2H_2O$ (Merck 1.06580, USA) in deionized-distilled water as the mobile phase solvent. To construct the UV254 calibration curve of LC-OCD, Suwannee River HA Std II (2S101H) and Suwannee River FA Std I (1S101F) (manufactured by IHSS) were dissolved in deionized-distilled water for the measurement. High-performance size-exclusion chromatography was used to separate components based on molecular weight. The compounds that were separated through the column were first measured using a UV254 detector, then combined with phosphate (pH 1.5), and finally, transferred to the TFR. Phosphate was used to remove the inorganic carbon. The inorganic carbon was removed through the top of the reactor by stripping the high purity nitrogen gas that was injected into the reactor. The organic carbon was transferred to the lower part by nitrogen gas, oxidized into CO_2 with a UV lamp that had a wavelength of 185 nm, and detected with an NDIR detector in real-time. The detected signal was converted into organic substance concentrations through a quantitative analysis program that had a molecular size detection limit of 5–50 μg/L. The NOM concentrations were calculated based on the area of the chromatogram peak. The FIFIKUS® program supplied by the LC-OCD manufacturer was used for the data processing and the results were converted to an Excel file. The NOM chromatogram measured by LC-OCD represents the characteristics of the samples. The first peak, about 20–40 min after the injection, involves a series of biopolymer peaks made up of organic colloid and protein, with a molecular weight of more than 20,000 g/mol. The second and third peaks represent humic materials and building blocks (polycarboxylic acid), which range from ~1,000 g/mol to 350~500 g/mol, respectively. The main component of the fourth peak is the organic acid of low molecular weight. The main components of the fifth peak include neutral and amphiphilic species (amino acid, alcohol, aldehyde, ketone, and others) with molecular weight less than 350 g/mol.

LC-OCD measures the mass of carbon which is in organic combination. Also, UV absorbance at 254 nm was measured. Analysis results were automatically classified into

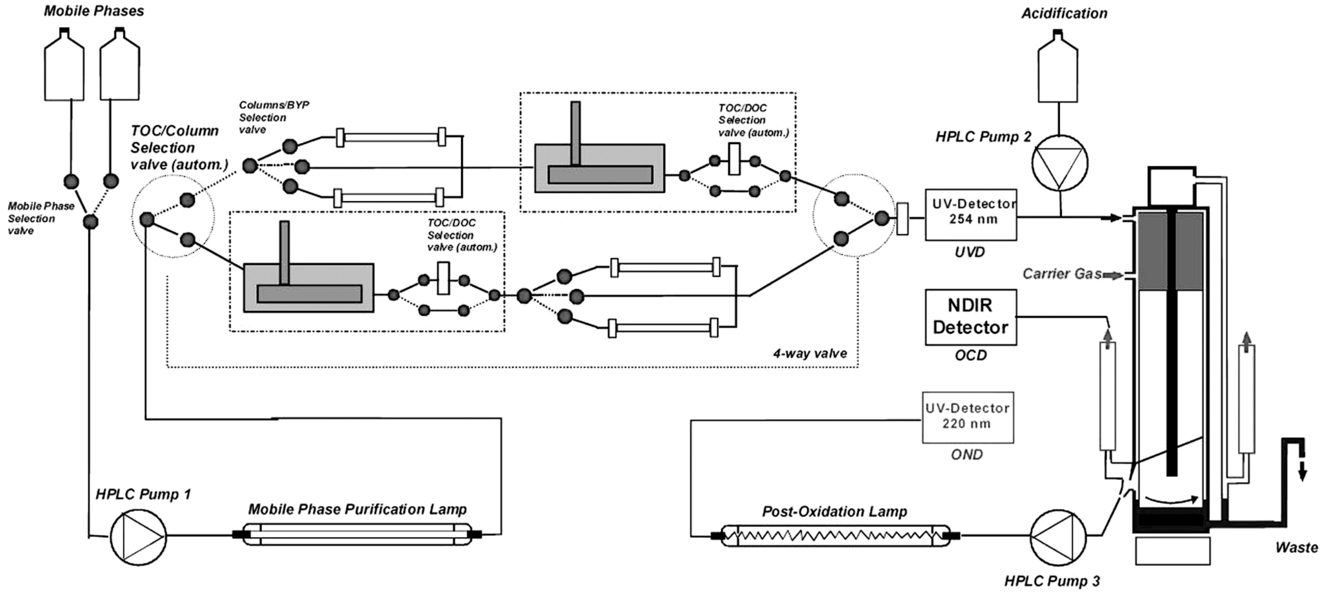

Fig. 1. Flow scheme of liquids in the LC-OCD system.

Table 3
Removal rate of organic matters (unit: %)

Section		BOD	COD	TOC	DOC
Total period	Maximum	74	88	65	63
	Minimum	–50	–107	0	–27
	Average	38	54	43	41
Initial stabilizing period (~6.10)	Maximum	71	74	56	60
	Minimum	–50	–107	45	46
	Average	11	–15	50	52
After stabilizing period (6.11~)	Maximum	74	88	65	63
	Minimum	18	–23	0	–27
	Average	46	60	41	39

total organic carbon (TOC), DOC, particular organic carbon (POC), hydrophobic organic carbon (HOC), and hydrophilic DOC, as shown in Table 2. Among these, hydrophilic DOC (or chromatographic dissolved organic carbon (CDOC)) was analyzed with its subdivisions, such as biopolymers, humic substances, building blocks, neutrals, and acids, and this category includes polysaccharides, low molecular weight organic acids, and low molecular weight neutrals. For the biodegradable dissolved organic carbon (BDOC) measurement, 1 ml of the source water was added to the sample for seeding of microorganisms, and the sample was incubated at approx. 25°C in the dark for 13 d. Afterward, it was filtered with a 0.45 μm membrane filter, and then the variation between the measured NOM concentration and the first NOM concentration was determined.

2.2.2. Other organic matter

The biochemical oxygen demand (BOD) was analyzed using the Standard Method 5210 B: 5 d BOD test and chemical oxygen demand (COD) was Standard Methods Part 5220 [17]. The DOC was analyzed after filtration using a 0.45 μm filter. TOC was analyzed using a TOC analyzer (SHIMADZU, Japan).

2.3. Analytical parameters

Analysis was conducted from May 7, 2015 to October 31, 2015; with monthly measurements of TOC, POC, DOC, HOC, CDOC, BOD, COD, NOM (Bio-polymer, Humic substances, Aromaticity, Mol-weight, Building blocks, Neutrals, Acids), Inorganic colloid, specific ultraviolet absorbance, BDOC for the filtrated water, river water, laterals, and monitoring wells.

3. Results and discussion

3.1. Natural organic matter

As shown in Fig. 2 and Table 3, the fraction of organic matter during the initial stage of the operation was compared with the fraction after 6 months of operation and no significant difference was observed. Moreover, in the case of river water, most of the organic matter was found to be NOM, consisting of humic substances (1,000–20,000 g/mol), building blocks (300–500 g/mol) and neutrals (~350 g/mol). The removal rate of TOC infiltrated water was 58% compared to river water at the initial stages of operation. After 6 months, the removal rate increased marginally to 59%. However, the contents of HOC increased from 3%–5% in river water to 11%–17% infiltrated water. These results differ from Zullei-Seibert [18] where hydrophilic organic matter was not efficiently removed, whereas hydrophobic matter. An investigation of NOM in the filtrated water showed a decrease in humic substances and an increase in building blocks and neutrals (~350 g/mol). The organic matter with large molecular weight is removed or degraded into smaller molecules during the RBF process. Particularly, 7%–9% of biopolymers in river water had a molecular weight of over 20,000 g/mol compared to 1% infiltrated water. This indicates that the NOM with larger molecular weight is mostly removed during the RBF process. In line with the findings of Kivimaeki et al. [13] and Gerlach and Gimbel [19], the fraction of maximum molecular weight in organic matter increased sharply as the collision efficiency increased. Therefore, a similar mechanism could occur at the initial stage of filtration. In the case of monitoring wells, inland of the HOC concentration was higher compared to the river water. Some amount of HOC is evident and the fraction of NOM in monitoring wells is similar to that of river water. From this, it is evident that there are analogous NOM components in the water in that area.

As presented in Fig. 3, the comparison of the removal rate of each organic carbon variation is as follows: For TOC, DOC, and CDOC, there was a removal rate of 50%–60% during the operation period. There was an increase in the removal rate of POC and HOC over time. The removal rate of organic matter, turbidity, algal particulates, and hydrophobicity increased over time. The removal rates of each part of NOM are shown in Fig. 4. Aromatic compounds, building blocks, and neutral components with a molecular weight of 350–1,000 g/mol were not removed as efficiently as those with lower molecular weight. Therefore, if there are high contents of those organic carbon variations, the removal rate of organic matter in the RBF process could decline.

3.2. Organic matter

The parameters of organic matter, BOD, COD, TOC, and DOC were analyzed. Analysis of the organic carbon fraction through LC-OCD was undertaken. As shown in Fig. 5, in the initial stages of operation, 50% of the organic carbon fraction was removed. Over time, the removal rate decreased and later showed a fluctuating profile, indicating destabilizing in the removal mechanism of organic matter. The profile of the COD removal rate was different owing to the analytical method that contributed to the oxidation of iron and manganese in the filtrated water. The profiles of BOD, TOC, and DOC are similar, and these values are regarded as the representative profile for organic matter. The average and maximum values for the removal rate to the time of operation are presented in Table 4. The negative minimum value is due to the difference in retention time on strata of river water and filtrated water. Where there are severe changes in water quality, as was evident in this study, there is a high possibility of significant errors in the result when calculating the removal rate based on water quality data, owing to the mixing of river water with groundwater.

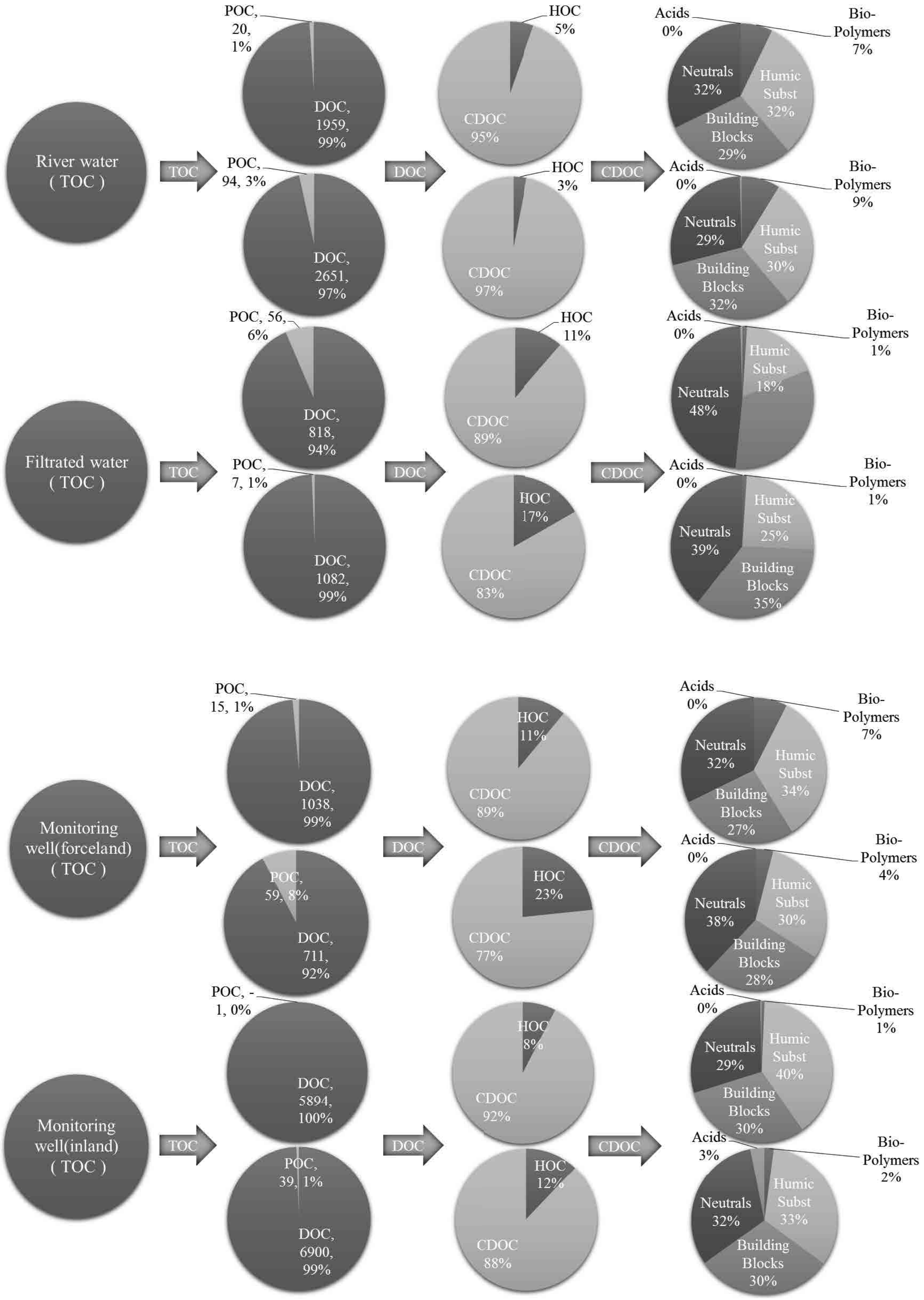

Fig. 2. Partitioning of organic carbon variations in May and October.

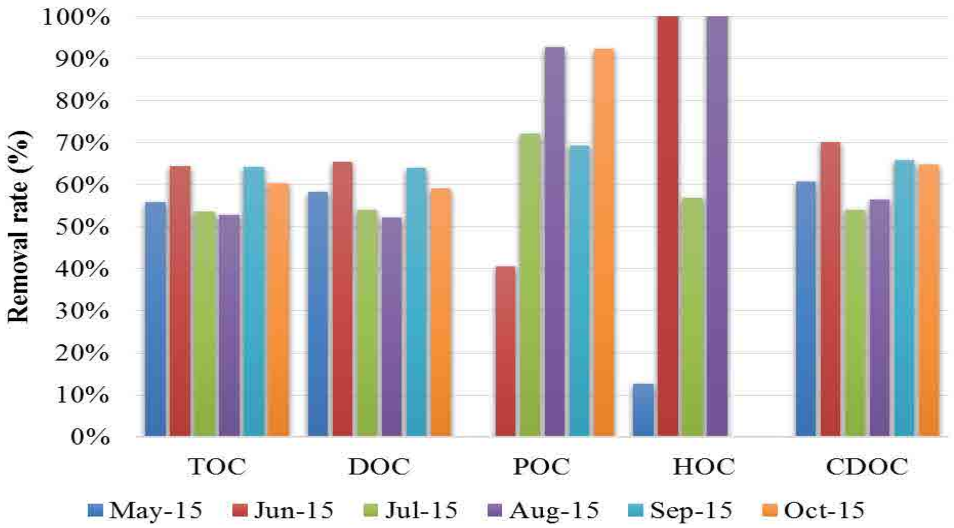

Fig. 3. Removal rate of OC contents.

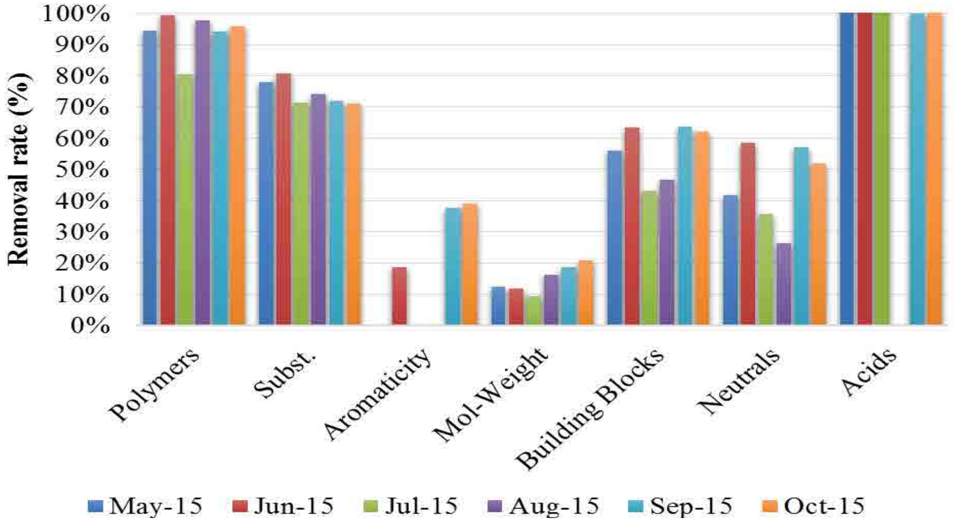

Fig. 4. Removal rate of NOM.

Thus, the removal efficiency presented in this study is based on the profile of the organic matter. There could be limitations when applying the removal rate in a closed system.

3.3. Biochemical oxygen demand

As presented in Figs. 6 and 7, the BOD of filtrated water corresponded with that of river water after a month during the initial stabilizing period. The average BOD concentration in river water was 2.4 mg/L and 1.4 mg/L infiltrated water with a removal rate of 44% during the time of operation. The monitoring well at force-land around the horizontal collector well, showed a high BOD concentration, possibly due to increased turbidity during sampling. The higher BOD concentration in the laterals in the initial period could be due to the sampling of stagnant water. After normalization of pumping (sampled after an extended period of draining water), the BOD in the laterals corresponded with the results of the filtrated water. Also, a part of the laterals, lateral (middle_1), showed high BOD concentration, indicating that the position of the laterals influences the water quality.

As mentioned previously, the results for BOD until the end of August lack reliability due to the problem of sampling in the individual laterals, however, the results of the laterals are compared to strata and depth. The concentration of BOD values to depth is shown in Table 5.

As presented in Fig. 8, the deviation in the concentration of BOD to depth is clear as the BOD in the river water increased dramatically according to data from October 21. As the BOD in the river water increased rapidly, so the BOD concentration in the laterals also increased in sequence, from the middle (2.7 mg/L), lower (2.1 mg/L), to upper layer (1.6 mg/L). This result corresponds with the earlier research of Grischek et al. [7] where, generally, removal of organic

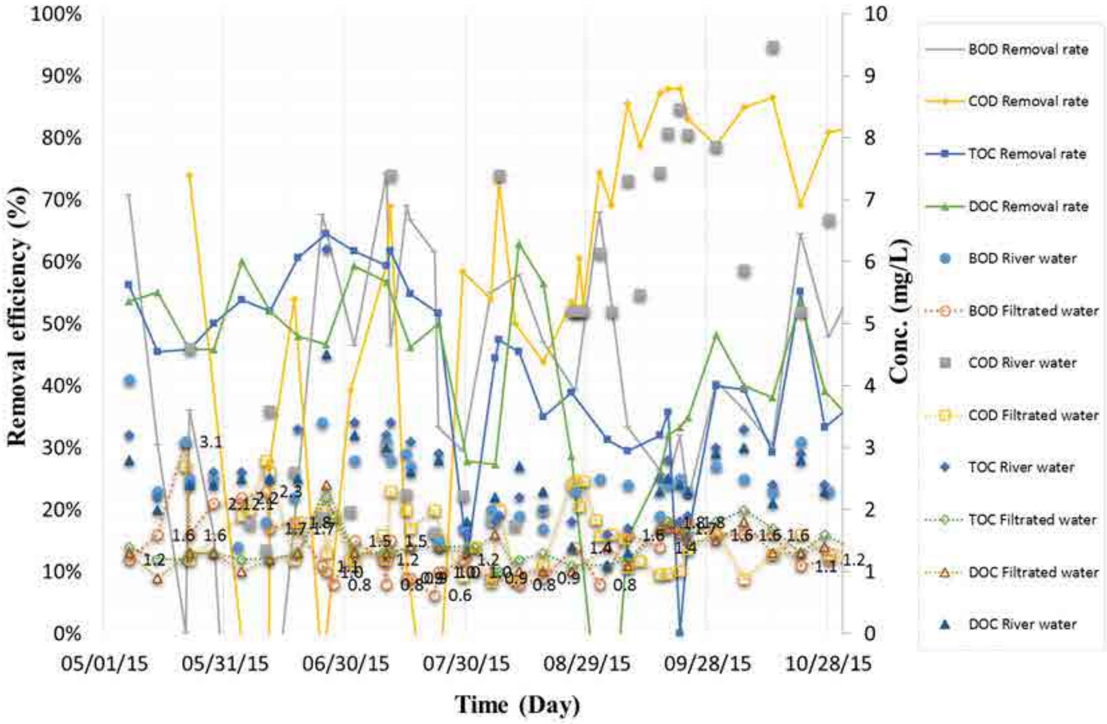

Fig. 5. Organic matter concentration profile at filtrated water and river water.

Table 4
BOD concentration profile with respect to depth (unit: mg/L)

Section	Filtrated water	River water	Laterals (upper)	Laterals (middle)	Laterals (lower)
Minimum	0.6	1.0	0.7	1.3	1.0
Average	1.4	2.3	1.7	2.0	1.9
Maximum	3.1	4.1	4.2	3.4	3.8
Minimum (5.7~6.15)	1.2	1.4	1.3	1.5	1.6
Average (5.7~6.15)	2.0	2.5	1.5	1.6	1.7
Maximum (5.7~6.15)	3.1	4.1	1.6	1.7	1.7
Minimum (6.16~)	0.6	1.0	0.7	1.3	1.0
Average (6.16~)	1.2	2.3	1.8	2.0	1.9
Maximum (6.16~)	1.8	3.4	4.2	3.4	3.8

matter occurs in the very first meter on the boundary of the river/aquifer. Moreover, the difference in water quality in the laterals to depth was not distinct.

As presented in Fig. 9, the three laterals in the upper layer showed very similar results for the BOD concentration of filtrated water after normalization of yield. Therefore, the upper layer of laterals was not influenced by changes in the concentration of BOD in the river water.

As presented in Fig. 10, the BOD concentration in the middle lateral (middle_1) is relatively high and destabilized, even after normalization in sampling. According to Verstraeten et al. [20], this may be due to the formation of preferential flow paths, geomorphic problems near forceland, or construction problems. This problem needs to be investigated with more long-term observations in both direct/indirect field studies.

As presented in Fig. 11, the BOD concentration in the lower laterals (lower_2) is relatively high with a destabilized profile, which may be due to sampling problems before August. After September, there were unknown influences like analytical errors or stained specimens that temporarily resulted in high concentration measurements. It is assumed that BOD in the lower laterals was not at a higher concentration than the river water.

3.4. Chemical oxygen demand

As presented in Fig. 12, the COD in the river water increased rapidly after the flood season and entering the dry season. However, the COD infiltrated water had an average concentration of 1.6 mg/L (0.8~2.8 mg/L), with no significant changes. In the case of COD, the high concentration

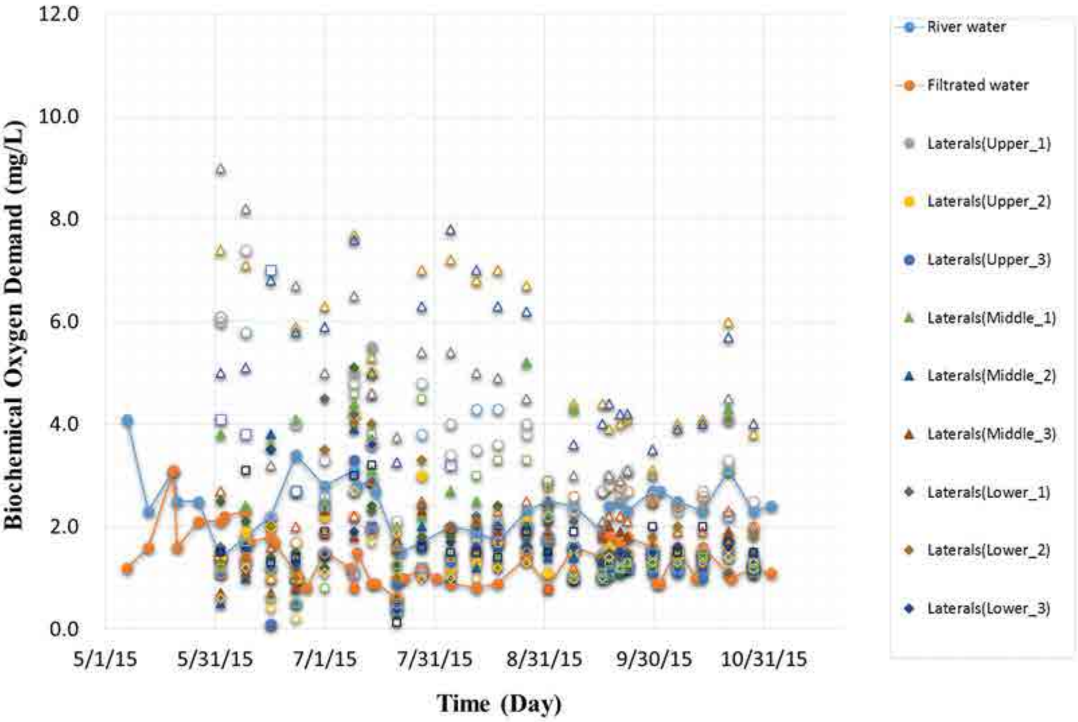

Fig. 6. BOD concentration profile.

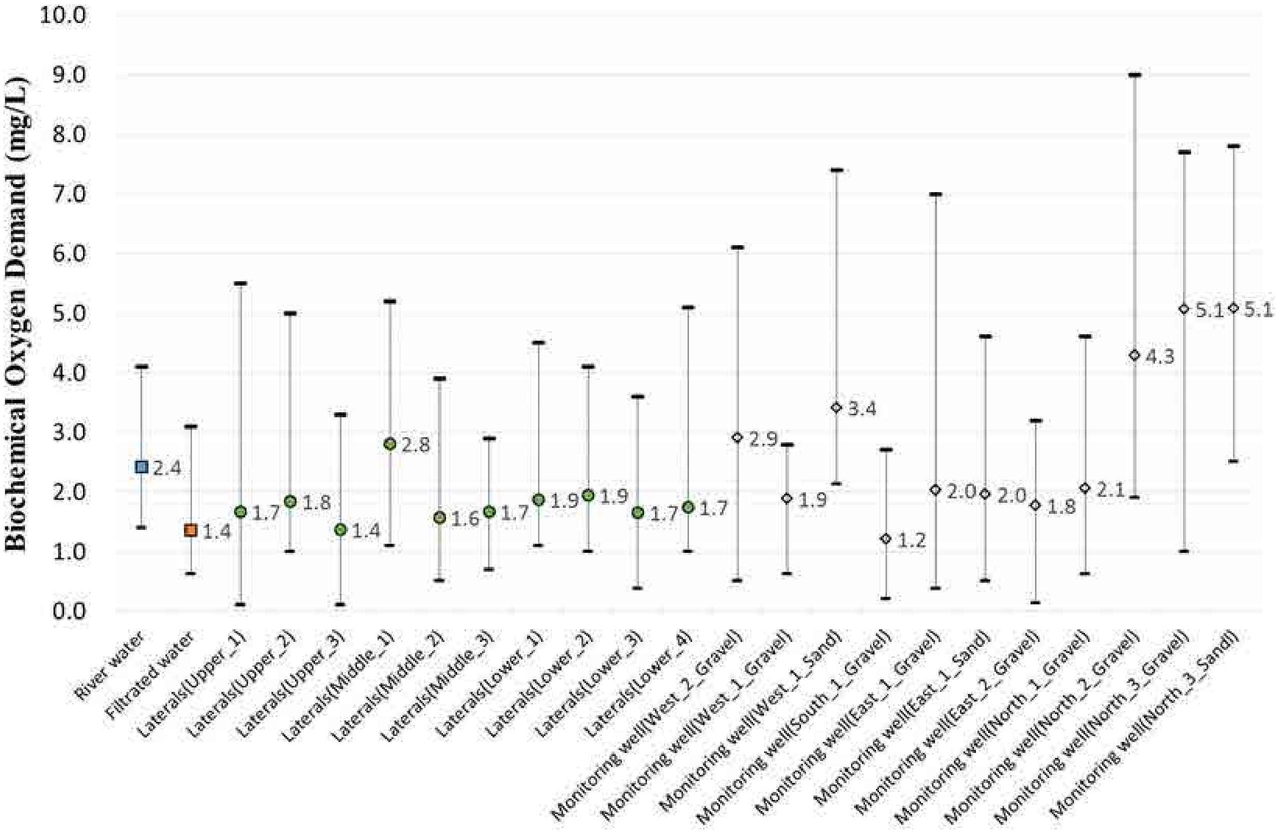

Fig. 7. Deviation of BOD concentration.

Table 5
COD concentration profile with respect to depth (unit: mg/L)

Section	Filtrated water	River water	Laterals (upper)	Laterals (middle)	Laterals(lower)
Minimum	0.3	1.4	0.8	0.9	1.0
Average	1.4	5.0	1.4	1.5	1.3
Maximum	2.7	9.5	3.0	2.5	2.3
Minimum (5.7~6.15)	0.5	1.4	1.0	1.3	1.2
Average (5.7~6.15)	1.7	2.8	1.2	1.3	1.3
Maximum (5.7~6.15)	2.7	4.6	1.5	1.3	1.3
Minimum (6.16~)	0.3	1.8	0.8	0.9	1.0
Average (6.16~)	1.4	5.3	1.5	1.5	1.3
Maximum (6.16~)	2.5	9.5	3.0	2.5	2.3

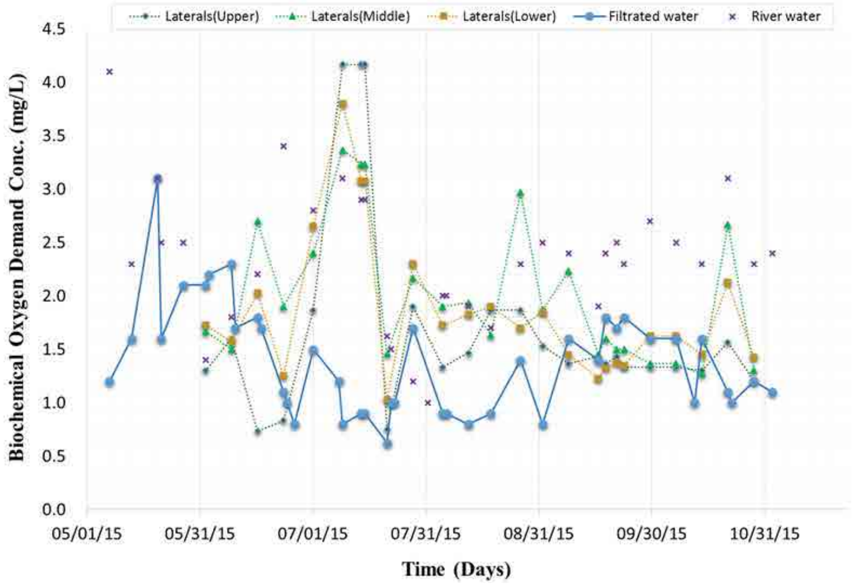

Fig. 8. BOD concentration profile with respect to depth in river water and horizontal collector well (average).

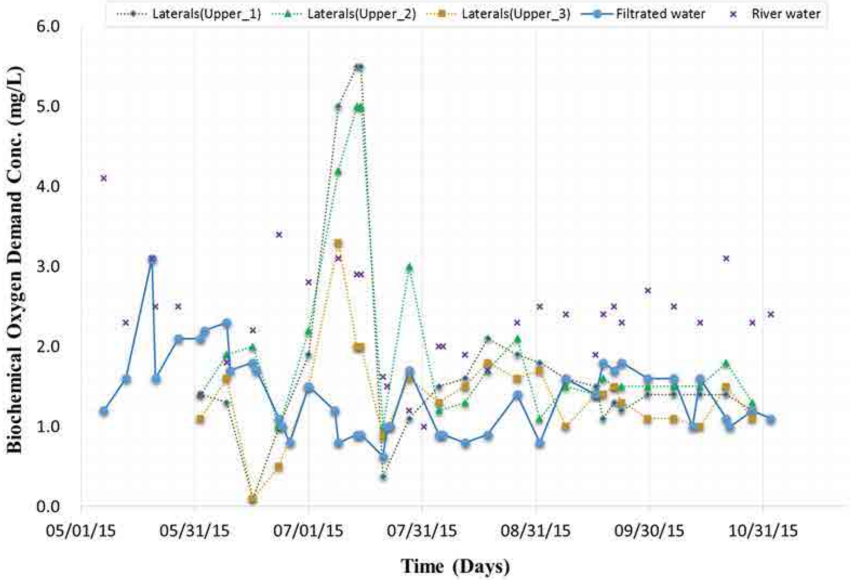

Fig. 9. BOD concentration profile with respect to depth in river water and horizontal collector well (upper layer).

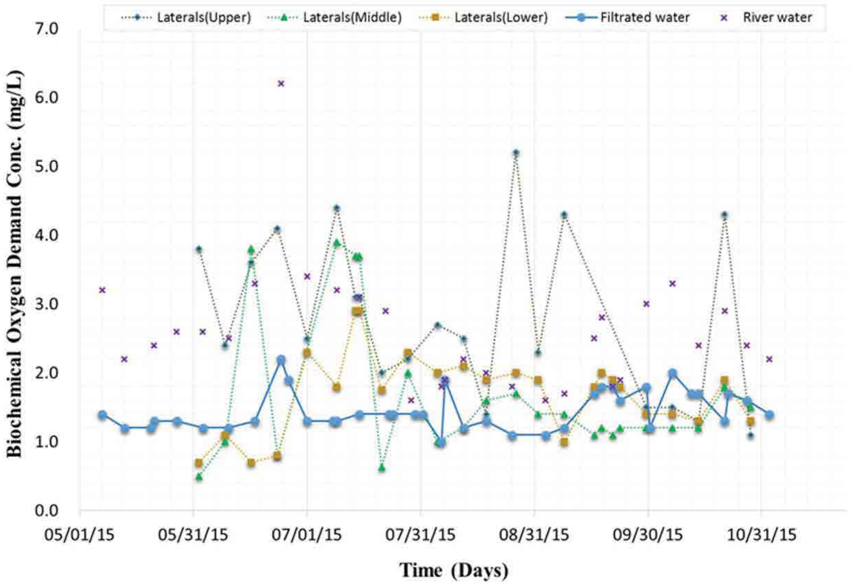

Fig. 10. BOD concentration profile with respect to depth in river water and horizontal collector well (middle layer).

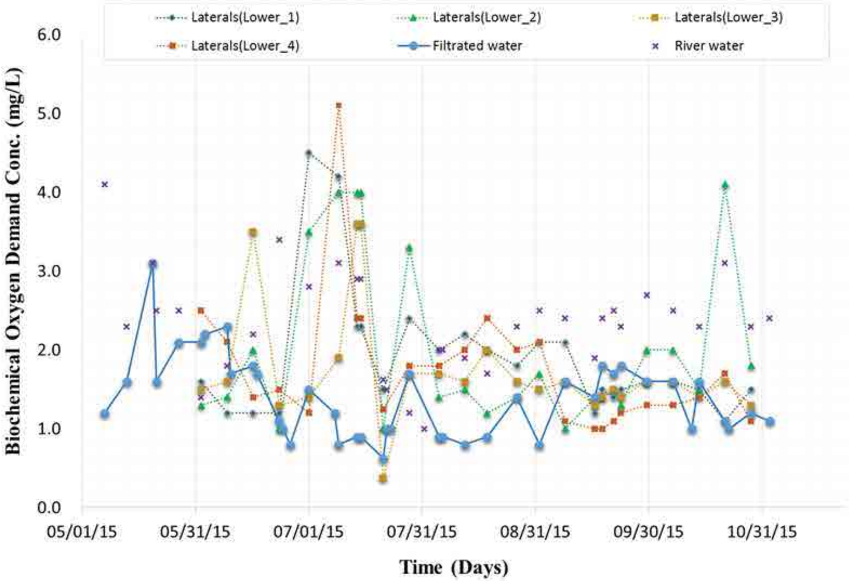

Fig. 11. BOD concentration profile with respect to depth in river water and horizontal collector well (lower layer).

Table 6
TOC concentration profile with respect to depth

Section	Filtrated water	River water	Laterals (upper)	Laterals (middle)	Laterals(lower)
Minimum	1.0	1.0	0.9	1.0	0.9
Average	1.5	2.6	1.3	1.6	1.3
Maximum	2.2	6.2	1.6	2.3	1.8
Minimum (5.7~6.15)	1.2	2.2	1.3	1.8	1.3
Average (5.7~6.15)	1.3	2.6	1.5	2.0	1.6
Maximum (5.7~6.15)	1.4	3.2	1.5	2.3	1.8
Minimum (6.16~)	1.0	1.0	0.9	1.0	0.9
Average (6.16~)	1.5	2.5	1.2	1.5	1.3
Maximum (6.16~)	2.2	6.2	1.6	1.8	1.6

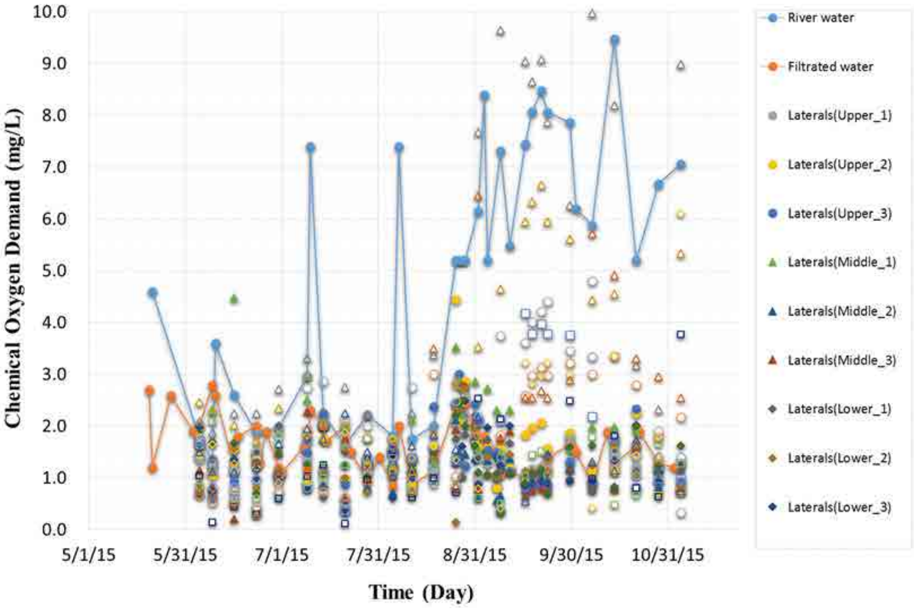

Fig. 12. COD concentration profile.

Table 7
DOC concentration profile with respect to depth (unit: mg/L)

Section	Filtrated water	River water	Laterals (upper)	Laterals (middle)	Laterals(lower)
Minimum	0.9	1.1	0.5	0.5	0.4
Average	1.4	2.4	1.1	1.3	1.1
Maximum	2.4	4.5	1.3	1.7	1.4
Minimum (5.7~6.15)	0.9	2.0	1.2	1.5	1.2
Average (5.7~6.15)	1.2	2.4	1.2	1.6	1.3
Maximum (5.7~6.15)	1.3	2.8	1.3	1.7	1.3
Minimum (6.16~)	1.0	1.1	0.5	0.5	0.4
Average (6.16~)	1.4	2.4	1.1	1.2	1.0
Maximum (6.16~)	2.4	4.5	1.3	1.6	

of iron contained in the filtrated water during the analysis process led to over-consumption of the oxidizer. Therefore, the result was calculated using the standard method with revised oxidizer consumption.

As the COD in the river water increased, the COD in the monitoring wells also increased. In the case of the Nakdong river, the COD increased during the flood season and decreased in the dry season. During the test operation period, the average concentration of COD in river water was 5.0 mg/L (1.4–9.5 mg/L), which was identical to the BOD. The average COD concentration in the middle lateral (middle_1) was 2.1 mg/L, which was high compared to the other laterals, as shown in Fig. 13.

The removal rate of COD showed fluctuation in the initial operation period, as shown in Fig. 14. However, the profile of COD concentration infiltrated water stabilized even when the COD concentration in the river water increased sharply after September. The trend in concentration in certain laterals to a depth that was observed in BOD was not observed in COD. Thus, inorganic matter with high rates of biological decomposition, the concentration of COD and removal efficiency differs from depth, in contrast to those that oxidize chemically.

As presented in Figs. 15–17, there is no difference in average COD concentration to depth and no difference between individual laterals.

3.5. Total organic carbon

The TOC infiltrated and river water also showed a similar profile to that of BOD, as shown in Table 6. When the TOC in river water increases temporarily, the filtrated water also increased temporarily, as shown Figs. 18–19. This means that river water can directly influence the concentration of organic matter infiltrated water regardless of other factors. This phenomenon can be explained by “the groundwater under the direct influence of surface water” (GWUDISW) (U.S. EPA, 2000) [21], for which additional

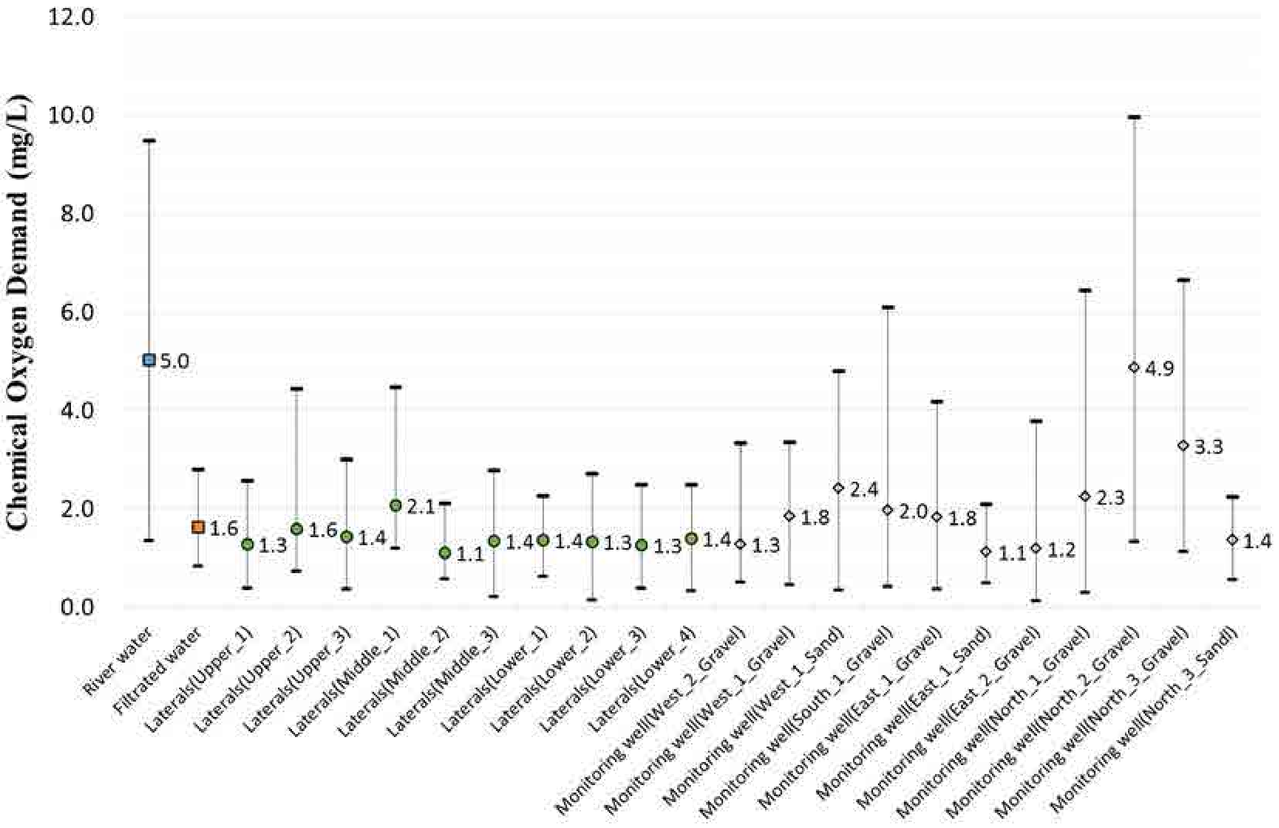

Fig. 13. Deviation of COD concentration.

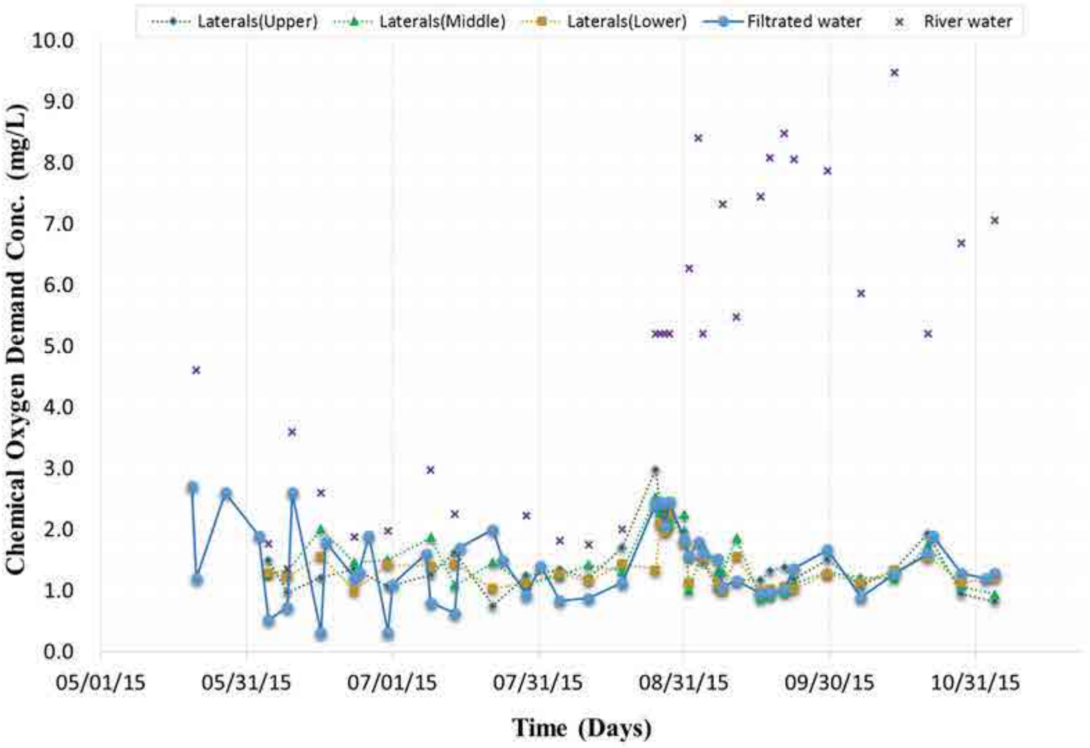

Fig. 14. COD concentration profile with respect to depth in river water and horizontal collector well (average).

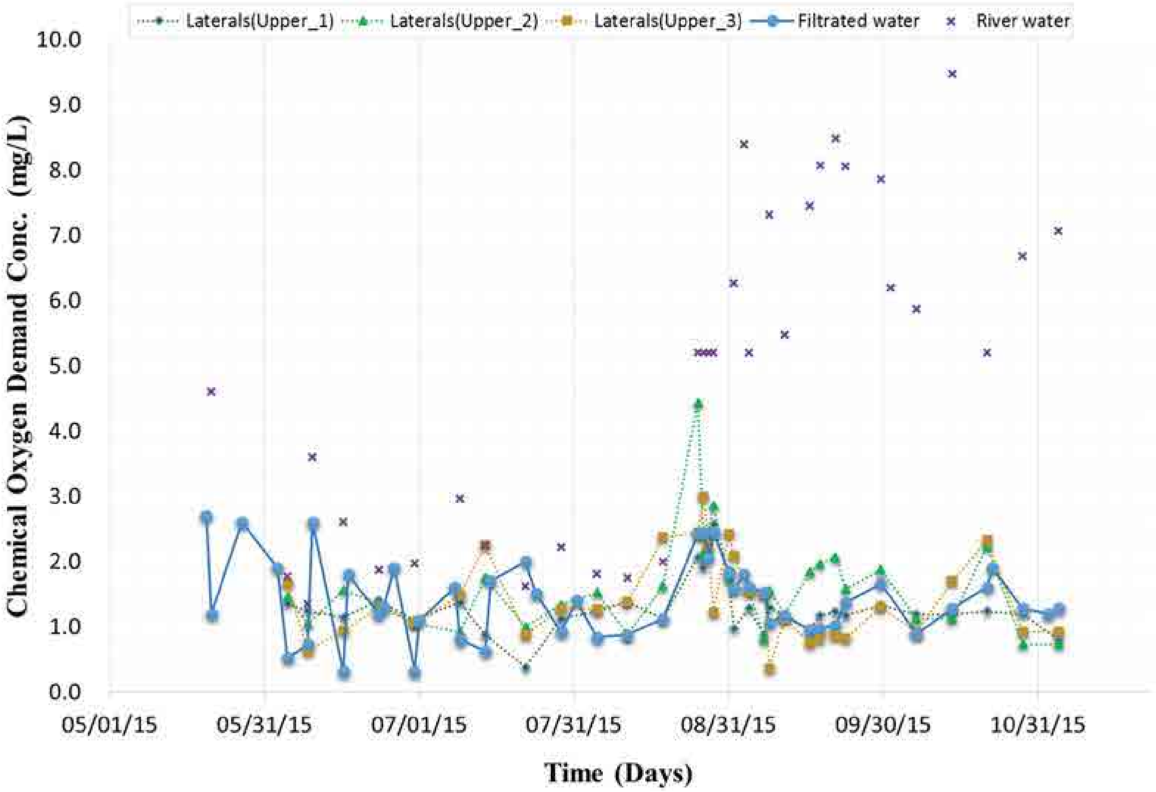

Fig. 15. COD concentration profile with respect to depth in river water and horizontal collector well (upper layer).

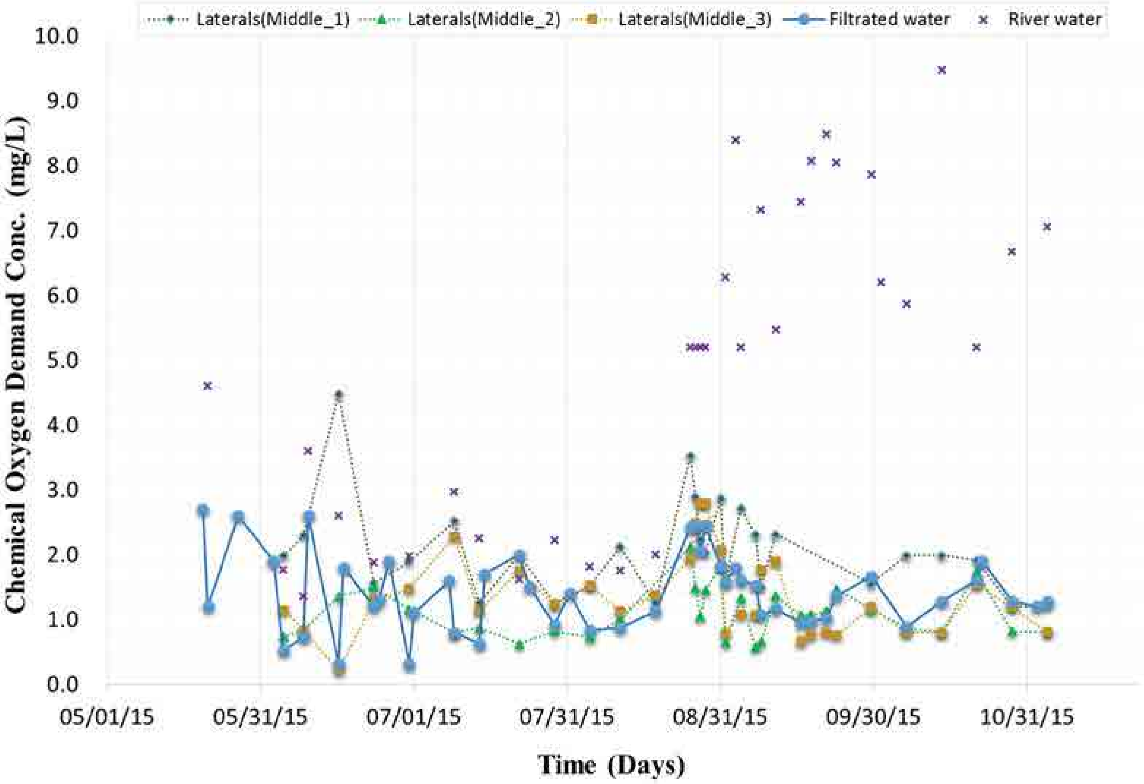

Fig. 16. COD concentration profile with respect to depth in river water and horizontal collector well (middle layer).

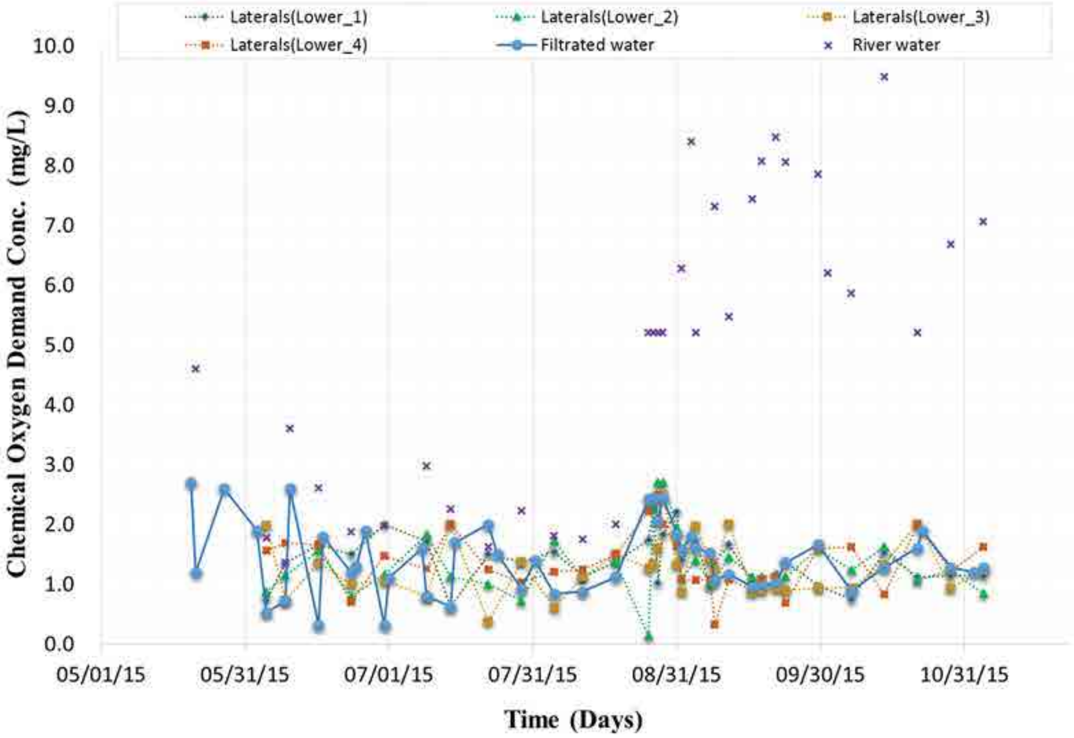

Fig. 17. COD concentration profile with respect to depth in river water and horizontal collector well (under layer).

water treatment must be implemented in the United States in terms of the proposed Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR). This applies to public water-supply systems that use either surface water or GWUDISW as their raw-water source [20]. In terms of the proposed rule, systems with *Cryptosporidium* concentrations greater than 0.075 oocysts per liter (oocysts/L) must implement additional treatment [21]. Monitoring wells North #2 and #3 adjacent to the force-land showed high TOC concentrations due to the consistent influx of organic matters from inland with high TOC concentration. The average TOC concentration of river water was 2.6 mg/L (1.6–6.2 mg/L) and 1.4 mg/L (1.0–2.2 mg/L) infiltrated water during the test operation period.

The concentration of TOC, as with COD, showed very stabilized concentration without intersecting with the TOC concentration of river water over the operational period. However, in the case of the laterals, only middle_1 (as shown in Fig. 20) presented a very high TOC concentration in the initial operation period. Though the TOC concentration reduced consistently over time, the TOC concentration remained higher than the other 9 laterals after 6 months of operation, as shown in Figs. 21–23. This trend was also evident in the BOD concentration profile pointing to a similar cause.

3.6. Dissolved organic carbon

As presented in Fig. 24, the DOC has a similar profile to that of TOC. The fraction of TOC and DOC is 93% (70%–100%) in the filtrated water, due to the removal of most particulate organic matter by filtration, sorption, and biodegradation during passage through the strata.

Although the profile of DOC is similar to TOC, as shown in Table 7, the profile was found to be more obvious in DOC. Monitoring wells North #2 and #3 adjacent to the force-land showed high DOC concentrations, due to the consistent influx of organic matters from inland with high TOC concentration. During the test operation period, the average DOC concentration in the river water was 2.4 mg/L (1.1–4.5 mg/L) compared to 1.4 mg/L (0.9–2.4 mg/L) infiltrated water, as shown in Fig. 26.

Compare to the other parameters of organic matter, the DOC profile was related to the DOC concentration of river water. After temporary discontinuation of operation at the middle lateral (middle_1), the other laterals showed a decrease in DOC concentration, however, the concentration of filtrated water from all the laterals did not decrease, as shown in Figs. 27–29.Analyzing the cause of this phenomenon is not considered possible based on the data.

4. Conclusions

In this study, the behavior of organic matter in an RBF facility with a full-scale horizontal collector well was analyzed. The results of the study are as follows:

- The initial NOM removal rate was 58% infiltrated water compare to the river water. After 6 months, the removal rate slightly increased to 59%.
- Following RBF, the HOC increased from 3%–5% in river water to 11%–17% infiltrated water. This result differs from the findings of Zullei-Seibert [17] where the removal efficiency of HOC (e.g. Dichloro-Diphenyl-Trichloroethane, heptachlor and diuron) exceeded that of hydrophilic organic matter.

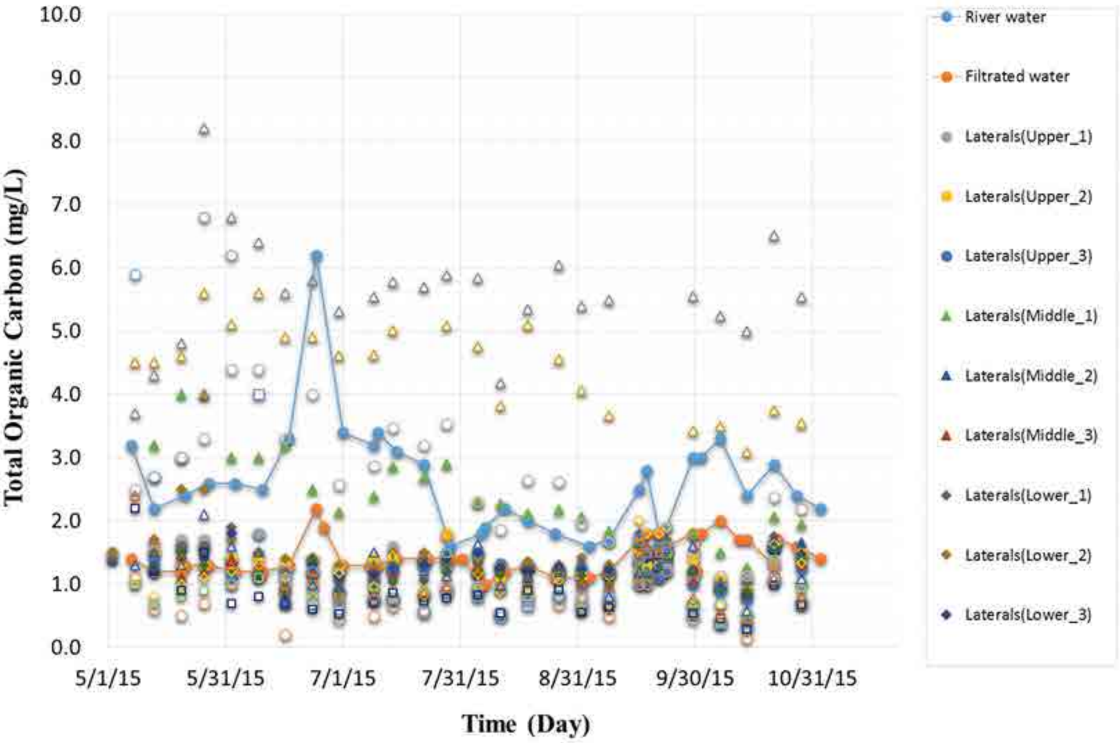

Fig. 18. TOC concentration profile.

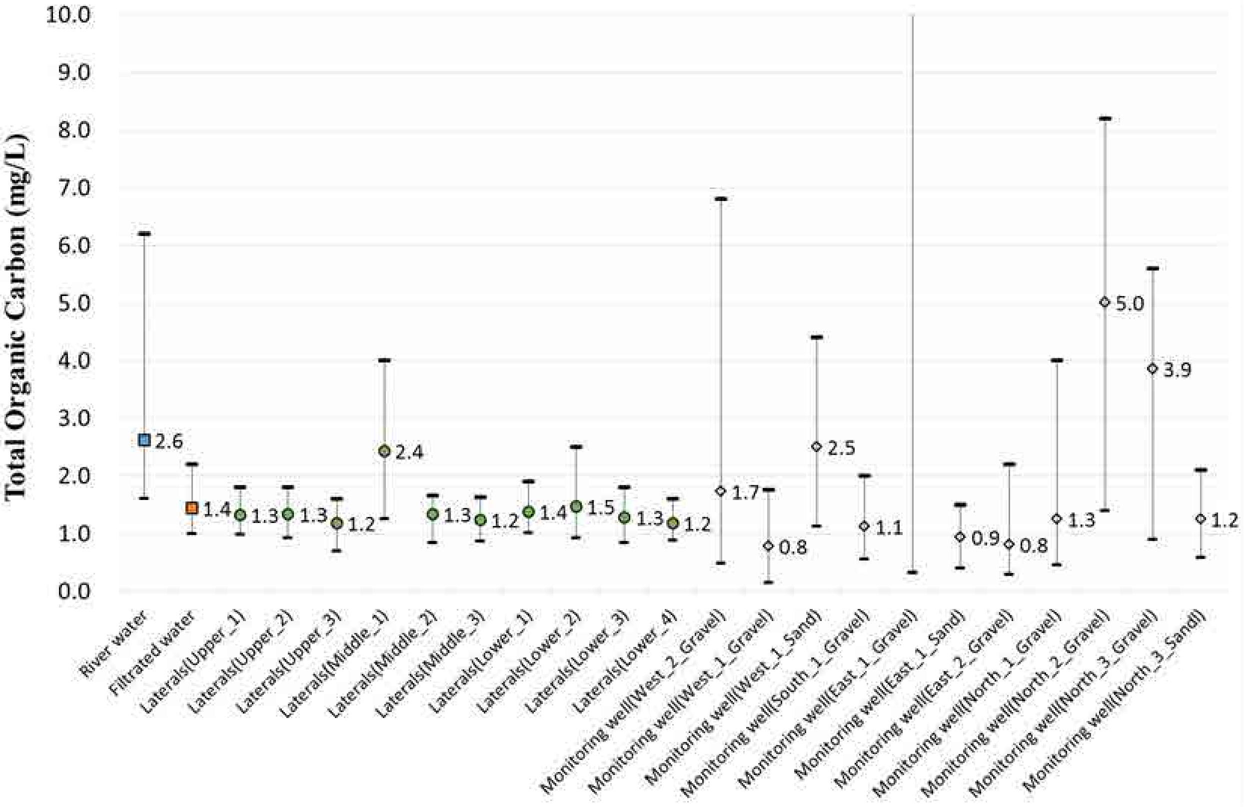

Fig. 19. Deviation of TOC concentration.

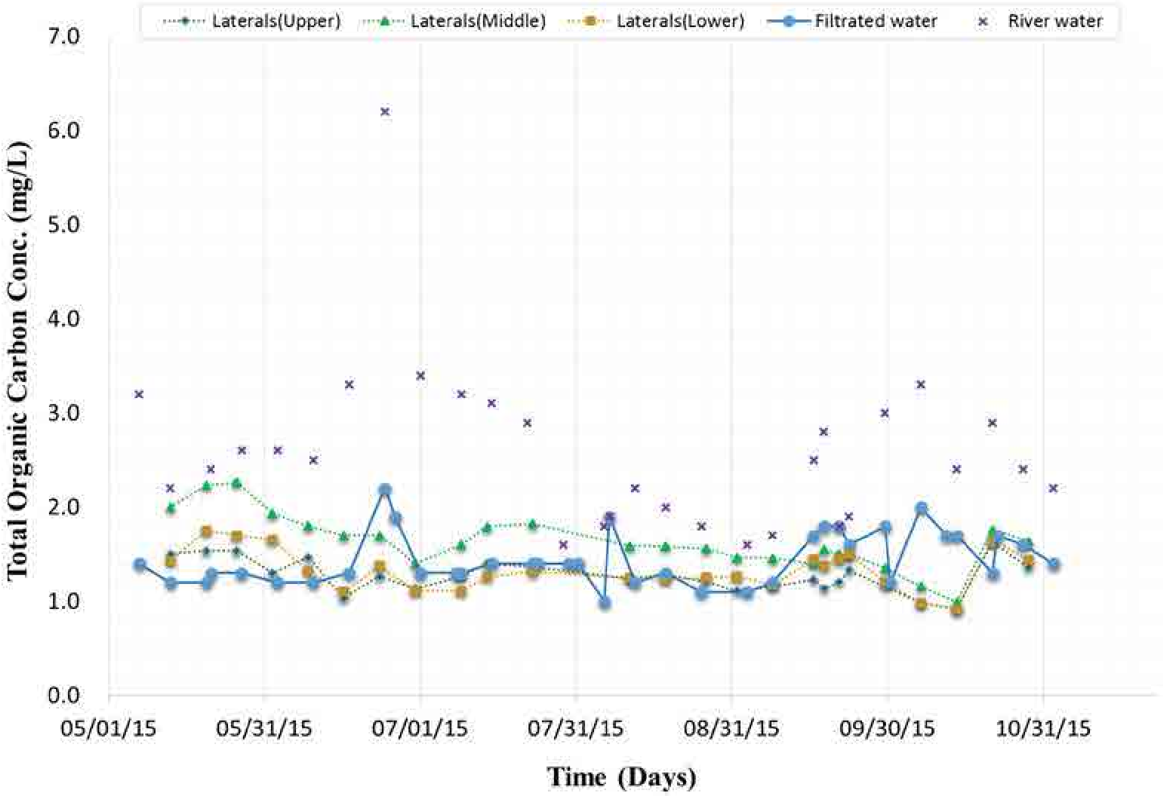

Fig. 20. TOC concentration profile with respect to depth in river water and horizontal collector well (average).

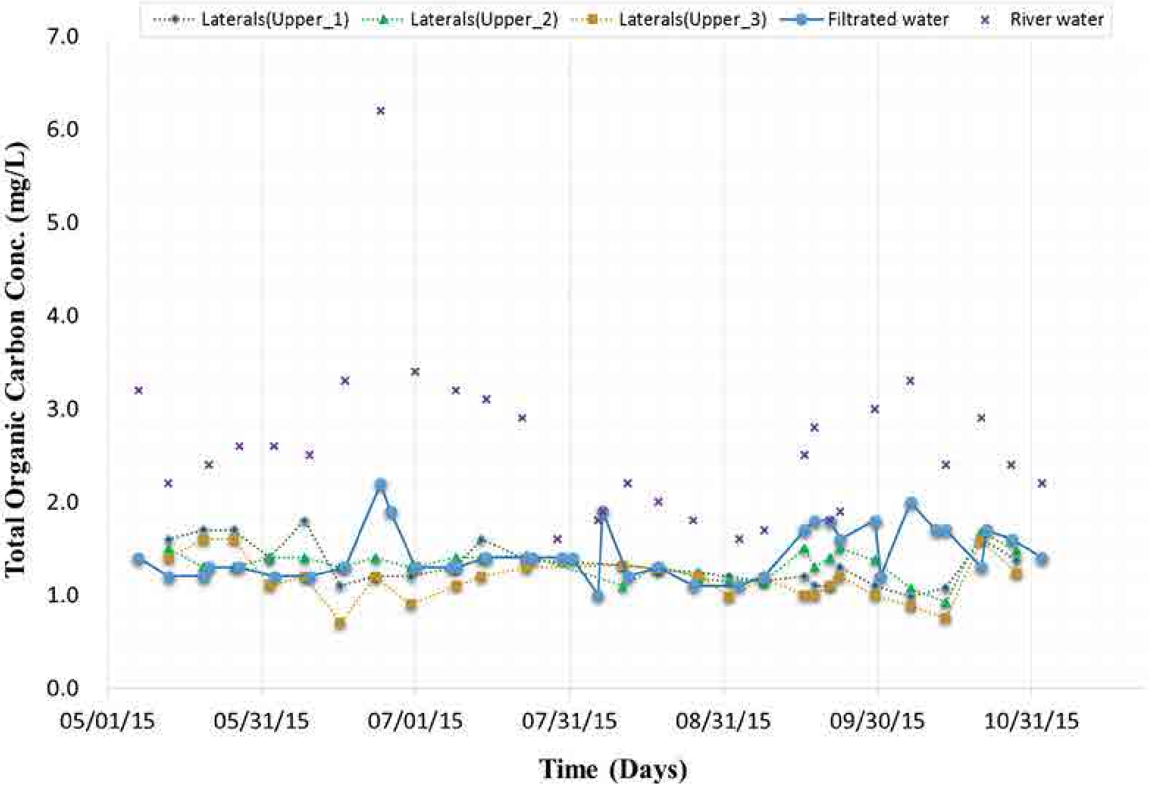

Fig. 21. TOC concentration profile with respect to depth in river water and horizontal collector well (upper layer).

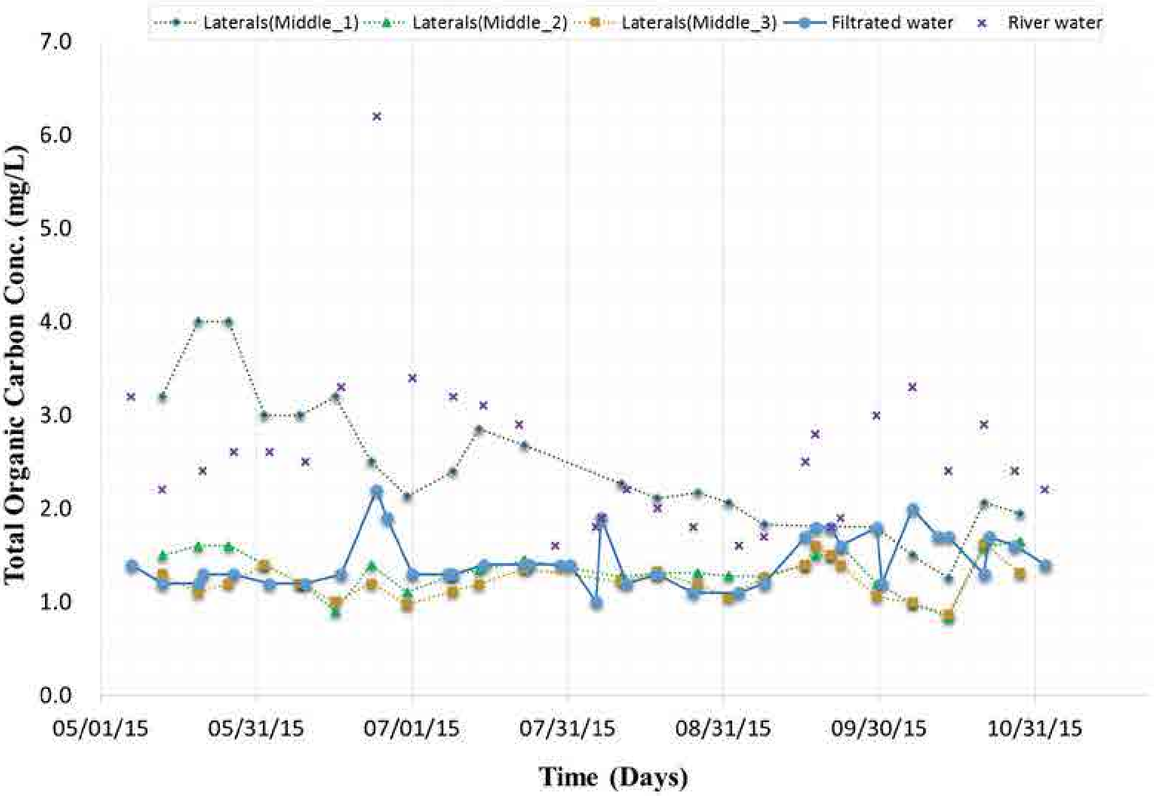

Fig. 22. TOC concentration profile with respect to depth in river water and horizontal collector well (middle layer).

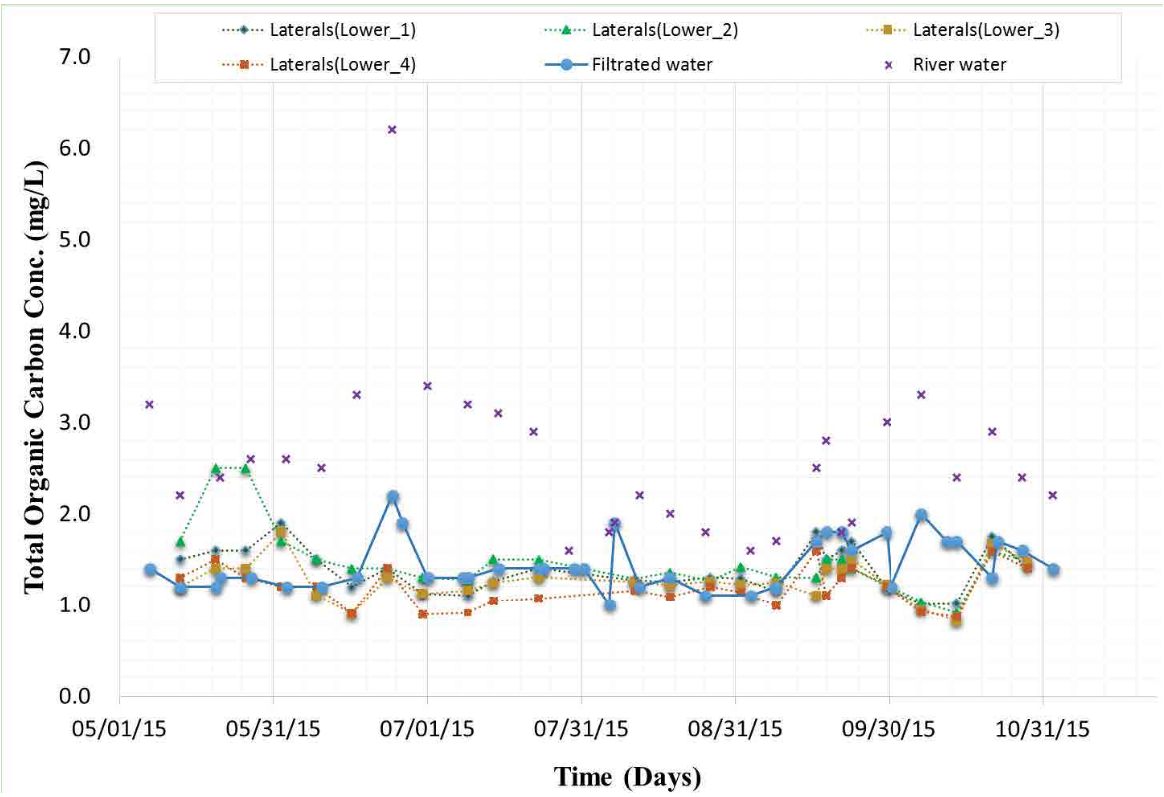

Fig. 23. TOC concentration profile with respect to depth in river water and horizontal collector well (under layer).

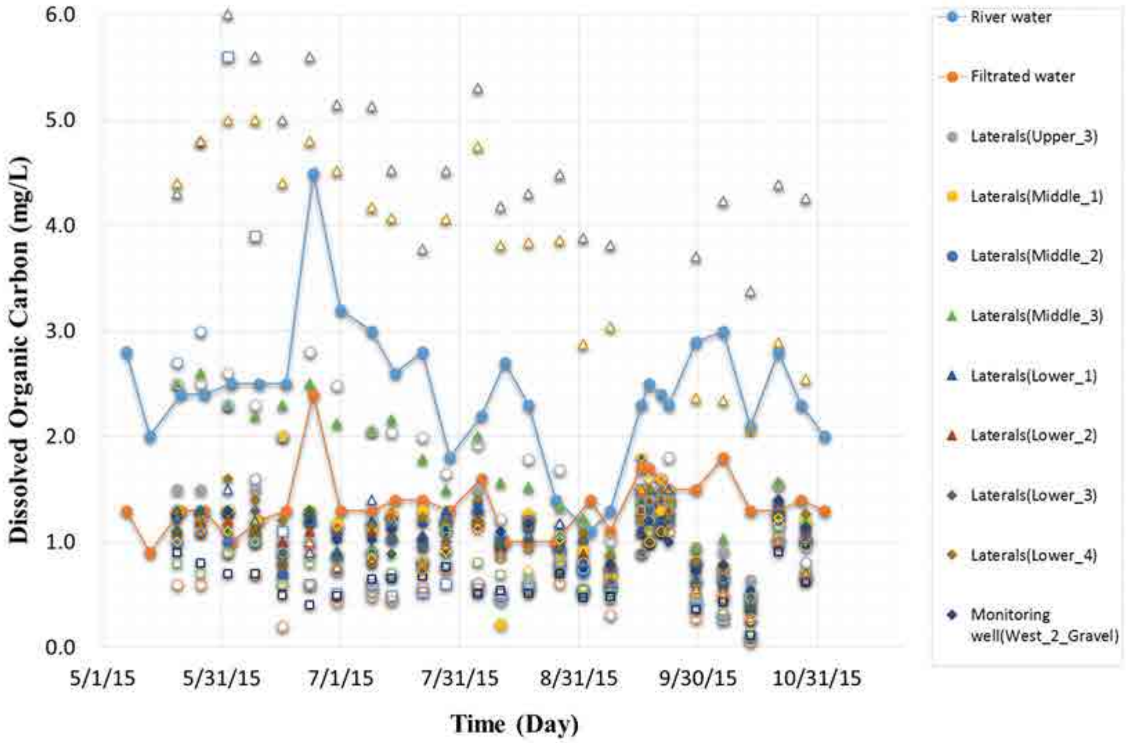

Fig. 24. DOC concentration profile.

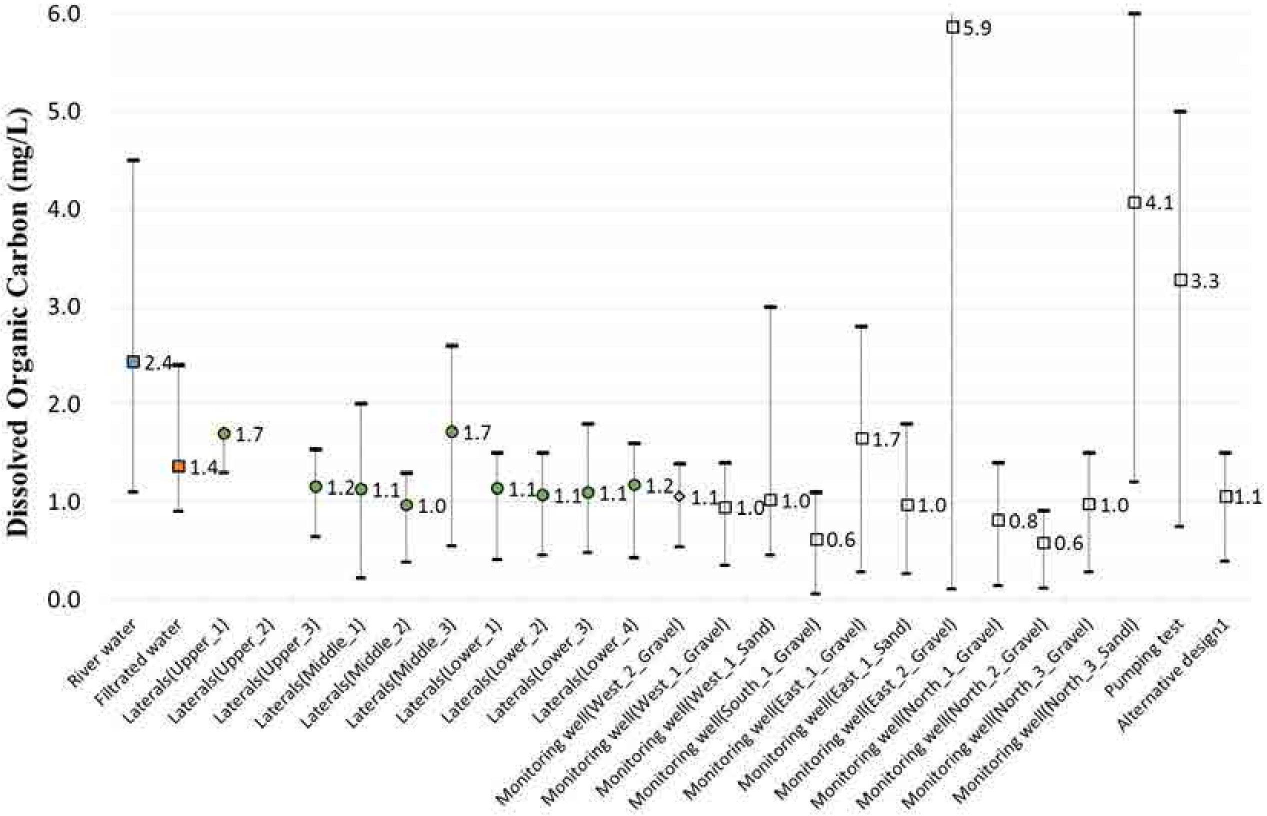

Fig. 25. Deviation of DOC concentration.

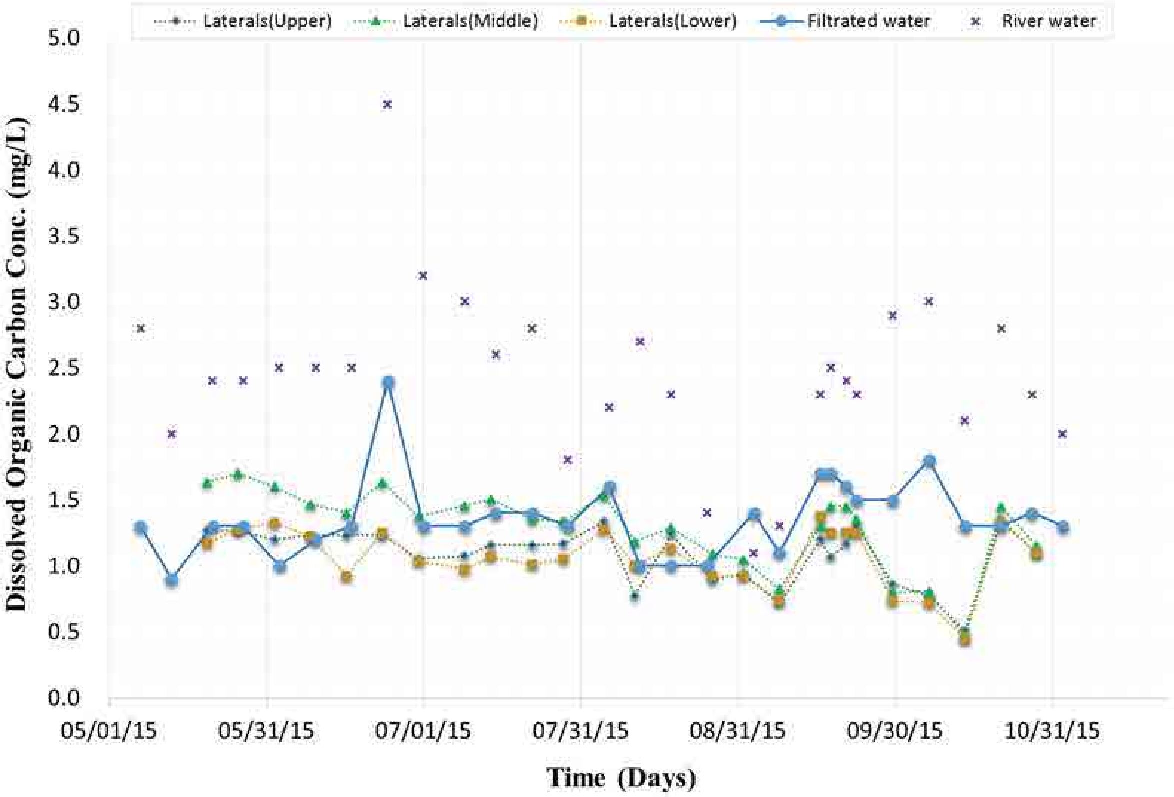

Fig. 26. DOC concentration profile with respect to depth in river water and horizontal collector well (average).

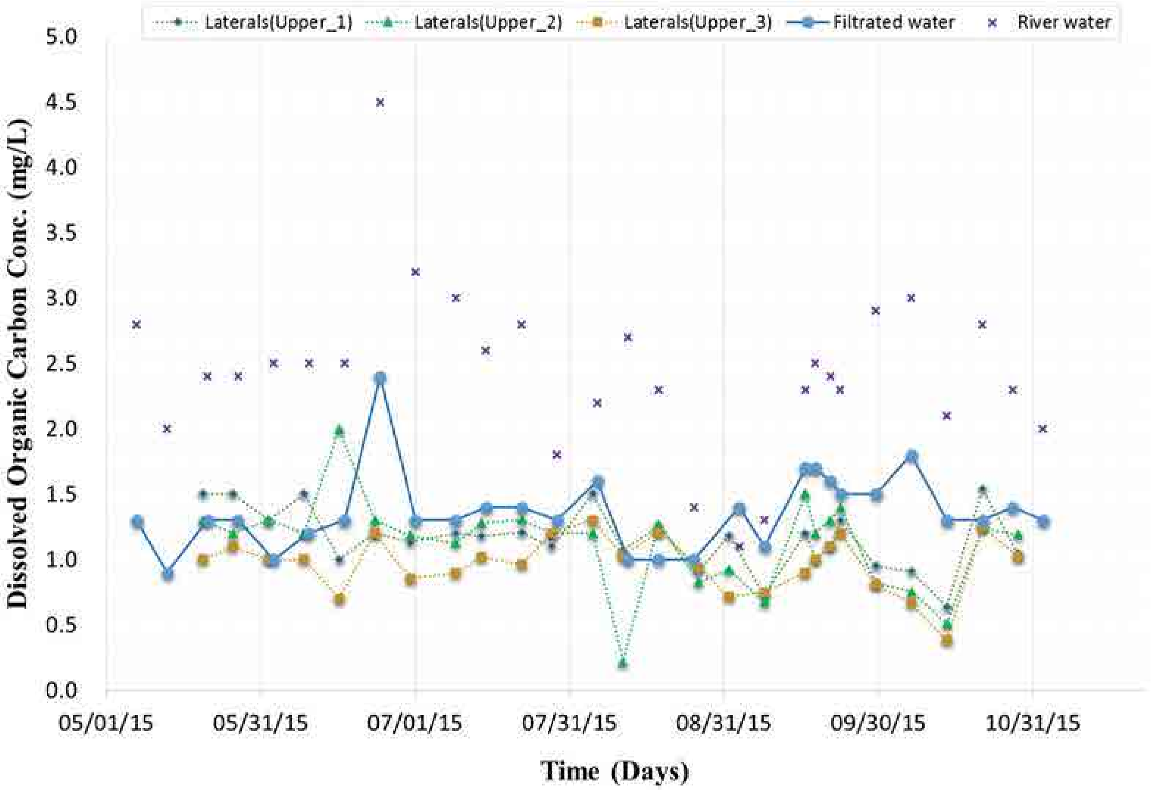

Fig. 27. DOC concentration profile with respect to depth in river water and horizontal collector well (upper layer).

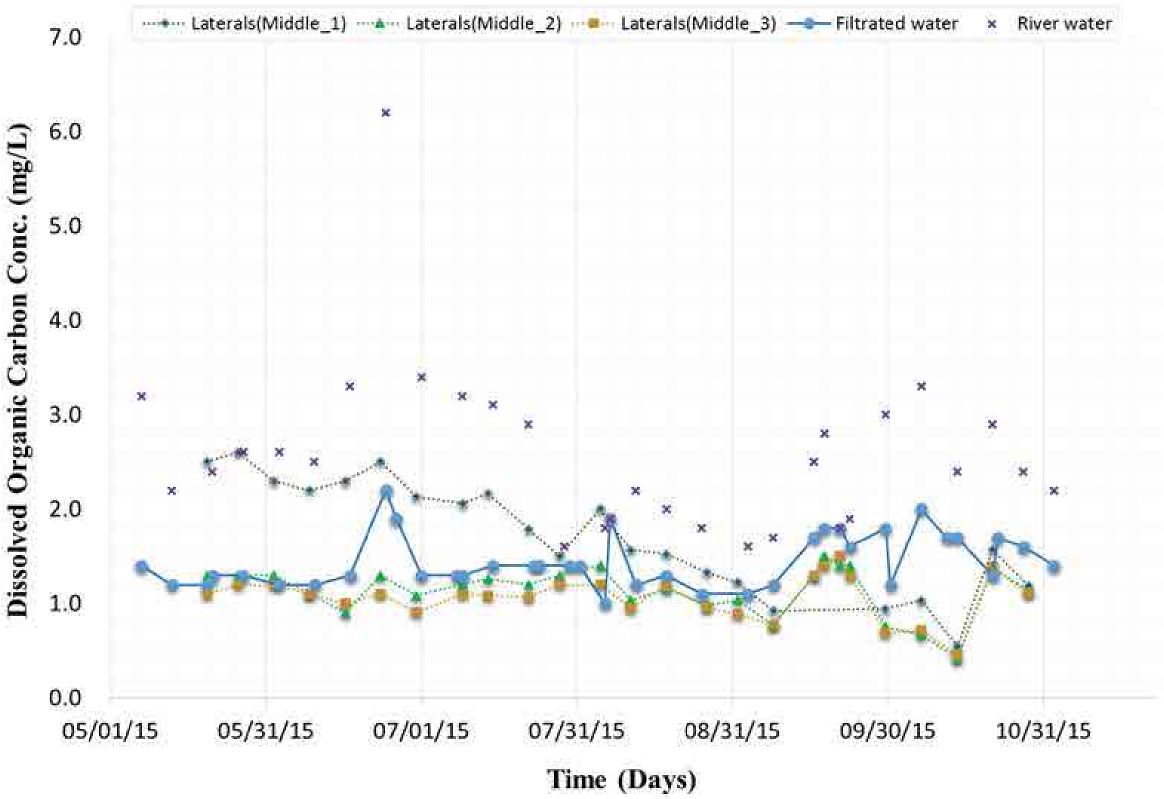

Fig. 28. DOC concentration profile with respect to depth in river water and horizontal collector well (middle layer).

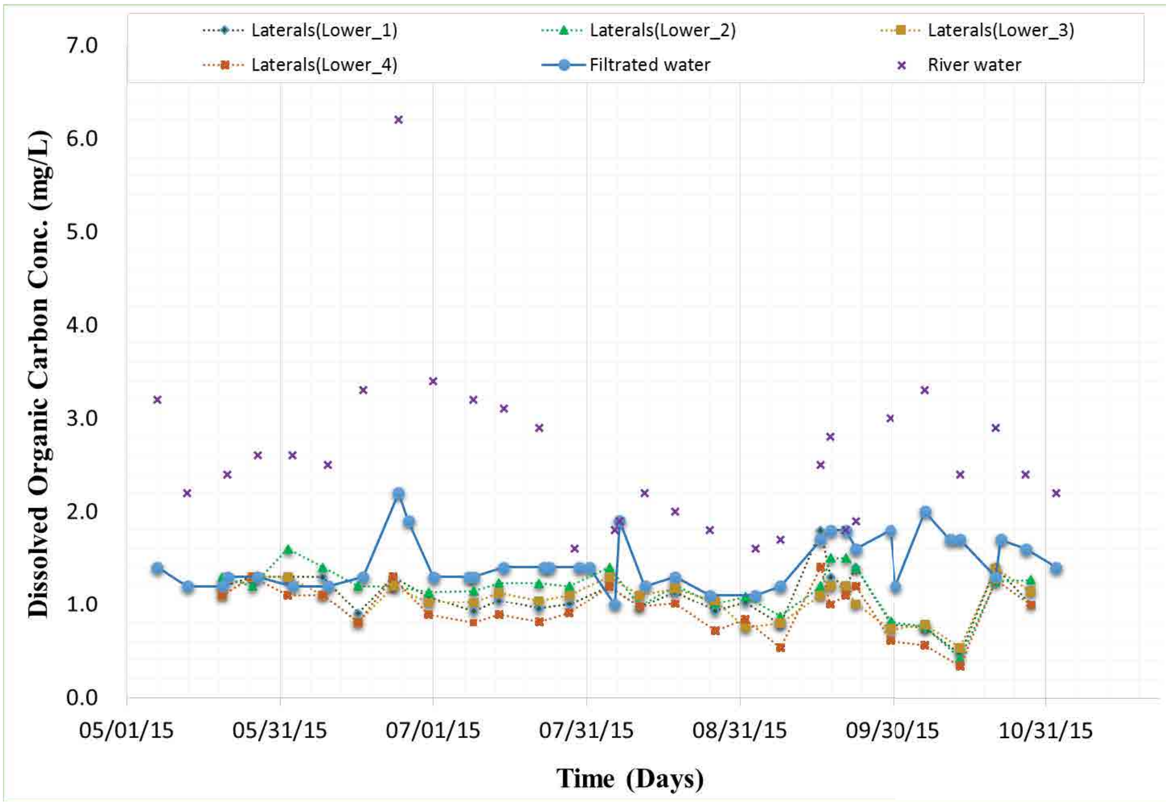

Fig. 29. DOC concentration profile with respect to depth in river water and horizontal collector well (under layer).

- Following RBF, humic substances decreased while building blocks and neutrals (~350 g/mol) increased. This shows that during the RBF process, organic matter with large molecular weights was removed or degraded.
- Through the RBF process, there was low removal efficiency of aromaticity, mol-weight, building blocks, and neutral components, with a molecular weight of 350–1,000 g/mol compare to that of organic matters with lower or higher molecular weight. Therefore, if there are high contents of such organic matter, the removal rate could decrease.
- The difference in organic matter to depth was negligible. This result corresponds with the earlier research that showed that the removal of organic matter occurs in the first several meters from the river/aquifer boundary.
- Where TOC in river water increases temporarily, the TOC of filtrated water also increases temporarily. This means that river water can directly influence the concentration of organic matter infiltrated water regardless of other factors owing to the GWUDISW phenomenon.
- Monitoring wells North #2 and #3 adjacent to force-land showed high TOC concentration due to the consistent influx of organic matter from inland with high TOC concentration. However, this had no significant impact on the filtrated water.

Additional studies on the effect of changes in the stream, such as seasonal changes, dry seasons, flood seasons, water temperature, and so on, are required. There is also a need for further studies on the influence of changes in the filtration mechanism through continuous operation on the behavior of organic matter.

Acknowledgements

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