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Study on water quality improvement by bank filtration

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ABSTRACT

The possibility of bank filtration as a water purification technique was assessed by comparing water quality of a river and bank filtrate obtained from a pilot plant operation during 7 months from November 2010 to May 2011. The research began with soil analysis, including soil adsorption characteristic, and then a comparison was performed in terms of total dissolved solids (TDS), suspended solids (SS), potassium permanganate ($KMnO_4$) consumption, biological oxygen demand (BOD), and ammonium (NH_4-N), nitrate (NO_3-N), iron (Fe), and manganese (Mn) concentrations. The study area showed high concentrations of Fe (470 mg/kg), Mn (80 mg/kg), and NH_4-N (15 mg/kg). The adsorption coefficients of k and $1/n$ were 0.00159 and 0.8714, respectively, which implied that adsorption of the soil depended on organic matter contents. Water quality comparisons revealed that TDS remained consistent, but SS was lower by 84% in bank filtration samples. NH_4-N concentration increased from 0 mg/L to $\geq$ 1 mg/L possibly due to agricultural activities in the study area, while NO_3-N concentration dropped to nearly 0 mg/L because of soil adsorption. Bank filtration reduced $KMnO_4$ consumption and BOD of river water by 54 and 71%, respectively. Concentrations of Fe and Mn significantly increased in bank filtration samples.

Keywords: Bank filtration; Water quality; River water; Bank filtrate; Soil analysis; Adsorption characteristics

1. Introduction

Water resources in Korea have been polluted because of the drastic post-1970s industrialization and urbanization, resulting in water shortage. More than 30 of 561 water treatment plants currently use seriously polluted surface water [1]. Areas downstream on the Nakdong River, including Busan and Gyeongsangnam-do, have to use the river as a water resource, despite degraded water quality due to upstream municipal and industrial wastewater discharge. Advanced water treatment has relieved this problem, but it is not a robust solution for completely reversing water contamination [2]. To ensure safe water quality and improve the withdrawal method, the government is currently trying bank filtration as an alternative water resource.

Compared with surface water abstraction, bank filtration has the following advantages: elimination of suspended solids (SS), particles, biodegradable compounds, bacteria, viruses, and parasites; partial

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elimination of adsorbable compounds; and equilibration of temperature changes and concentration of dissolved constituents in filtrate [3,4]. Undesirable effects of bank filtration on water quality include the following: increase in hardness, increase in ammonium and dissolved Fe and Mn concentrations, and the formation of hydrogen sulfide (H_2S) and other malodorous sulfur compounds as a result of changing redox condition [5].

Beneficial attenuation processes occur mainly from mixing, biodegradation, and sorption within two zones: (1) the biologically active colmation layer, where intensive degradation and adsorption processes occur within a short residence time and (2) along the main flow path between the river and abstraction borehole, where degradation rates and sorption capacities are lower and mixing is greater [3,4]. Diffusion of contaminated sources in catchment run-off, especially from agricultural activities, can adversely affect river water quality and therefore bank filtrate. Several studies demonstrated potential for denitrification or the increase in concentrations of specific metabolite compounds like triazine and acetamide herbicides. Bank filtrate is sometimes high in Fe and Mn [6–8]. Today, about 25% of bank filtration sites in Sweden are considered unsuitable for direct use [9]. Pilot plant tests recently showed bank filtration of Nakdong River water significantly increased Fe and Mn concentrations up to 23.99 and 3.45 mg/L, respectively [10].

Gimhae city in Gyeongsangnam-do is using Nakdong River and performing costly treatment to improve water quality, so the city is developing bank filtration as an alternative water resource. The investigation on soil characteristics for pollution and adsorption was performed to support the bank filtration development. The water quality of the river was compared with that of bank filtrate obtained during 7 months of pilot plant operations from November 2010 to May 2011, and then guidelines for future bank filtration development were suggested.

2. Methodology

2.1. Study area

The study area was Tanseom, located in Gimhae city of Gyeongsangnam-do. As shown in Fig. 1, the study site is a dune formed at the confluence of the Nakdong and Milyang rivers. The area is all alluvial layer and has historically been agricultural. Strawberry and rice paddy farming occurred during the study period. The soil analysis and determined adsorption characteristic were performed to assess underground environments and the effect of agricultural activities. Three sampling sites, approximately 5–10 m apart, were chosen to represent the entire area (Fig. 1).

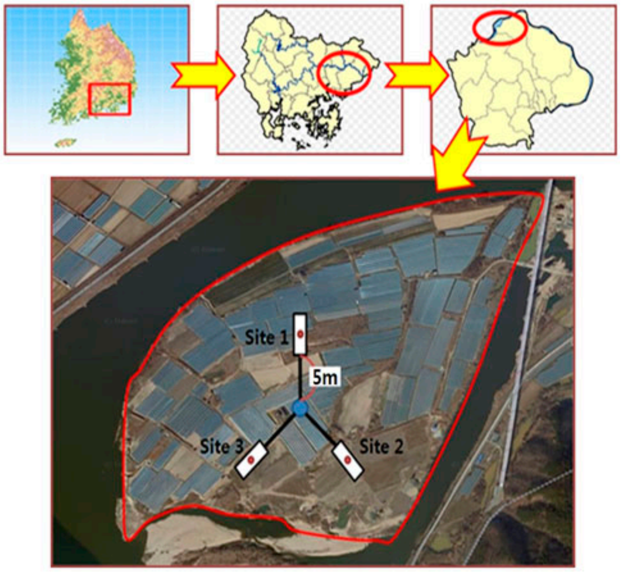


Fig. 1. Photo of study area and sampling sites.

Fig. 2 shows the alluvial layer cross-section and the bank filtration borehole obtained by drilling. Sand mostly comprised the surface until 23 m depth and 2 m beneath that was an impermeable clay layer. Then, 10 m beneath the clay layer was highly permeable, sandy gravel. As shown in Fig. 2, bank filtrate was pumped 1,000 m^3/d from the permeable layer within the borehole for analysis.

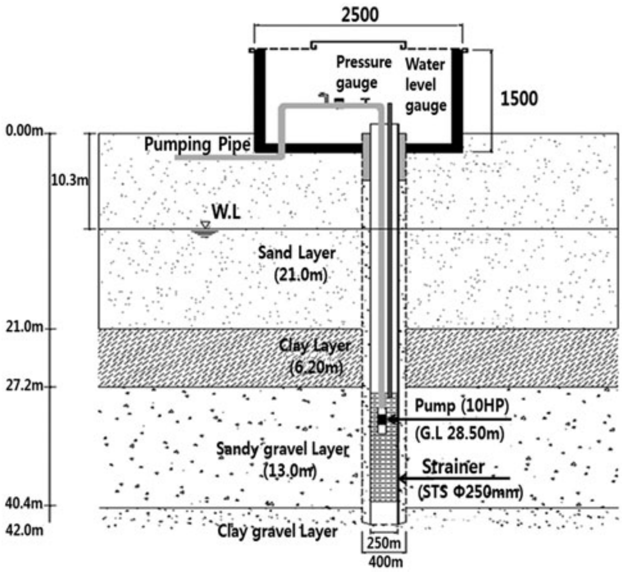


Fig. 2. Diagram of borehole and alluvial layer.

2.2. Material and method

The concentrations of NH_4-N, nitrate (NO_3-N), nitrite (NO_2-N), and Fe and Mn at the three sites were analyzed according to protocols described in Standard Method for Water and Wastewater [11]. Soil samples were collected at 5 m depth intervals up to a total depth of 30 m from each site. Before analysis, soil samples were treated with 0.1 N hydrochloric acid (HCl) and filtered.

Adsorption characteristics of soils were determined at the equilibrium state of a batch test in which the adsorbent was soil taken from each site and the adsorbate was potassium chloride (KCl). Each soil sample was placed into a vial with 50 mL KCl (50 meq/L) and shaken for 75 h. Then, vials were centrifuged for 10 min at 4,500 rpm, and filtrate samples were collected via vacuum filtration through 0.45 μm pore size Whatman fiber filter.

A pilot bank filtration plant operated at the three sites from November 2010 to May 2011. River water and bank filtrates from all sites were collected twice a week. Water quality analysis in terms of total dissolved solids (TDS), SS, potassium permanganate ($KMnO_4$) consumption, biological oxygen demand (BOD), and NO_3-N, NH_4-N, and Fe and Mn concentrations were performed according to protocols described in Standard Method for Water and Wastewater [11].

3. Results and discussion

3.1. Soil analysis

Table 1 shows average concentrations of NH_4-N, NO_3-N, NO_2-N, and Fe and Mn contained in 1 kg of soil from each site. NH_4-N concentration was larger than that of NO_3-N and NO_2-N: 30 mg/L at site 3 located downstream of the other sites. Fertilizer used in agricultural activities flowed downstream by the flow contributing to high NH_4-N concentrations. The negligible amounts of NO_3-N and NO_2-N revealed that the underground conditions were not oxic enough to convert NH_4-N into NO_3-N through NO_2-N.

Table 1
Results of soil analysis in the study area

	Site 1	Site 2	Site 3
Fe (mg/kg)	825	56	530
Mn (mg/kg)	118	30	91
NH_4-N (mg/kg)	9	7	30
NO_3-N (mg/kg)	<0.33	<0.05	<0.14
NO_2-N (mg/kg)	0.150	0.120	0.205

Fe and Mn concentrations were high at all sites. Fe concentration exceeded 50 mg/kg and Mn concentration exceeded 30 mg/kg. Concentrations at site 1 and 3 were higher than that at site 2. Fe concentration at site 1 was almost 15 times higher than that at site 2. Hallberg et al. [9] reported the quality of groundwater can vary greatly over a distance of just a few meters. They found that two wells less than 10 m apart in Finland showed significantly different concentrations of Fe and Mn, and were probably separated by an iron precipitation zone.

3.2. Adsorption characteristic of soil

Adsorption is important in the transportation of soil pollutants. Adsorption on the surface or boundary of particles is the result of cohesion between atoms, ions, or molecules. There are three categories of adsorption: ion exchange, physical adsorption, and chemical adsorption [12]. Ion exchange is the movement of pollutants to adsorbent surface due to electrical affinity. Physical adsorption is attraction due to van der Waals forces. Chemical adsorption is due to a reaction resulting in morphological changes to the pollutant. Adsorption ability is also affected by pollutant solubility: the ability is inversely related to pollutant affinity to the solvent. Factors affecting adsorption are concentration, pollutant molecule size, molecular weight and structure, and molecular porosity. Temperature and pH are also important factors. Soil adsorption is measured at equilibrium, which is achieved after several hours to days depending on soil composition. The relationship between the equilibrium concentration and the amount of pollutant in the soil is represented by Freundlich adsorption isotherm:

$$\frac{x}{m} = kC^{1/n} \tag{1}$$

where x is the amount of pollutant adsorbed on soil, m is the amount of soil, C is the equilibrium concentration, and k and n are the coefficients of the equation. The relationship between the equilibrium concentration and solid weight obtained from batch tests is shown in Table 2. The coefficients in Eq. (1) were obtained from the regression, and they are shown in Table 3.

In general, larger k values in soil implies more adsorption of organic compounds and the coefficient $1/n$ indicates the relationship between the amount of organic compounds adsorbed on the soil and

Table 2
KCl concentration and absorbent amount used for the experiment

KCl concentration	Absorbent (g)	KCl concentration	Absorbent (g)	KCl concentration	Absorbent (g)
0.01 mol	5	0.03 mol	5	0.05 mol	5
	10		10		10
	15		15		15

Table 3
Relationship of equilibrium concentration and solid state weight ratio

		0.01 mol			0.03 mol			0.05 mol		
		5 g	10 g	15 g	5 g	10 g	15 g	5 g	10 g	15 g
Site 1	A (mg/g)	0.349	0.227	0.217	0.778	0.543	0.424	1.064	0.748	0.622
	B (mg/L)	0.711	0.700	0.680	2.159	2.128	2.109	3.622	3.578	3.541
Site 2	A (mg/g)	0.429	0.261	0.190	0.346	0.512	0.588	1.435	1.273	0.910
	B (mg/L)	0.703	0.693	0.688	2.202	2.134	2.060	3.584	3.473	3.455
Site 3	A (mg/g)	0.553	0.316	0.236	1.580	1.191	1.226	2.360	1.643	1.733
	B (mg/L)	0.690	0.682	0.675	2.079	1.998	1.869	3.492	3.399	3.208

Note: (A) A solid state weight ratio, (B) Equilibrium concentration.

equilibrium concentration in suspension [13]. Table 4 shows the *k* values ranged from 0.000277 to 0.00278. The largest value indicates most adsorption of organic compounds occurred at site 1. Values of $1/n$ ranged from 0.6919 to 1.0981. Values exceeding 1 depend on the amount of clay, while values less than 1 depend on the amount of organic compound [14]. In theory, adsorption at site 1 and 2 was driven by clay content, and that at site 3 was driven by organic compounds.

3.3. SS and TDS

Monthly values of average TDS and SS are shown in Fig. 3(a) and (b), respectively. SS in the river decreased up to 84% with bank filtration, while TDS slightly increased. Lee et al.'s research on another Nakdong River agricultural field found that turbidity was effectively removed by bank filtration, but TDS—including Ca, Mg, Na, K, Cl, Si, CO^{3-}, and Fe and Mn dissolved from the soil–water reactions within the aquifer—remained high [15]. Another study on the Ohio River showed that bank filtration reduced river SS reading from 50–400 NTU to ≤ 1 NTU in bank filtrate [16]. Reduction in SS was due to straining of large particles and van der Waals attraction between smaller particles. Increase in TDS by bank filtration depends mostly on aquifer's redox condition characterized by the presence or absence of redox sensitive species, such as dissolved oxygen, nitrate, sulfate, and methane [7]. Intensive microbial and respiratory activities also decrease redox potential leading to anoxic conditions and subsequent dissolution of TDS [17]. Our results show that bank filtration reduces SS, but further treatment is required to ameliorate increased TDS from anoxic environments.

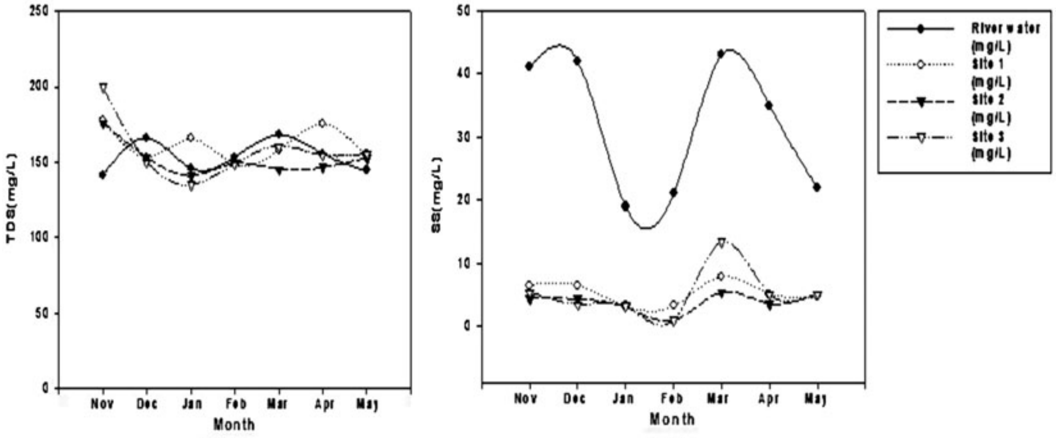
Table 4
Adsorption coefficient of each sample

Sample	*k*	$1/n$
Site 1	0.00278	0.6919
Site 2	0.00150	0.8242
Site 3	0.00028	1.0981

3.4. NH_4-N and NO_3-N

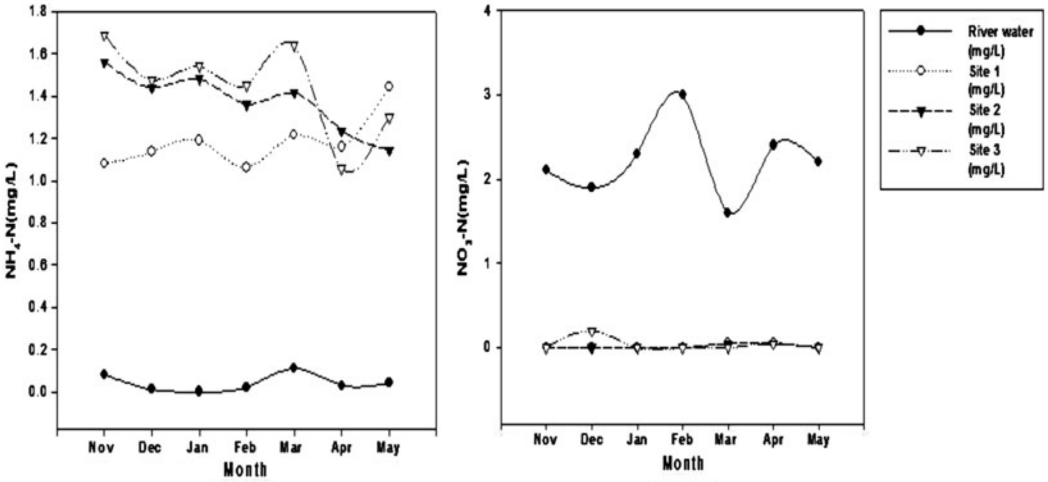
Fig. 4(a) shows monthly concentrations of NH_4-N in river and bank filtrates for all sites. Significant concentrations of NH_4-N (≥10 mg/L) were detected in bank filtrate of all the three sites, while river values were consistently ≤1 mg/L. Concentrations detected in bank filtrate exceeded the drinking water guideline concentration (≤0.5 mg/L).

Nitrogen compounds generally exist in either organic or inorganic form and were converted to NH_4-N, NO_3-N, or NO_2-N according to biological decomposition [18]. The quality of bank filtrate is much better than that of river water, but it can be polluted by nitrogen compounds from fertilizer or live-



(a) TDS (b) SS

Fig. 3. Comparison of water qualities of river water and bank filtrate.



(a) NH_4-N (b) NO_3-N

Fig. 4. Comparison of water qualities of river water and bank filtrate.

stock waste run-off. The historical agricultural use of the study area could explain the higher NO_4-N concentration at site 3 compared to that at sites 1 and 2, which agrees with soil analysis results listed in Table 1.

Ammonium accumulation could be another reason for high NH_4-N. Organic matter accumulated in soil within alluvial layers undergoes bacterial decomposition into ammonia gas and ammonium in suspension, some of which is oxidized into NO_3-N by surface nitrogen-fixing bacteria. The remainder is accumulated within the aquifer due to the prevalence of reduction under anoxic conditions [19].

Fig. 4(b) shows the NO_3-N concentrations of both river and bank filtrate. The concentration in river water was 2.0–3.0 mg/L, while bank filtrate concentrations from all sites were nearly 0 mg/L. Generally, NO_3-N in river water is converted into N_2 gas by denitrification under anoxic conditions [18,19]. This may be due to bank filtration significantly reducing high concentrations of NO_3-N in river water.

3.5. Organic substance ($KMnO_4$ consumption and BOD)

$KMnO_4$ consumption and BOD were measured to determine if bank filtration remove organic substances. $KMnO_4$ consumption is general measure of organic substances, as per Korean drinking water guideline. Fig. 5(a) shows the $KMnO_4$ consumptions of river water and bank filtrates at all sites. Bank filtration reduced $KMnO_4$ consumption well although there was a significant seasonal variation. $KMnO_4$ consumption of river water average 7.13 mg/L, while values at site 1, 2, and 3 were 2.49, 2.99, and 4.45 mg/L, respectively. Fig. 5(b) shows reduction in BOD due to bank filtration, despite significant variation. River water BOD average was 3.17 mg/L, while values at site 1, 2, and 3 were 0.95, 1.04, and 0.81 mg/L, respectively.

Average reduction in $KMnO_4$ consumption by bank filtration was 65, 58, and 38% for sites 1, 2, and 3, respectively. Average reduction in BOD by bank filtration was 70, 67, and 75% for sites 1, 2, and 3, respectively. This indicates that the bank filtration reduced BOD to a slightly greater extent than it reduced the $KMnO_4$ consumption. BOD reflects the amount of biodegradable organic substances' presence, while $KMnO_4$ consumption indicates the presence of both biodegradable and nonbiodegradable organic substances. Organic substances that infiltrate into the soil would be adsorbed by soil or will form a suspension and be further reduced by biodegradation. Our results show that organic substances in the study area were mostly removed by biodegradation rather than adsorption.

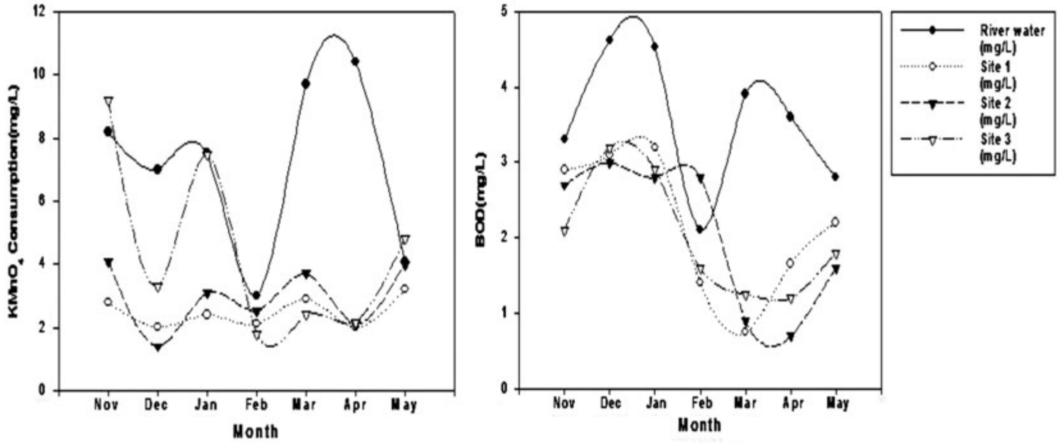
Several researchers reported that the removal of organic substances by bank filtration depends on initial concentration in surface water, transmissivity, organic composition (degradable or nondegradable), and retention time. It is also affected by temperature and redox condition [16,17,20]. These studies show biologically degradable substances readily degraded under oxic conditions, even within the first meters of infiltration depth, while complex compounds required long retention times for degradation under anoxic or anaerobic conditions.

3.6. Fe and Mn

Fig. 6(a) shows the variation of Fe concentrations. As can be expected from the soil analysis, a higher concentration of Fe was detected in the bank filtrate than in the river water. Site 3's Fe concentration during January and February was as high as 4 mg/L. The Fe concentration of the river water averaged 0.13 mg/L, but those at site 1, 2, and 3 were 1.1, 1.03, and 2.17 mg/L, respectively. These values were 15–70 times greater than values reported at 7 Chilseo-myeon, Haman-gun (0.07 mg/L), Buk-myeon Chanwon city (0.06 mg/L), and Daesan-myeon Changwon city (0.03 mg/L) [21]. This is because the research area was once known for iron production [22], suggesting significant dissolution of iron in groundwater.

Fig. 6(b) shows Mn concentrations of river water and bank filtrates. All bank filtrate of Mn concentrations exceeded river water. The average river water concentration was 0.04 mg/L, while those at sites 1, 2, and 3 were 0.84, 0.69, and 0.75 mg/L, respectively, Concentrations of bank filtrates were similar to values reported at Chilseo-myeon, Haman-gun (0.64 mg/L), Buk-myeon Chanwon city (0.89 mg/L) and Daesan-myeon Changwon city (1.00 mg/L) [21].

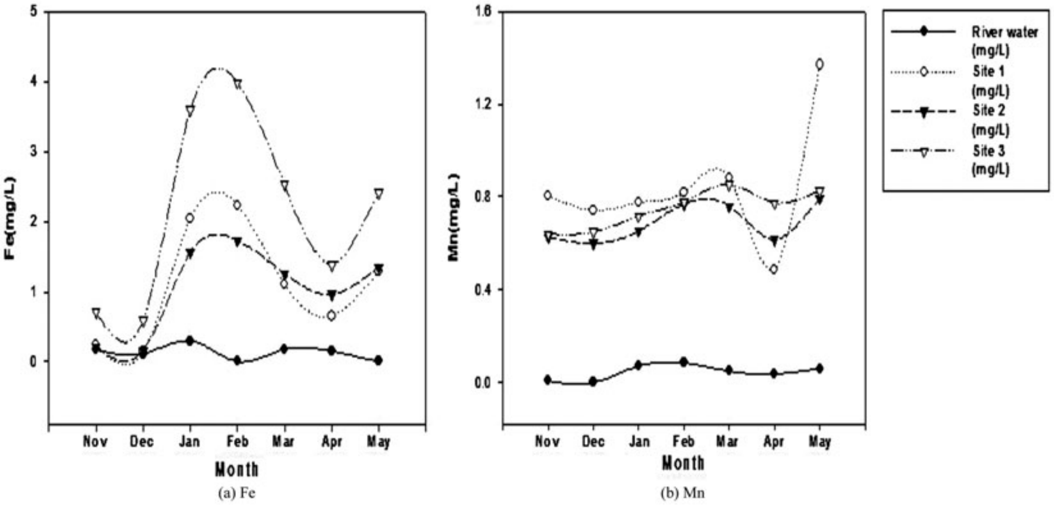
In general, more oxygen is consumed than supplied by infiltrating river water in riverbed sediments, causing a reduction zone development. Under this anoxic condition, denitrifying and sulfate-reducing bacteria further decrease the redox potential of the system [19]. The resulting highly reduced environment usually affects stability of surface mineral coatings, e.g. Fe and Mn oxyhydroxides [23]. In addition, mobilized Fe and Mn can significantly degrade water quality. Research related to characteristics of Korean bank



(a) KMnO4 comsumption

(b) BOD

Fig. 5. Comparison of water qualities of river water and bank filtrate.



(a) Fe

(b) Mn

Fig. 6. Comparison of water qualities of river water and bank filtrate.

filtration showed the complete consumption of oxygen and nitrogen resulted in release of Fe and Mn into the bank filtrate, when infiltrated river water retention times in riverbed sediments exceeded five days [24].

4. Conclusions

The following conclusions were drawn from soil analysis, adsorption characteristics of soil, and water quality comparison between river and bank filtrate samples:

- Soil analysis revealed a higher NH_4-N concentration (30 mg/L at site 3) compared to NO_3-N and NO_2-N, which was possibly due to the presence of agricultural fertilizer. It also showed high concentrations of Fe and Mn (more than 50 mg/kg of Fe and 30 mg/kg of Mn).
- Adsorption characteristics showed that k values ranged from 0.000277 to 0.00278 and $1/n$ values were from 0.6919 to 1.0981. Adsorptions at site 1 and 2 were dependent on clay content and that at site 3 was dependent on organic compounds.
- SS in the river reduced as much as 84% by bank filtration, while TDS slightly increased by soil–water reaction within aquifer.
- High concentration of NH_4-N (more than 10 mg/L) was detected in the bank filtrate, while that in river water remained less than 1 mg/L. NO_3-N concentration in river water was 2.0–3.0 mg/L, while that in bank filtrate was nearly 0 mg/L.
- Average reduction in $KMnO_4$ consumption by bank filtration was 65, 58, and 38% for sites 1, 2, and 3, respectively. Average reduction in BOD was 70, 67, and 75% for sites 1, 2, and 3, respectively. Organic substances in the study area might be removed by biodegradation rather than adsorption.
- While the average Fe concentration of the river water was 0.13 mg/L, values at sites 1, 2, and 3 were 1.1, 1.03, and 2.17 mg/L, respectively. While the average Mn concentration of river water was 0.04 mg/L, values at sites 1, 2, and 3 were 0.84, 0.69, and 0.75, respectively.

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