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Phosphorus release rates from sediments and pollutant characteristics in Han River, Seoul, Korea

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Abstract

The Han River is 469.7-km long and drains a 26 219-km^2 watershed. The sediments in the river are highly polluted due to inputs from upstream tributaries as well as partially treated municipal wastewaters that are discharged to the river. The water quality and strategy for control are important because the river is the primary drinking water supply for the City of Seoul, as well as being a major source for irrigation and industrial water. The Jamsil submerged dam partitions the river to isolate an upstream area for drinking water, but also captures sediments. Samples from four sites were studied to determine sediment pollutant concentrations and phosphorus release rates. Phosphorus tends to desorb from sediments when the concentration of overlying water is less than 1.4 mg/l. Water column P concentrations range from 0.04 to 0.1 mg/l, which suggests that sediments will act as a P source. In a series of batch experiments, P was released at approximately 15–20 mg/m^2 week in the winter (1–5 °C) and as much as 90 mg/m^2 week in the summer (20–24 °C), and is also a function of pH and dissolved oxygen concentration. The sediment total phosphorus concentration, which averages 833 mg/kg, is evenly distributed among non-apatite-P (33%), apatite-P (32%) and residual-P (34%). An equilibrium model is proposed to describe release rate.
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Keywords: Phosphorus release rate; Sediment; Han River; Jamsil submerged dam; Non-point sources

1. Introduction

The Han River, the largest river in Korea, is the primary water source for more than 20 million people in Seoul and the surrounding area. It starts in north-east Kangwon-Do and travels to the Yellow Sea through Seoul. The river is 469.7-km long with a watershed area of 26 200 km^2. The river is highly developed and has been straightened and channeled for flood control. Its banks are lined with roads and parks. Paldang Dam, which is located upstream of Seoul, moderates high flows to provide flood control. All of these modifications reduce flowing velocity, which increases the opportunity for sediment accumulation in the lower reaches. The river also receives stormwater and urban runoff, and the total suspended solids and

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phosphorus loads are 70–80% attributable to non-point sources (Choi et al., 1994).

Sediments have accumulated behind the Jamsil Dam and in other areas and are known to have adsorbed pollutants on particle surfaces. Therefore, sediment resuspension or pollutant desorption may be an important source of pollutants to the water column, and this potential release is a growing concern for the users of the river (Hakanson and Jansson, 1983). The reentry of pollutants can be accelerated by various chemical or physical changes in the overlying water, and the desorbed pollutants may contribute to eutrophication, or impact drinking water supplies (Lijklema et al., 1993; Stumm and Morgan, 1996).

Water quality downstream of the Jamsil Dam area is impacted by treatment plants. The Jungrang wastewater treatment system is the largest in Asia ($\sim 2 \times 10^6$ m^3/day) and discharges into the Han River downstream of the Jamsil Dam. It was recently expanded to provide secondary treatment, but does not perform nutrient removal. The reduction in pollutant release from the expanded plant is not large enough to restore down stream water quality.

It is proposed that controlling phosphorus is the best approach to reducing eutrophication. Nitrogen and other nutrients are introduced from non-point sources and there is little opportunity at present to make these nutrients rate limiting (Bostrom, 1988; Wetzel and Likens, 1992). To achieve water quality goals it will be necessary to further reduce phosphorus sources in upstream tributaries and reducing or eliminating phosphorus release from sediments may also be required (Abrams and Jarrell, 1995).

The research described in this paper focuses on phosphorus release from sediments as a function of overlying water characteristics. It was sponsored by the City of Seoul and the Korea Engineering Consultants Corporation. The objective was to assess possible sediment impacts on the Han River in the Jamsil Dam area. This manuscript concentrates on Jamsil submerged dam (JSD) sediments. An upstream source, the Chungpyunk Lake, is described in another paper (Kim et al., 2002), and these two papers are the first publication of Han River sediment data. This paper describes phosphorus release studies as well as a model to describe potential release rates to the water column. The data were collected over a 4-year period from 1994 to 1998.

2. Materials and methods

2.1. Study area

The study area is shown in Fig. 1 and includes the City of Seoul. The Jamsil Dam area is located in the eastern part of the Seoul. This area is called 'Jamsil submerged dam' because a submerged weir maintains minimum water level, and prevents back mixing from the lower, more polluted, sections of the river. Maintaining a minimum water level is necessary to create a stable volume for drinking water treatment plants.

This area is generally protected from point source discharges. Seoul's major treatment plant, the large Jungrang wastewater treatment plant, discharges downstream of the weir. Only the Jayang municipal wastewater treatment, a small plant, discharges into the upstream area. Although the hydraulic detention time (1.5 h) of this section of the river is short compared to lakes, there is ample time for sediments to deposit. Table 1 shows the distribution of point and non-point pollutant sources from the Seoul area to the river. Non-point sources are responsible for approximately 70–80% of the phosphorus input. Table 2 shows the river's flow rate and water quality. The flow rate is very high during summer or rainy season (July to September), and ranges from 1100 to 1400 m^3/s. A disproportional amount of pollutants are washed into the area during the rainy season. The flow rates during the winter season are approximately 200 m^3/s.

2.2. Sampling and analysis methods

Water, disturbed sediment and undisturbed sediment samples were collected from the study area over a 5-year period from 1994 to 1998. Four sampling locations were selected for collecting sediments (SP-1 to SP-4, see Fig. 1); water samples were collected at these sites and others as well. Disturbed sediment samples were collected with a Ponar Grab style sampler and undisturbed

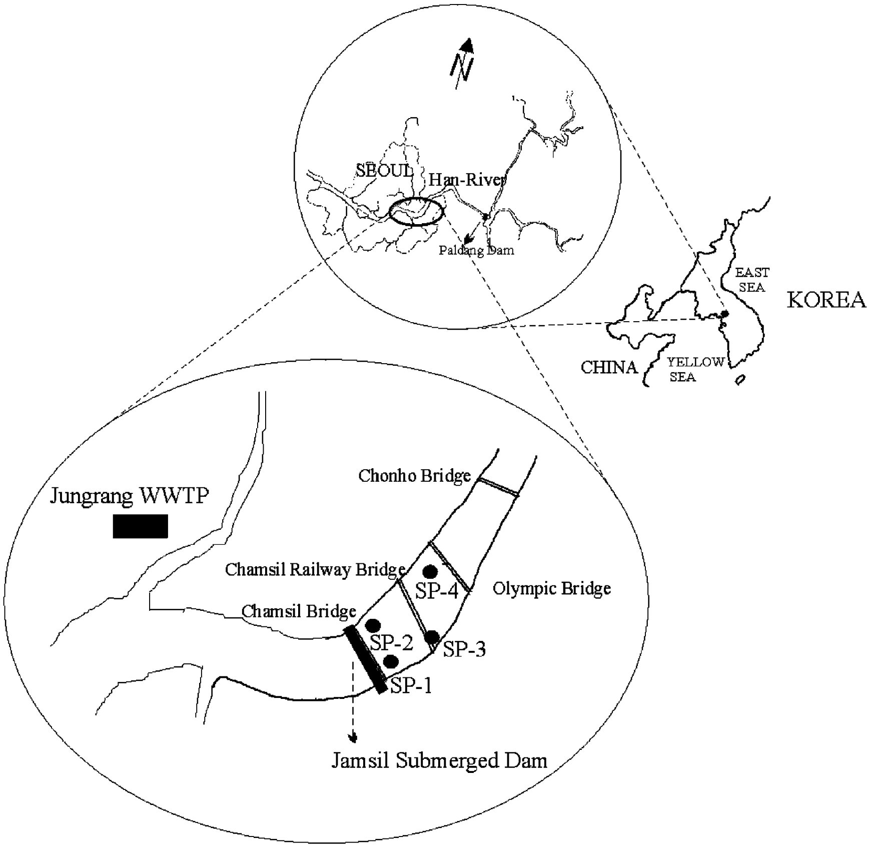

Fig. 1. Research area of Han River in Seoul, Korea.

sediment samples were collected by divers with acryl tubes (4-cm diameter by 50-cm long). Phosphorus types were determined using the procedure of Hieltjes and Lijklema (1980). This procedure successively extracts phosphorus from sediments using different solvents and conditions (Williams et al., 1980).

Phosphorus was first extracted using 50 mg of dried sediment with 50 ml of 1 M NH_4Cl at pH 7. The sample was mixed and extracted for 2 h. The supernatant was filtered and analyzed for phosphorus using ion chromatography. This procedure removes loosely associated phosphorus, called adsorbed-P or 'NH_4Cl extractable P,' which is adsorbed to the surface of clays and small particles. It is believed that adsorbed-P is the most available phosphorus. The sediment residue from this extraction is next extracted with 0.1 M NaOH

Table 1
Annual pollutants loadings from Seoul area in the Han River (ton/year, Choi et al., 1994)

Parameters	Annual loading	Point sources	Non-point sources
COD	4128	2768 (67.1%)	1360 (32.9%)
TSS	30 991	9125 (29.7%)	21 775 (70.3%)
Total N	2523	1165 (46.2%)	1358 (53.8%)
Total P	400	79 (19.7%)	321 (80.3%)

for 17 h. Phosphorus precipitated with metal ions, such as Fe or Al, is separated, and is called non-apatite-P (NAI-P) or NaOH-P. This type of phosphorus is generally less available than adsorbed-P, but can be released in the natural environment by increasing pH or reducing redox potential, and can be used by aquatic plants. The residual is next extracted for 17 h with 50 ml of 0.5 M HCl solution. This type of phosphorus is called apatite-P or 'HCl extractable P.' Phosphorus released by this extraction is usually precipitated with inorganic salts such as calcium. The remaining phosphorus or unextractable phosphorus is called residual-P and is calculated by difference with sediment total P, measured using *Standard Methods* (AWWA et al., 1995). This type of phosphorus exists with organic compounds and it is difficult to separate. The sampling procedures and analysis methodologies are described in greater detail elsewhere (Kim and Choi, 1996; Kim et al., 2002).

2.3. Phosphorus release experiments

Two methods were used to evaluate phosphorus release. The first, called forced release, was performed by mixing 200 g of wet sediment with 500 ml distilled water and shaken at 20 °C for 48 h. The second method, called natural release, used 6-cm diameter by 45 cm tall acryl tubes without mixing, containing varying amounts of sediment and overlying water, treated in different ways.

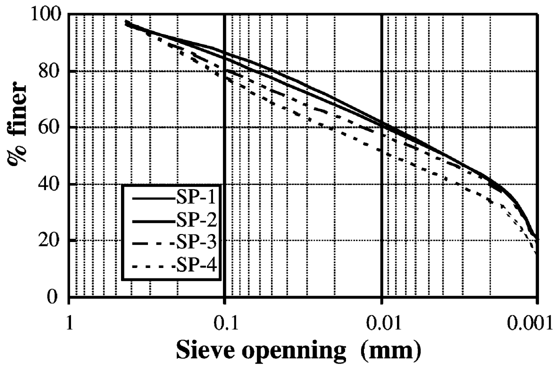

Fig. 2. Sediment particle distributions.

Three different overlying waters, Han River water, distilled water and deoxygenated distilled water (nitrogen gas stripping followed by sodium sulfite addition), were used to perform the tests. Other experimental conditions are shown in the accompanying figures and tables, and the details are available elsewhere (Kim et al., 2002).

3. Results and discussion

3.1. Particle size distributions

The particle size distributions are shown in Fig. 2, and were similar for all four sites. The sediments averaged 39±3% clay, 36±3% silt and 25±2% sand. Using the Unified Soil Classification method

Table 2
Monthly mean water quality of Han River during research periods

Month	Flow rate (m^3/s)	Temperature (°C)	pH	Turbidity (NTU)	Conductivity (μmhos/cm)	TSS (mg/l)	VSS (mg/l)	TP (mg/l)	PO_4–P (mg/l)
1	184	1±0.5	7.3±0.11	4.5±1.4	85±2.8	6.1±1.1	2.6±0.6	0.035±0.001	0.007±0.001
2	214	1±0.7	7.2±0.09	5.0±1.2	94±3.6	6.4±1.2	2.0±0.5	0.050±0.005	0.004±0.002
3	258	3±0.8	7.8±0.12	4.8±1.2	102±3.7	6.1±1.2	2.8±0.7	0.059±0.003	0.005±0.001
4	310	8±1.2	7.5±0.14	4.7±0.1	108±3.9	5.4±1.3	1.6±0.8	0.062±0.006	0.006±0.001
5	396	16±1.6	7.8±0.18	5.1±1.1	115±4.5	5.9±1.6	2.4±0.6	0.057±0.002	0.006±0.002
6	647	23±2.1	7.6±0.17	4.9±1.3	124±5.1	6.0±1.5	2.6±0.6	0.094±0.009	0.009±0.002
7	1476	23±2.1	7.7±0.11	6.5±2.1	136±4.5	8.5±1.8	4.5±0.8	0.110±0.010	0.010±0.005
8	1149	25±1.6	8.0±0.12	7.1±1.8	149±4.1	10.4±1.6	3.4±0.8	0.105±0.007	0.008±0.003
9	1110	20±1.7	7.6±0.14	5.6±1.2	132±3.4	8.5±1.6	2.9±0.9	0.098±0.006	0.007±0.002
10	325	18±1.5	8.0±0.10	5.1±1.1	127±3.1	6.5±1.7	2.3±0.8	0.085±0.007	0.005±0.002
11	272	16±2.1	7.5±0.09	4.8±1.5	119±3.2	7.3±1.6	2.5±0.6	0.067±0.004	0.005±0.001
12	234	5±1.0	7.2±0.12	4.1±0.1	105±2.5	4.4±1.5	2.1±0.5	0.054±0.003	0.005±0.002

Ranges are standard deviations.

Table 3
Mean sediment concentration as a function of depth

Parameters	Sediment depth (cm)	Minimum	Maximum	Mean	S.D.	Confidence intervals	
						99% upper	99% lower
COD (mg/kg)	0–15	18 950	35 680	28 181.2	4279.7	30 575.2	25 787.2
	15–30	8950	28 950	20 780.5	4779.4	23 454.0	18 107.0
	30–45	14 510	29 840	21 910.8	4381.1	24 361.6	19 460.1
Total N (mg/kg)	0–15	950	1980	1410.4	261.5	1556.7	1264.1
	15–30	645	1578	1110.0	208.0	1226.4	993.6
	30–45	480	1250	710.9	186.5	815.2	606.6
Total P (mg/kg)	0–15	580	1450	1010.8	278.1	1166.3	855.3
	15–30	346	1150	760.2	216.2	881.2	639.3
	30–45	450	1250	679.6	183.7	782.4	576.8
Ignition loss (%)	0–15	4.6	11	6.8	2.0	7.9	5.7
	15–30	4	8.8	5.5	1.4	6.3	4.7
	30–45	3.1	6.4	4.5	0.8	5.0	4.1

(Das, 1990), the sediments are classified as silty clay.

3.2. Concentration vs. water and sediment depth

Monthly mean water quality data are shown in Table 2. Samples were collected and analyzed twice per month and were performed over the entire research period. The concentrations of most water quality parameters except pH are generally higher in the summer than winter seasons. For example, TSS and specific conductivity were approximately 3 mg/l and 40 μmhos/cm greater, respectively, in the summer. Monthly mean PO_4–P concentration ranged from 0.0035 to 0.0095 mg/l. To (1974) noted that when soluble phosphorus concentration exceeds 0.01 mg/l, phosphorus sorbs to suspended solids, which suggests that P release from sediments may occur in the Jamsil Dam area.

Table 3 shows the results of the undisturbed sediment analysis as a function of sediment depth. Mean pollutant concentrations decrease with sediment depth, except for COD, and the differences between levels are significant at the 99% confidence level. The differences in concentration may represent changing sediment pollutant concentrations over time, but may also be caused by removal mechanisms. Anaerobic degradation could reduce COD and organic content (e.g. ignition loss), and can accelerate the release of nitrogen and phosphorus to the water column. Generally, one expects decreasing pollutant concentrations with increasing sediment depth, due to biodegradation, or release due to the changing conditions caused by biodegradation.

The river depth in the study area is generally 7–9 m. Pollutant concentrations increase with depth, suggesting stratification and sedimentation of pollutants (Kim et al., 2002). The DO concentration ranges from 6 to 7.5 mg/l at the surface and decreases to 5–6 mg/l near the sediments.

3.3. Phosphorus types

The mean concentrations among phosphorus types in the sediments are shown in Fig. 3, which represents 16 samples for each site. The majority of the phosphorus is distributed among NAI-P, apatite-P and residual-P, and were similar for all sites, although the absolute concentrations are different. Adsorbed-P was very low at all sites, ranging from 0.1 to 2% of the total P. Site SP-4, which is the most upstream from the dam of all four sites, had the lowest concentrations.

3.4. Case studies of phosphorus release rates

Table 4 shows the results of 27 anaerobic and aerobic forced released tests of sediments from all

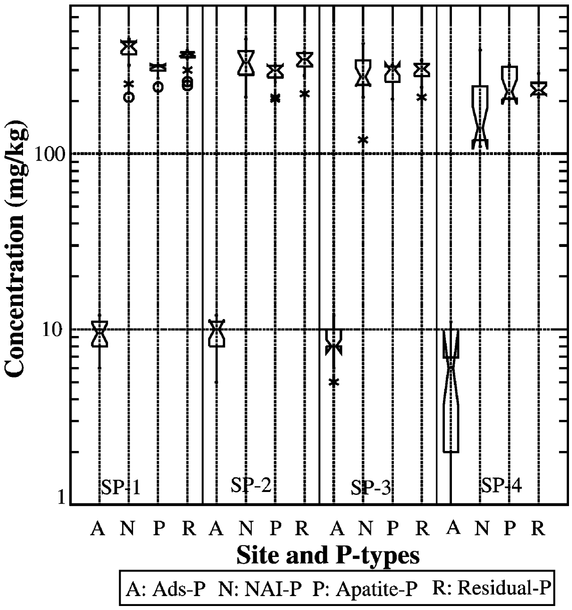

Fig. 3. Phosphorus types in sediments for each site.

four locations. Initial sediment water content, COD and total P concentrations are shown, along with the mass released during the experiment. The initial COD and total P ranged from 18 990 to 35 550 mg/kg and 580 to 1150 mg/kg, respectively. The total P concentration of the sediments is much higher than that of other lakes and rivers in Korea, which range from 400 to 700 mg/kg (The Ministry of Environment, 1990). The forced release of COD under anaerobic conditions ranged from 3340 to 7880 mg/kg or 19% of the total COD; forced total P release was also 19% (105–220 mg/kg). Under aerobic conditions, release was much less, and was 8.8 and 10% for COD and total P, respectively.

A series of natural phosphorus release experiments were performed using blended, undisturbed samples. Sections of sediments from different depths were blended to create an average or composite sample. Sediments from site SP-1 were used for all natural release experiments except Case 5. Sediments from site SP-1 were preferred because they were highest in concentration and the site is closest to the submerged dam and drinking water intakes. Table 5 shows five of seven cases, with each case representing a series of experiments to evaluate an effect or hypothesis. The other two cases are shown in the following figures.

Case 1 shows the impact of overlying water depth. Different water depths were used with identical sediment mass. There is no significant difference in phosphorus release with water depth. Case 2 shows a similar series of experiments, except with changing sediment mass and depth. The release rates are similar to the changing water depth experiments, and release rate ranged from 57 to 68 mg/m^2 week.

Case 3 shows phosphorus release rate as a function of temperature in anaerobic conditions (overlying water DO = 0.5 mg/l). Phosphorus release rate increased dramatically with increasing temperature, increasing from 15.8 mg/m^2 week at 2 °C to 115.8 mg/m^2 week at 35 °C.

Case 4 in Table 5 shows the effect of phosphorus concentration in overlying water. Increased phosphorus concentration reduced release rate, suggesting an equilibrium phenomenon. The sediments absorbed phosphorus only at the highest initial concentration of 2 mg/l. Case 5 shows release rates with Han River water, which most closely reflects actual conditions. The initial phosphorus concentration was approximately 0.05 mg/l. Release rate ranged from 44 to 68 mg/m^2 week. These rates are similar to the rates observed with distilled water at the same initial DO concentration.

Case 6 evaluated the impact of initial DO concentration in the overlying water. Fig. 4 shows the release rates as well as the changes in pH and DO that occurred during the test. The release rate is approximately 105 mg/m^2 week under anaerobic conditions, but decreases to 40 mg/m^2 week when the initial DO is 7 mg/l. Phosphorus release rate is 2.5 times greater under anaerobic conditions.

Case 7 evaluated the effect of pH on phosphorus release. The experiment was conducted over 7 days under anaerobic conditions. Fig. 5 shows the release rates and the change in pH. The sediments tended to neutralize the pH of the overlying water, with acid pHs increasing and basic pHs decreasing. The release rates show a minimum between initial

Table 4
Sediment concentrations and forced release mass

Site	Concentrations and release mass	COD		Ignition loss		Water content		Total P	
		(mg/kg)	S.D.	(%)	S.D.	(%)	S.D.	(mg/kg)	S.D.
SP-1	Initial conc.	35 550	8150	6.4	1.3	42.1	5.18	1150	240
	Released mass (anaerobic)	7880 (22.2%)	2428	–		–		220 (19.1%)	44.5
	Released mass (aerobic)	3370 (9.5%)	820	–		–		115 (10.0%)	21.3
SP-2	Initial conc.	26 570	7060	5.1	1.3	47.0	5.34	980	210
	Released mass (anaerobic)	4780 (18.0%)	1870	–		–		176 (18.0%)	52.3
	Released mass (aerobic)	1860 (7.0)	910	–		–		88 (9.0%)	26.8
SP-3	Initial conc.	18 990	8940	6.0	1.3	52.1	4.78	900	180
	Released mass (anaerobic)	3340 (17.6%)	1280	–		–		170 (18.9%)	38.9
	Released mass (aerobic)	1490 (7.8%)	1070	–		–		97 (10.8%)	19.4
SP-4	Initial conc.	34 180	9570	4.5	1.3	47.6	4.71	580	145
	Released mass (anaerobic)	6490 (19.0%)	1560	–		–		105 (18.1%)	46.4
	Released mass (aerobic)	3810 (11.1%)	1100	–		–		55 (9.5%)	29.6
Mean	Initial conc.	29 970	8981	5.5	1.1	47.2	4.09	883	228
	Released mass (anaerobic)	5622 (18.8%)	1580	–		–		168 (19.0%)	41.4
	Released mass (aerobic)	2633 (8.8%)	990	–		–		89 (10.1%)	20.1

pHs of 7 and 10. The rate varies from 40 to 25 mg/m^2 week.

3.5. Annual release rate

The annual release rate can be calculated using the previously described experimental results and sediment accumulation areas. Accumulated sediment volume is approximately 25 000 m^3 over 0.128 km^2 on the north side, and 203 000 m^3 over 0.507 km^2 on the south side. The laboratory measured release rates can be applied to the sediment areas and compared to water quality P concentration.

The average release rate is 1.4 ton/year for aerobic conditions (DO = 7 mg/l, pH 6.2) and increases to 5.5 ton/year for anaerobic conditions (DO = 0 mg/l, pH 5). The mass rates of phosphorus in Han River water to the Jamsil area range between 200 and 400 ton/year for total P and 23–40 ton/year for PO_4–P in the winter, and between 3400 and 5100 ton/year for total P and 225–440 ton/year for PO_4–P in the summer, respectively (Kim et al., 2002). This is much greater than the release rate estimated from the batch experiments. Furthermore, estimates of the total phosphorus mass in the sediments using our data range from 360 to 460 ton.

This initial analysis suggests that sediment phosphorus release under normal circumstances will not significantly change Han River water quality. Han River phosphorus concentration would need to decrease to approximately 0.13 μg/l before sediment P release would equal river concentration. These estimates should be used cautiously, since other pollutants contained in sediments may have an impact. Also a catastrophic release in

Table 5
Phosphorus release rate with changing environmental conditions

Case 1. Phosphorus release rate with change of water depth (Sample SP-1, 20 °C, pH 6.8, sediment depth = 8 cm, anaerobic)				
Water depth (cm)	3	5	8	15
Release rate (mg/m^2 week)	57.2	67.2	61.8	68
Case 2. Phosphorus release rate with change of sediments depth (Sample SP-1, 20 °C, pH 6.8, water column depth = 10 cm, anaerobic)				
Sediments depth (cm)	3	5	8	15
Release rate (mg/m^2 week)	58.5	61.4	60	64.1
Case 3. Phosphorus release rate with temperature change (Sample SP-1, pH 6.8, water column depth = 10 cm, sediment depth = 8 cm, anaerobic)				
Temperature (°C)	2	10	20	35
Release rate (mg/m^2 week)	15.8	35.8	89.8	115.8
Case 4. Phosphorus release with change of phosphorus concentration of overlying water (Sample SP-1, 20 °C, pH 6.7, water column depth = 10 cm, sediment depth = 8 cm, anaerobic)				
Initial phosphorus conc. (mg/l)	2	1	0.5	0.1
Final phosphorus conc. (mg/l)	1.3	1.2	1.52	1.7
Release rate (mg/m^2 week)	−12.5	8.4	56.2	64.5
Case 5. Phosphorus release when using in situ water as overlying water (20 °C, DO 4.5, pH 6.6, water column depth = 10 cm, sediment depth = 8 cm)				
Site	SP-1	SP-2	SP-3	SP-4
Release rate (mg/m^2 week)	67.5	54.9	57.4	43.7

sediments (e.g. a large flood or earthquake that mobilized sediments) would have a large environmental impact.

3.6. Modeling phosphorus release rates

The previously described laboratory studies show that temperature, DO and pH have a major impact on phosphorus release rate. In order to better quantify the rates as a function of the various conditions, a simple model is proposed:

$$V\frac{dC}{dt} = FA = K(C_s - C)A \tag{1}$$

where F is the release rate from sediment (g/m^2 day) and is proportional to the area (A, m^2), a transfer parameter (K) and driving force. The driving force is equal to the difference in P concentration between the sediments (C_s, g/m^3) and overlying water concentration (C, mg/l). The parameter K is estimated from laboratory experiments. Eq. (3) can be rearranged to separate the variables, as follows:

$$\frac{dC}{(C_s - C)} = \frac{KA}{V}dt \tag{2}$$

Eq. (2) can be integrated and becomes Eq. (3) with $C=0$ at $t=0$, as follows:

$$\ln\left(\frac{C_s - C}{C_s}\right) = -\frac{KA}{V}t \tag{3}$$

Eq. (3) can be rearranged to create the exponential form as shown in Eq. (4), or can be solved

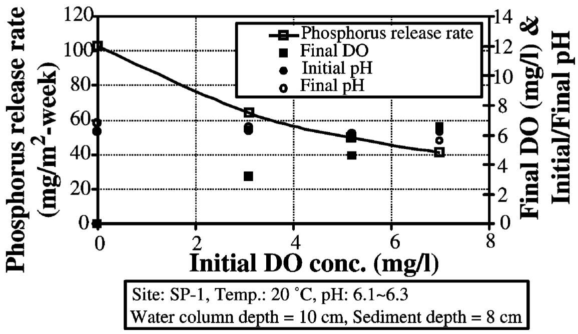

Fig. 4. Phosphorus release rate with DO change (Case 6).

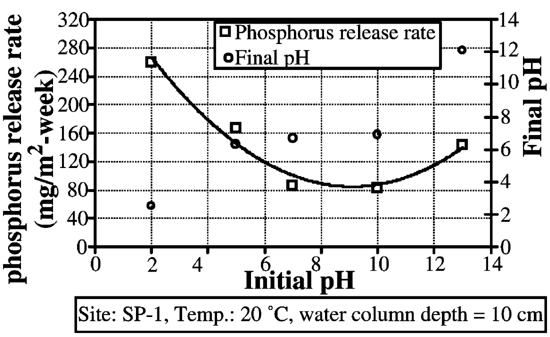

Fig. 5. Phosphorus release rate with pH change (Case 7).

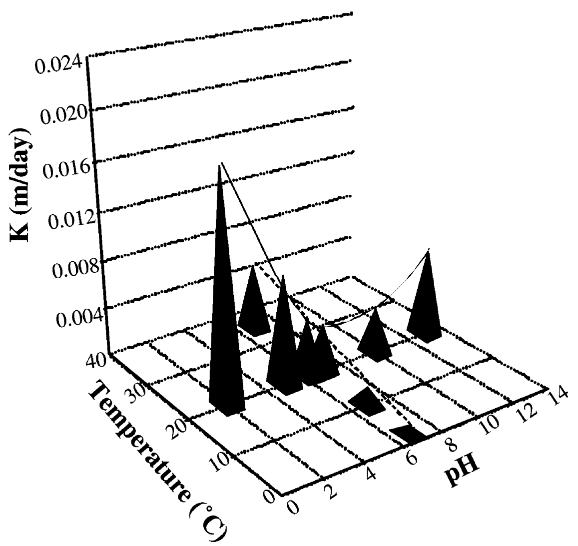

Fig. 6. K-value as a function of pH and temperatures for anaerobic conditions.

explicitly for K as shown in Eq. (5).

$$C = C_s\left[1 - \mathrm{Exp}\left(-\frac{KA}{V}t\right)\right] \tag{4}$$

$$K = -\frac{V}{tA}\ln\left[\frac{(C_s - C)}{C_s}\right] \tag{5}$$

The value of K was estimated from the anaerobic experiments in case studies 1 through 7 as a function of pH and temperature. Fig. 6 shows the value of K as a function of pH and temperature. Too few experiments were conducted with aerobic conditions to graph K values, but they ranged from 0.00283 m/day at DO = 3.1 mg/l to 0.00176 m/day at DO = 7 mg/l for 20 °C and pH 6.2. These values are less than measured under anaerobic conditions for the same pH and temperature. The next section describes P release experiments over time, and were used to verify the model.

3.7. Release rate studies vs. time

Fig. 7 shows natural phosphorus release as a function of time for aerobic (DO = 6 mg/l) and anaerobic conditions (DO < 0.5 mg/l) in the overlying water. After 120 h, the anaerobic and aerobic mass releases are approximately 90 and 30 mg P/m^2. The smooth lines are the model predictions for the K values described in the last section. None of the data points shown in Fig. 7 were used to estimate K values; therefore, the data act as a validation for the model. The model slightly under predicts anaerobic concentration but fits aerobic concentrations better. The fits have R^2 of 0.95 and 0.85 for anaerobic and aerobic conditions, respectively.

3.8. Sediment pollutant concentrations over time

During the 4-year study period, a large number of sediment samples were collected and analyzed for COD, total nitrogen, total phosphorus and ignition loss. The various concentrations are shown as a time series in Fig. 8. The upper graph shows the results for site SP-1 over a 3.5-year period. The bottom shows site SP-2 over 5-month period. Periodic dredging occurred during the 3.5-year period, but did not have a noticeable effect on sediment characteristics.

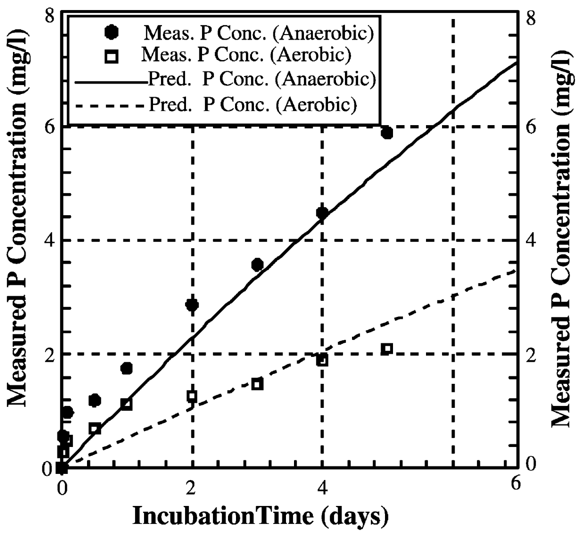

Fig. 7. Measured and modeled phosphorus concentration changes with incubation time.

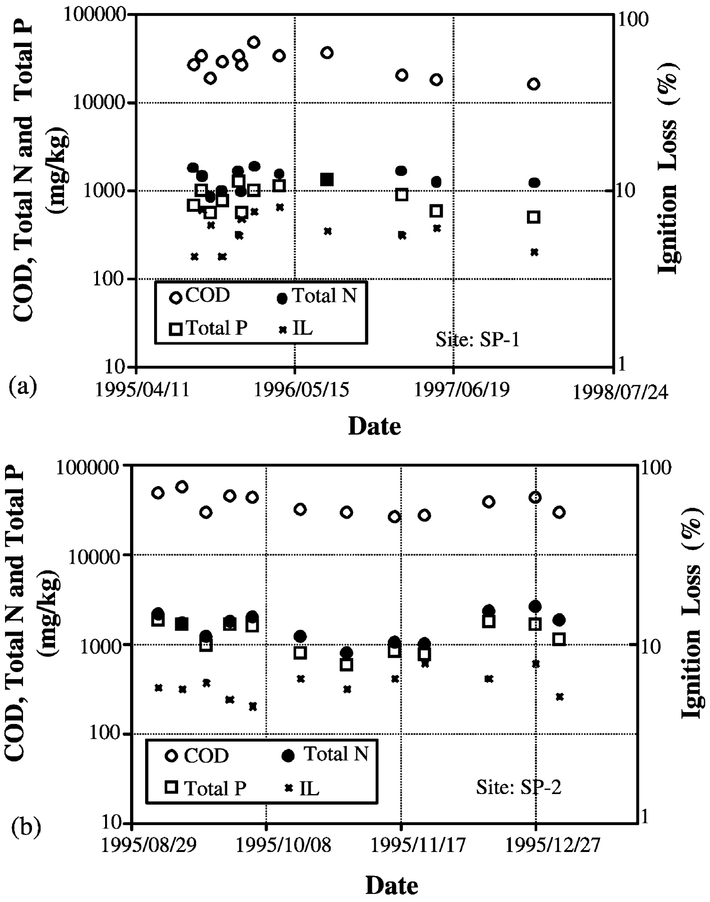

Fig. 8. Pollutant concentrations change in sediment: (a) site SP-1 during 3.5 years and (b) site SP-2 during 5 months.

4. Conclusions

This investigation evaluated sediment characteristics including pollutant concentrations, particle sizes, phosphorus existence types and release rates, and water quality in the JSD area of the Han River. The sediments are highly polluted because of various sources of pollutants. The release rate, as measured in laboratory reactor tubes with long exposures, is low, as compared to the current total phosphorus load in the river. The release rates are low compared to the phosphorus loading in the river, and suggest that water quality will not be significantly impacted under normal conditions. The following specific conclusions are made:

(1) The mean composition of sediments in the JSD, Han River, are clay 39 ± 3%, silt 36 ± 3% and sand 25 ± 2%, and are classified as silty clay, according to the Unified Soil Classification system.

(2) The COD and total P in the sediments ranged from 18 990 to 35 550 mg/kg and 580–1150 mg/kg, respectively. The mean COD, total P and total N concentrations in sediments are 29 970, 883 and 1080 mg/kg, respectively. Mean ignition loss is 5.5%.

(3) Mean nitrogen and phosphorus concentrations and ignition loss decrease with sediment depth and the differences between levels are significant at the 99% confidence level. COD concentration shows no statistically significant trend. The

trend might suggest a removal mechanism in the sediments.

(4) Phosphorus is distributed nearly evenly among NAI-P, apatite-P and residual-P forms. Very little adsorbed-P was found.

(5) The forced release of COD under anaerobic conditions ranged from 3340 to 7880 mg/kg or 19% of the total COD. Forced total P release was 105–220 mg/kg, and also averaged 19% of the total P. Under aerobic conditions, release was much less, and was 8.8% for COD and 10% for total P.

(6) Natural phosphorus is released at varying rates depending upon environmental conditions. In aerobic conditions, the release rate is 20–40 mg/m^2 week, which is less than half the anaerobic rate of 80–100 mg/m^2 week.

(7) In bench scale experiments, the phosphorus release rate was relatively constant for different sediment and overlying water depths, and ranged from 57 to 68 mg/m^2 week in anaerobic, near neutral pH conditions. Release rate is a function of pH and is minimum at neutral pH.

(8) Phosphorus release rate is strongly influenced by temperature, increasing from 18 mg/m^2 week at 0 °C to 118 mg/m^2 week at 35 °C. The Han River varies from 1 to 24 °C, which means that temperature will affect release rates.

(9) An equilibrium model is proposed which uses a single parameter, K, and accurately predicted P concentrations in time series experiments. The value of K was estimated as a function of pH and temperature.

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