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Phosphorus removal characteristics of chemical coagulation process to decrease phosphorus loadings in stream water from agricultural area

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ABSTRACT

Phosphorus (P) loadings, along with those of other nutrients, are a major cause of eutrophication. Operation reports of a phosphorus treatment pilot plant (PTPP) installed in Saemangeum Reservoir to decrease P loadings of stream water from an upstream agricultural area were examined. This was aimed at assessing the treatment efficiency and P removal characteristics of chemical coagulation for advanced nutrient removal and determining the optimal coagulant dose for P removal, based on the mole ratio of aluminum to phosphorus (Al:P). Aspects of coagulant dose operation for rainfall events and parameters affecting P removal efficiency were examined. Total phosphorus (TP) concentration of treated water in the PTPP was maintained below 0.1 mg/L; this satisfies the water quality criterion for TP discharge from wastewater treatment plants in the Saemangeum watershed. The P removal efficiency increased with increasing rainfall intensity because of the influent suspended solids washed out from non-point-source pollution by rainfall, whereas organic matter decreased P removal. The empirical molar Al:P vs. effluent-soluble TP associated with the minimal soluble P concentrations in treated water varied from 2–6:1, a high range compared with the typical coagulation process for P removal in municipal wastewater treatment plants.

Keywords: Alum; Chemical coagulation; Non-point source pollution; Nutrients removal; Phosphorus loading; Rainfall

1. Introduction

The Saemangeum Reservoir, an artificial lake in South Korea, has an extensive water surface area of 118 km^2. Increasing demands to reduce phosphorus (P) loadings discharged from the upstream agricultural area require greater efficiency in water treatment because large amounts of agricultural nutrients enter the Saemangeum watershed. Algal growth has gradually increased in the water body every summer, and P control is becoming the main issue in water quality management in the Saemangeum Reservoir [1]. There is an urgent need to decrease upstream pollutant loadings so that the water quality meets the criteria for domestic and agricultural water resources.

The target total phosphorus (TP) concentration for the Saemangeum Reservoir is in the range of 0.05–0.1 mg/L in. A low P concentration is required to satisfy the criterion (a limit of 0.1 mg/L) for both the effluent of municipal wastewater treatment plants and surface water in the upper watershed. Therefore, the local government is taking treatment facilities into account in attempting to decrease the P loadings of surface water at several points in the upstream portion of the Saemangeum watershed.

In a similar case concerning natural surface water, a phosphorus elimination plant (with a capacity of 518,000 m^3/d) was used to remove P loadings from surface water in Lake Tegel, which contains 23 million tons of water and is a source of tap water for Bonn and Siegburg, Germany [2,3]. In response to intensive eutrophication problems, phosphorus elimination plants were installed at their main inflows in the early 1980s, resulting in substantial decreases in TP concentrations (from several hundred mg/m^3 before the installation to a few tens of mg/m^3 after the installation), as well as decreases in phytoplankton biomass.

In Wahnbach Reservoir, to control the mesotrophic condition of the lake water, the P loading had to be decreased by approximately 90% of the total maximum daily loads (TMDLs) because almost all of the TMDLs were discharged into the lake from the upstream watershed. The average P concentration reduced to less than 90 mg/m^3 using coagulation and multiple filtration processes (432,000 m^3/d) for the upstream water of the Wahnbach Reservoir. The organic phosphate concentration was reduced to approximately 30 mg/m^3, and the treatment processes made it possible to maintain the effluent P concentration at approximately 5 mg/m^3 after sedimentation as a pre-treatment process [4].

Coagulation has been used to treat lake water and sediments in many locations, such as the Foxcote Reservoir in England [5], Terra Nova in the Netherlandst [6], Vadnais Lake in the United States [7], and others. According to Bakker et al. [8], various iron salts have been added in 10 field studies as a restoration measure, and P retention increased in most cases.

The theoretical molar ratio of Al:P for chemical phosphorus removal is expressed by Eq. (1) as follows [9]. During wastewater treatment, aluminum ions react with hydroxyl ions at pH levels above 6 and produce various aluminum hydroxide ($Al(PO_4)_n^{3-n}$) or complicated hydroxyl aluminum phosphate ($Al(PO_4)_{(3-n)/3}(OH)_{n(s)}$) precipitates. These precipitates are the result of the competing reaction between aluminum hydroxide and aluminum phosphate that occurs because of the pH and phosphate concentration. Because aluminum ions in water react with hydroxyl ion and phosphate ion under different conditions, as shown in Eqs. (1)–(3), the molar ratio of Al:P for phosphorus removal must be greater than the stoichiometric ratio of the precipitate, 1:1.

$$Al^{3+} + H_nPO_4^{n-3} \rightarrow AlPO_4 + nH^+ \quad (1)$$

$$Al^{3+} + OH^- \rightarrow Al(OH)_n^{3-n} \quad (2)$$

$$Al(OH)_n^{3-n} + (3-n)/3H_nPO_4^{3-n} \rightarrow \left[Al(PO_4)_{(3-n)/3}(OH)_n\right]_{(s)} + n(3-n)/3H^+ \quad (3)$$

The stoichiometric molar ratio of Al:P is variable, indicating the formation of aluminum–hydroxy–phosphate precipitates. Based on the literature, Power et al. [10] concluded that although a mechanism of adsorption/ion exchange of phosphate ions with aluminum hydroxide flocs has been proposed, there is also evidence for the direct precipitation of insoluble aluminum phosphates. However, the stoichiometric 1:1 molar ratio of Al:P in $AlPO_4$ cannot be achieved in the field, and the actual ratio between added aluminum and removed P is 2:1 or higher.

In this study, a small-scale phosphorus treatment pilot plant (PTPP) was installed in the midstream of the Saemangeum watershed and operated to evaluate the treatment efficiency and P removal characteristics of a chemical coagulation process as an alternative for P treatment. Based on the daily operation reports from the PTPP, the removal efficiency of P was evaluated every day, and the treatment characteristics of the chemical coagulation were evaluated to determine the optimal conditions for coagulation to reduce P loadings discharged from the upstream into the lake water. The treatment process involved the use of a coagulation chamber and subsequent sedimentation tank. The operation of the plant and results of the coagulation and sedimentation processes were evaluated over a period of 5 months. The present study was conducted with the following objectives:

- To establish a small-scale PTPP in the midstream of the Saemangeum watershed to treat P loading,
- Determination of optimal dose of chemical coagulant for P removal,
- Determination of resulting water quality to evaluate coagulate efficiency.

2. Materials and methods

2.1. Study area

The Saemangeum Reservoir, is located downstream of the Mankyung River in South Korea. The lake water of the Saemangeum Reservoir is used for domestic and agricultural purposes in the reclamation area, according to the Master Plan of Saemangeum National Project. Therefore, even the P contained in the stream water needs to be treated to meet the P concentration criterion for water quality in the Saemangeum watershed.

Most of the watershed of the Mangyeong River, which encompasses the three smaller watersheds listed in Table 1, covers agricultural land. The effluent of the municipal wastewater treatment plant (which has a capacity of 403,000 m^3/d) flows continuously into the upstream branch of the Mangyeong River, as shown in Fig. 1. Non-point source pollutants enter the water body during intensive rainfall events, including large quantities of suspended solids (SS) from the agricultural land. There are few industrial complexes within the watershed. Hence, the types of pollutants that are common in industrial wastewater, such as heavy metals, have hardly any influence on the water quality of the entire stream. The PTPP was constructed at the end point of the midstream of the Mankyung River to evaluate the treatment efficiency and P removal characteristics of a chemical coagulation process as an alternative for decreasing the P loading discharged upstream.

The operation of the PTPP was initiated at the end of the summer (August 2016), when heavy rains are frequent, and terminated in early winter (December 2016), when farming ends because of low temperatures and dry weather. The P loadings discharged from the upstream of the Mangyeong River are summarized in Table 1 [11].

Table 1
Phosphorus source and daily P loadings flow into the watershed installed the intake point of PTPP

Watershed	Source	Total (kg/d)	Domestic (kg/d)	Livestock (kg/d)	Industry (kg/d)	Land (kg/d)	Etc. (kg/d)
Mangyeong A (forest area)	PS	36.839	29.456	0	5.808	0.053	1.522
	NPS	284.516	1.405	143.617	0.005	139.489	0
	Sub-total	321.355	30.861	143.617	5.813	139.542	1.522
Mangyeong B (agriculture area)	PS	145.093	119.553	1.659	4.847	0.078	18.956
	NPS	313.087	1.569	159.317	0.013	152.188	0
	Sub-total	458.18	121.122	160.976	4.86	152.266	18.956
Jeonju A (urban area)	PS	159.473	149.989	0	6.538	2.326	0.62
	NPS	177.283	19.65	11.153	1.414	145.066	0
	Sub-total	336.756	169.639	11.153	7.952	147.392	0.62
Sum	PS	341.405	298.998	1.659	17.193	2.457	21.098
	NPS	774.886	22.624	314.087	1.432	436.743	0
	Sub-total	1,116.291	321.622	315.746	18.625	439.2	21.098

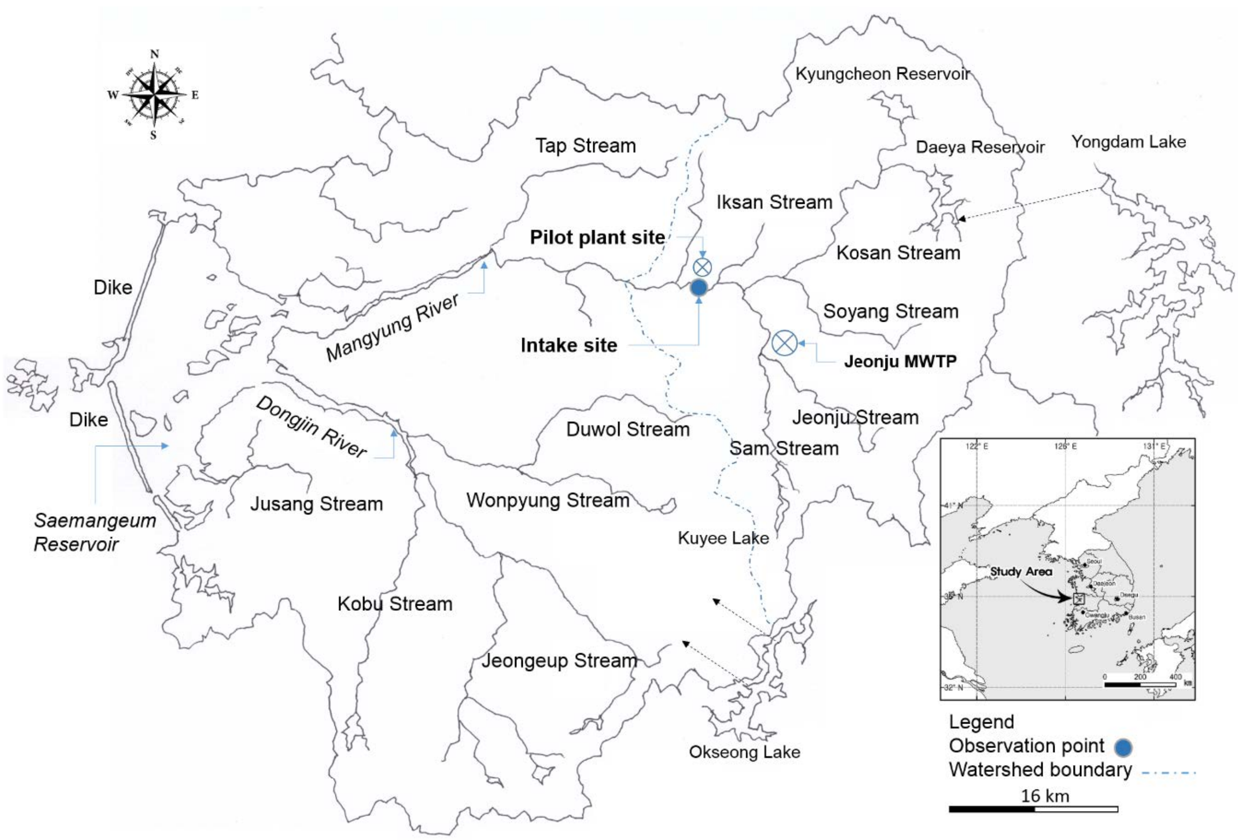

Fig. 1. Map of study area and location of PTPP.

2.2. Phosphorus treatment pilot plant

The intake equipment of the PTPP was installed with a floating gate valve at a point where stream water flows at all times and is conveyed through a conducting pipeline (0.32 km long). The PTPP (capacity 500 m^3/d) was used with a conventional chemical coagulation process to treat the influent stream, as shown in Table 2 and Fig. 2.

2.3. Operation and measurements

The coagulation process of the PTPP was conducted under a velocity gradient G in the range of 300–500 s^{-1} for 1 min for rapid mixing, followed by a G in the range of 15–85 s^{-1} for 20 min for slow mixing. The subsequent sedimentation process was conducted for 4 h to precipitate the P particles formed by the preceding coagulation, at a

Table 2
Main processes of pilot plant

Processes	Shape	Number	Volume (m^3)	Dimension	Residence time
Grit chamber	Rectangle	1	3.9	1.2 W × 1.8 L × 1.8 H	9.3 min
Rapid mixing tank	Square	1	1.2	0.9 W × 0.9 L × 1.5 H	3 min
Flocculation tank	Square	2	15.1	2.1 W × 4.0 L × 2.1 H	40 min
Sedimentation tank	Circle	1	82.9	Ø6.5 × 2.8 H	4.0 h

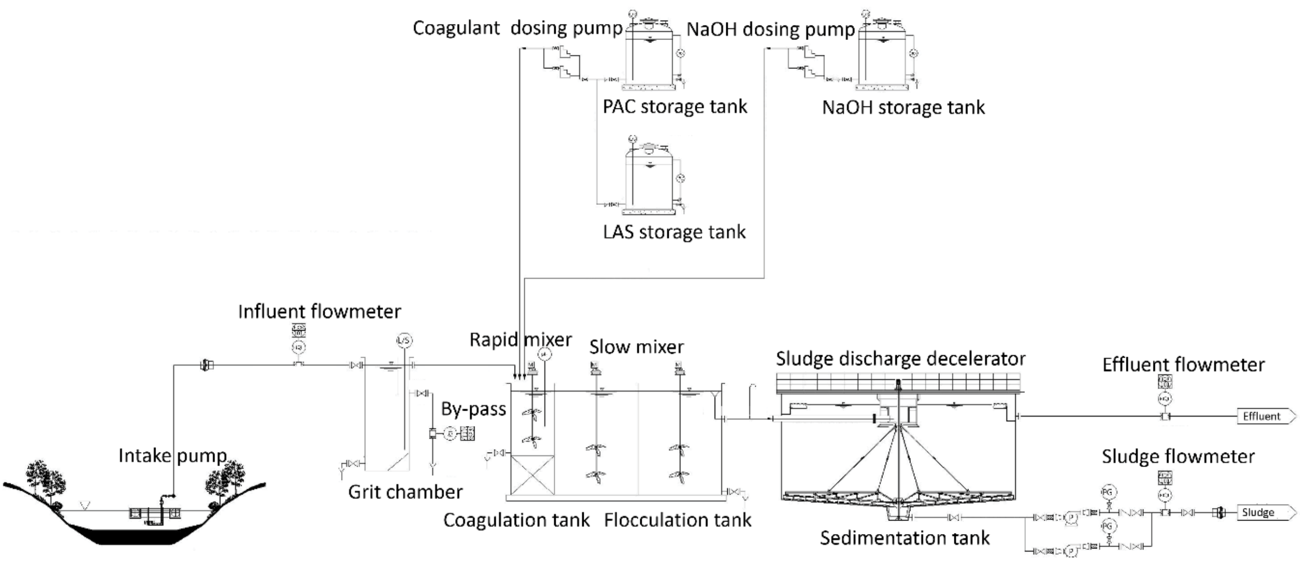

Fig. 2. Schematic diagram of the phosphorus treatment pilot plant (PTPP).

hydraulic loading rate of 15 m^3/m^2 d and weir loading rate of 50 m^3/m d.

The daily coagulant dose was determined using a jar test. The coagulants that were used alternately were polyaluminum chloride (PAC), $Al_nCl_{(3n-m)}(OH)_m \times 14H_2O$ as Al_2O_3 10% and liquid aluminum sulfate (LAS), $Al_2(SO_4) \times 18H_2O$ as Al_2O_3 8%. The influent and effluent of PTPP were measured every day, and on the basis of the daily water quality, the P removal efficiency was evaluated to monitor the performance of the coagulation process and the influence of rainfall on the P treatment. The water quality was measured by the Standard Methods for the Examination of Water and Wastewater [12].

Table 3 presents a summary of the results of water quality measurements made by a national monitoring network [13] during 1989–2017 for the monitoring point "Kimje" in the Mangyeong River.

3. Results and discussion

3.1. Daily operation summary

3.1.1. Water quality and treatment efficiency for study period

The water temperature of the influent gradually declined and was in the range of –1.7°C to 29.6°C (16.0°C on average) during the application of the coagulation process with the PTPP. The flow rate of the PTPP was in the range of 197–564 m^3/d (455 m^3/d on average). The coagulants were alternately dosed based on the results of the jar test, which was carried out daily. The doses were in the ranges of 13.7–97.5 ppm (39.5 ppm on average) for PAC and 20.6–62.1 ppm (34.8 ppm on average) for LAS. Removal of P from water in the coagulation unit requires not only the proper coagulant dose but also sufficient alkalinity of the raw water. The alkalinity of the influent was in the range of 35.7–100.9 mg/L as $CaCO_3$ (74.76 mg/L as $CaCO_3$ on average) while the theoretically required alkalinity was calculated to be in the range of 22.1–33.2 mg/L as $CaCO_3$, depending on the coagulant dose. Thus, additional alkalinity was not necessary.

Recent work by Szabó et al. [14] showed that although there is an optimum pH range for P removal, this optimum range is relatively wide (5–7) and the effectiveness of P removal diminishes outside this range. In the removal of phosphate from water to induce precipitation, the molar ratio and pH are key parameters in determining the residual phosphate concentration [15]. The precipitation reactions are dependent on the phosphate concentration and pH, depending on the composition of the wastewater [16]. In addition, other hydrolysis products of aluminum may form, depending mainly on the pH [17]. In this study, the pH was comparatively stable, in the range of 6.5–7.8, with an average of 7.27 for the influent and 7.16 for the effluent. The range of influent turbidity was 1.36–9.55 nephelometric turbidity units (NTU), which is typical for stream water, and

Table 3
Water quality of Kimje point located nearby PTPP in Mangyeong River

Month	pH	DO (mg/L)	BOD (mg/L)	COD (mg/L)	SS (mg/L)	TN (mg/L)	TP (mg/L)	PO_4–P (mg/L)
1	7.51	9.16	6.51	12.63	16.02	9.99	0.52	0.11
2	7.44	9.07	6.49	13.44	18.62	9.84	0.55	0.12
3	7.54	9.51	6.69	12.52	23.11	10.01	0.52	0.14
4	7.60	8.95	6.20	12.20	20.72	7.22	0.42	0.13
5	7.57	8.84	6.76	12.07	15.49	7.34	0.45	0.13
6	7.46	8.05	6.26	12.22	19.91	6.80	0.46	0.18
7	7.56	7.68	5.30	10.08	34.98	4.53	0.32	0.10
8	7.61	7.64	4.95	9.20	26.17	4.42	0.30	0.10
9	7.60	8.30	5.16	9.18	18.76	4.88	0.34	0.11
10	7.62	9.30	5.37	10.58	20.99	6.39	0.37	0.06
11	7.60	9.00	5.69	11.25	18.95	8.13	0.42	0.10
12	7.41	9.31	5.67	11.39	17.50	8.44	0.43	0.11
Mean	7.54	8.73	5.92	11.40	20.93	7.33	0.43	0.12

the effluent turbidity range was 0.39–3.26 NTU (1.27 NTU on average).

Fig. 3 presents the influent and effluent P concentrations, including the removal efficiency of the PTPP, over the 5-month study duration. The effluent TP concentration was in the range of 0.019–0.076 mg/L (0.043 mg/L on average), and the TP removal efficiency was in the range of 23.0%–77.6% (57.6% on average), under an influent TP concentration in the range of 0.060–0.192 mg/L (0.104 mg/L on average). As a result, the TP concentration of treated water in the PTPP was stably maintained below 0.1 mg/L, which is the water quality criterion for TP for discharge water from wastewater treatment plants. The influent concentration of PO_4-P was in the range of 0.003–0.096 mg/L (0.030 mg/L on average), and the effluent concentration of PO_4-P was in the range of 0.001–0.021 mg/L (0.009 mg/L on average). The removal efficiency of PO_4-P was thus in the range of 16.7%–91.3% (63.2% on average), which is a higher range than for TP.

3.1.2. Water quality and treatment efficiency for rainfall events

Over the course of the 5-month study period, rainfall events occurred on 50 d, and the amounts of rainfall were in the range of 0.04–95.2 mm/d (1.904 mm/d on average) over the whole period. For eight of the rainfall events, bi-hourly measurements were obtained for use in assessing the influence of rainfall on the P treatment characteristics of the PTPP.

The variations in the TP and PO_4–P concentrations, including the removal efficiency, are illustrated in Fig. 4. The TP removal efficiency during the rainfall events was in the range of 32.4%–87.7% (68.1% on average), which is approximately 10% higher than for the study period as a whole, that is, 0.064–0.299 mg/L (0.133 mg/L on average) in the influent and 0.013–0.079 mg/L (0.037 mg/L) in the effluent. The TP concentration did not increase drastically during the rainfall events because the watershed considered in this study has a wide catchment area that comprises primarily agricultural land and forest. The TP concentration of the effluent was also stably below the criterion limit of 0.1 mg/L.

The PO_4–P concentrations during the rainfall events were in the range of 0.001–0.150 mg/L (0.040 mg/L on average) in the influent and in the range of 0.001–0.021 mg/L (0.006 mg/L) in the effluent. The removal efficiency of PO_4–P was approximately 17% higher for the rainfall events than for the study period as a whole, that is, in the range of 40.0%–97.4% (80.3% on average).

The increase in removal efficiency was higher for PO_4–P than for TP. Considering that rainfall greatly increased the SS in the stream water, the increase in removal efficiency during the rainfall events is noteworthy. Fig. 5 shows the relationship between P removal efficiency and rainfall intensity. The P removal efficiency increased as the rainfall intensity increased.

3.2. Comparison of P treatment characteristics

The influence of rainfall on the P removal efficiency is described in the previous section. Fig. 6 illustrates how the P removal efficiency changed with the water quality during the rainfall events. The removal efficiencies of TP and PO_4-P increased as the influent SS increased, whereas the removal efficiency of both decreased as the influent chemical oxygen demand (COD) increased.

Previous studies reported the physical adsorption reaction on the surface of aluminum hydroxide occurs differently depending on the concentration. On the adsorption sites of aluminum hydroxide, silicate competes with phosphate (PO_4^{3-}), which is detected at low concentrations (less than 5 μM) in natural water. However, at higher PO_4^{3-} concentrations, color and COD are the main variables that decrease phosphate removal from lake water [18,19]. The crosscurrent results of this study lead us to conclude that the influent SS that is increased temporarily by rainfall enhances the P removal efficiency in the coagulation process, which is considered to be because the P originated from non-point source pollution. The PO_4–P of the influent does not seem to

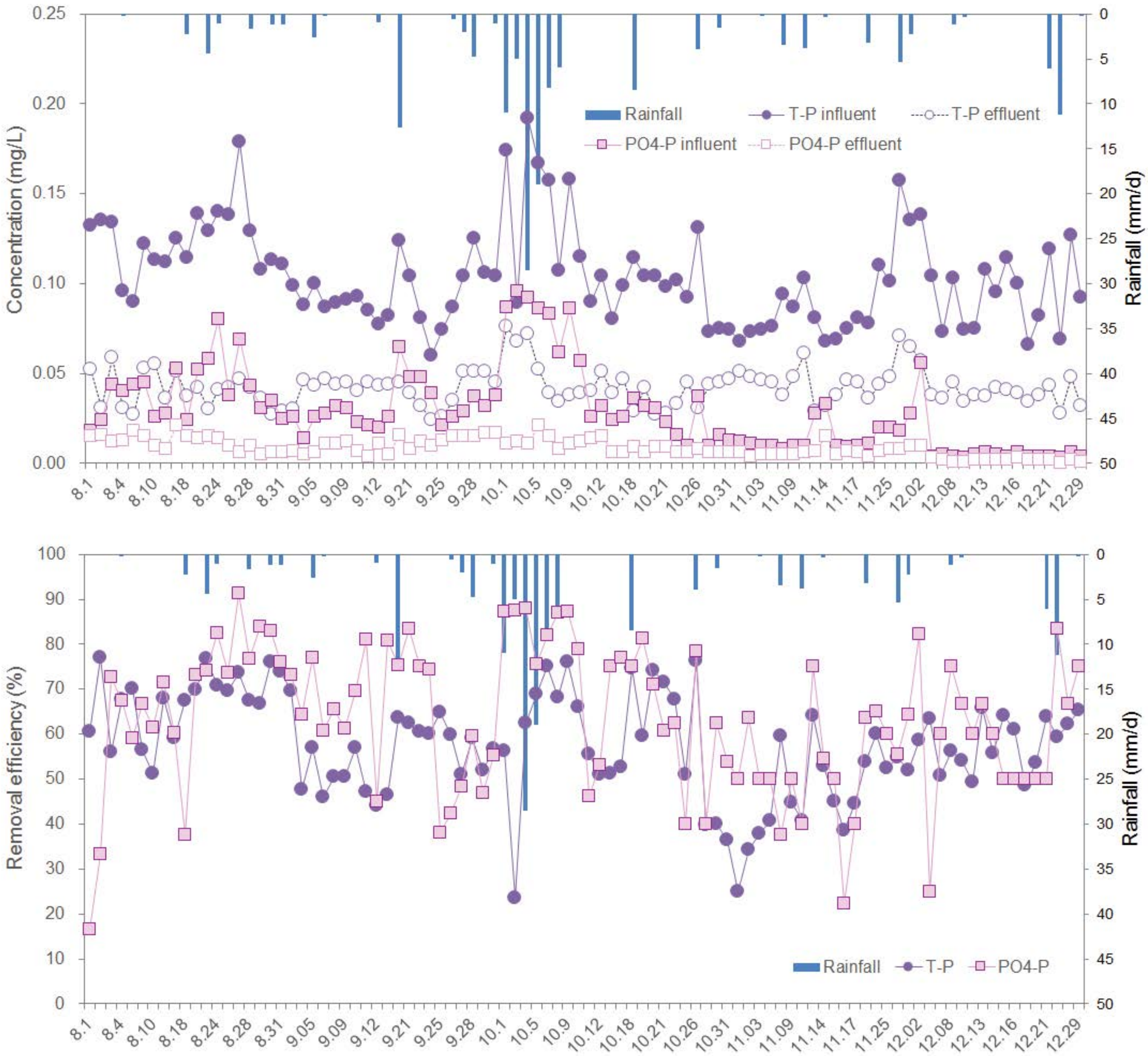

Fig. 3. Changes in phosphorus concentration and removal efficiency vs. operation time for PTPP.

compete with silicate on the adsorption sites of aluminum hydroxide, because the P concentration of the influent was not less than 5 μM on rainy days. Meanwhile, organic matter such as COD that was washed out into the water body by rainfall hindered P removal, as shown in Fig. 6b.

To compare the influences of SS and COD in the influent on the P removal efficiency of the PTPP, the P removal efficiency on dry days (i.e., the rest of the study period except the rainy days) was plotted as shown in Fig. 7. In contrast to the removal efficiency during rainfall events, the P removal efficiency decreased as the influent SS increased on dry days. The P removal efficiency increased with decreasing influent COD, as in the case of the rainfall events.

As with the P treatment characteristics during rainfall events, organic matter decreased the P removal efficiency of the coagulation process. It was also noted that during dry weather (days other than those when rainfall events occurred), the composition of the SS in the influent consisted of an organic component, as shown in Fig. 7b. The COD and biological oxygen demand (BOD) concentrations of the influent varied in proportion to the influent SS during rainfall events, whereas there was not a relation between SS and COD during dry weather. Consequently, the influent SS during dry weather, which was considered to be primarily organic matters, decreased the P removal efficiency of the coagulation process.

Phosphate removal can be achieved via two types of reactions in chemical coagulation: precipitation in the form of $AlPO_4$ particles, and sorption of P on the surface of alum flocs ($Al(OH)_3$). As reported in a previous study by Galarneau and Gehr [20], regardless of the amount of coagulant injected under the conditions of insufficient soluble phosphate in

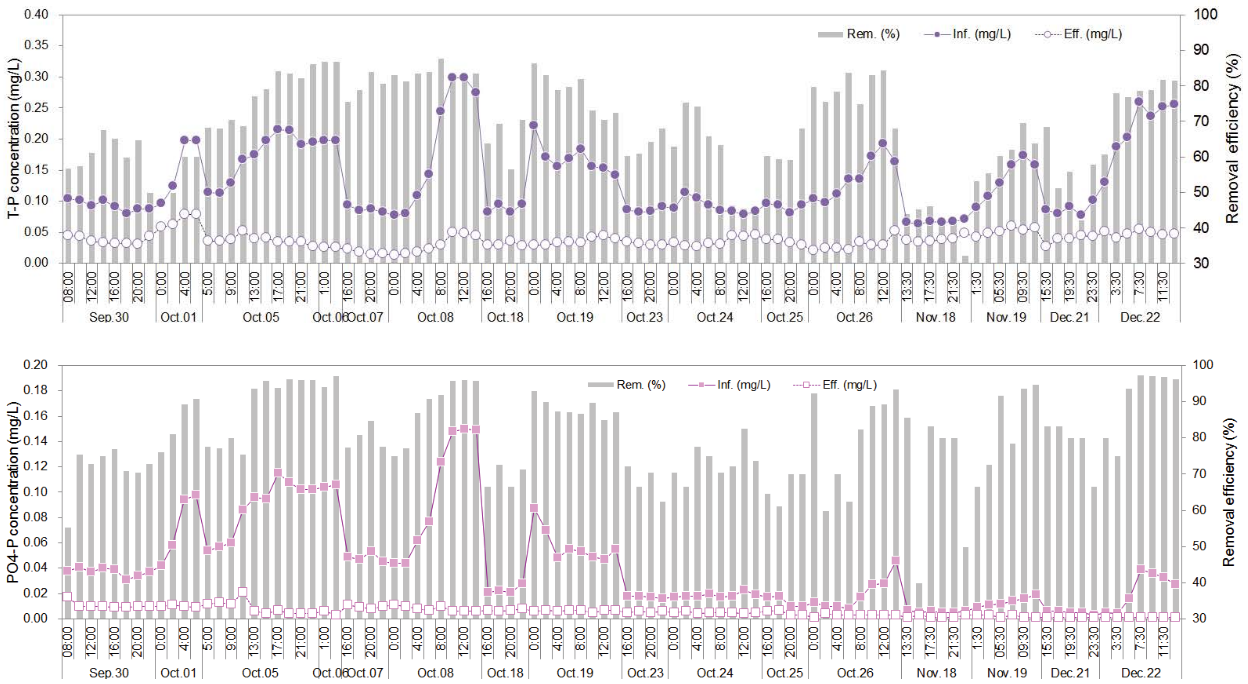

Fig. 4. P concentration and removal efficiency during rainfall events.
Note: Rainfall events: Sep 30–Oct 01 (11.6 mm/d), Oct 05–Oct 08 (33.2 mm/d), Oct 16–Oct 17 (29.6 mm/d), Oct 23–Oct 26 (7.8 mm/d), Nov 18–Nov 19 (13.4 mm/d), Dec 21–Dec 22 (23.9 mm/d).

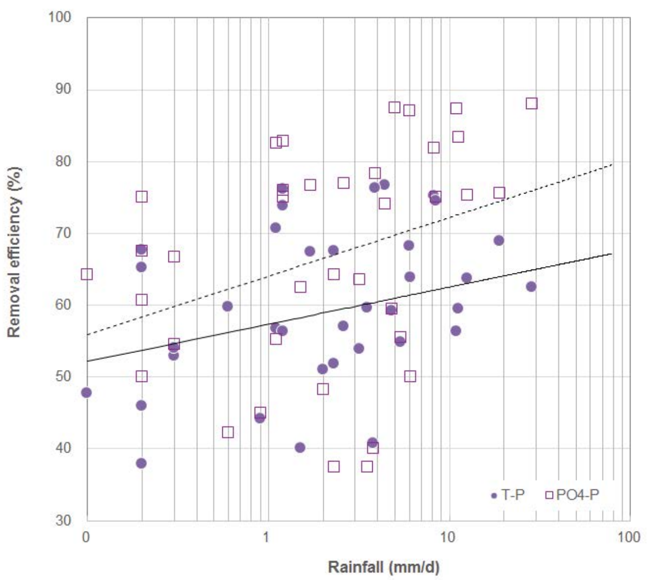

Fig. 5. P removal efficiency vs. rainfall intensity.

water, orthophosphate ion was not efficiently removed via classical chemical $Al(PO_4)$ precipitation. The concentration of soluble phosphate ion under neutral pH was 2.24 g/L for the solution to be in equilibrium with $Al(PO_4)$ particles. Consequently, in this experiment, phosphate removal by chemical coagulation seemed to be associated with the sorption of P onto the surface of $Al(OH)_3$ flocs, as corroborated by theoretical equilibrium and experiment results.

3.3. Molar ratio of P to Al

Two types of coagulants, PAC and LAS, were used to compare the resulting P removal efficiencies, and the two coagulants yielded similar results. Two competing reactions are involved when alum is added to phosphate-containing water. Disregarding the reactions between condensed and organic phosphates, the main reactions involve competition between the formation of aluminum hydroxides and aluminum phosphate. However, other compounds can be engaged in the formation of aluminum phosphate, and the actual ratio between added aluminum and removed P varies with the condition of water quality [21].

At high P concentrations, such as that of raw water in a wastewater treatment plant, proper treatment can be achieved with a low molar ratio of Al:P (1–3:1) to achieve high P removal efficiency. However, coagulation with a high molar ratio of Al:P is required to achieve high P removal efficiency at low P concentrations. Moreover, owing to the additional coagulants for the particles in water, the precise molar ratio of Al:P is difficult to predict in application of the coagulation process to P treatment. In a previous study by Johnson and Amirtharajah [22], the optimal molar ratio of Al:P to treat P in a mixed liquor of activated sludge and the effluent of a secondary settling chamber (TP > 0.5 mg/L, SS > 20 mg/L) was found to be in the range of 3–4:1.

Fig. 8 illustrates the operating Al:P molar ratio range in the treatment of P in the PTPP coagulation process. The operating Al:P molar ratio range in this study was wide and high (in the range of 1–7:1) in comparison with that in previous studies. The operating range of the coagulant dose

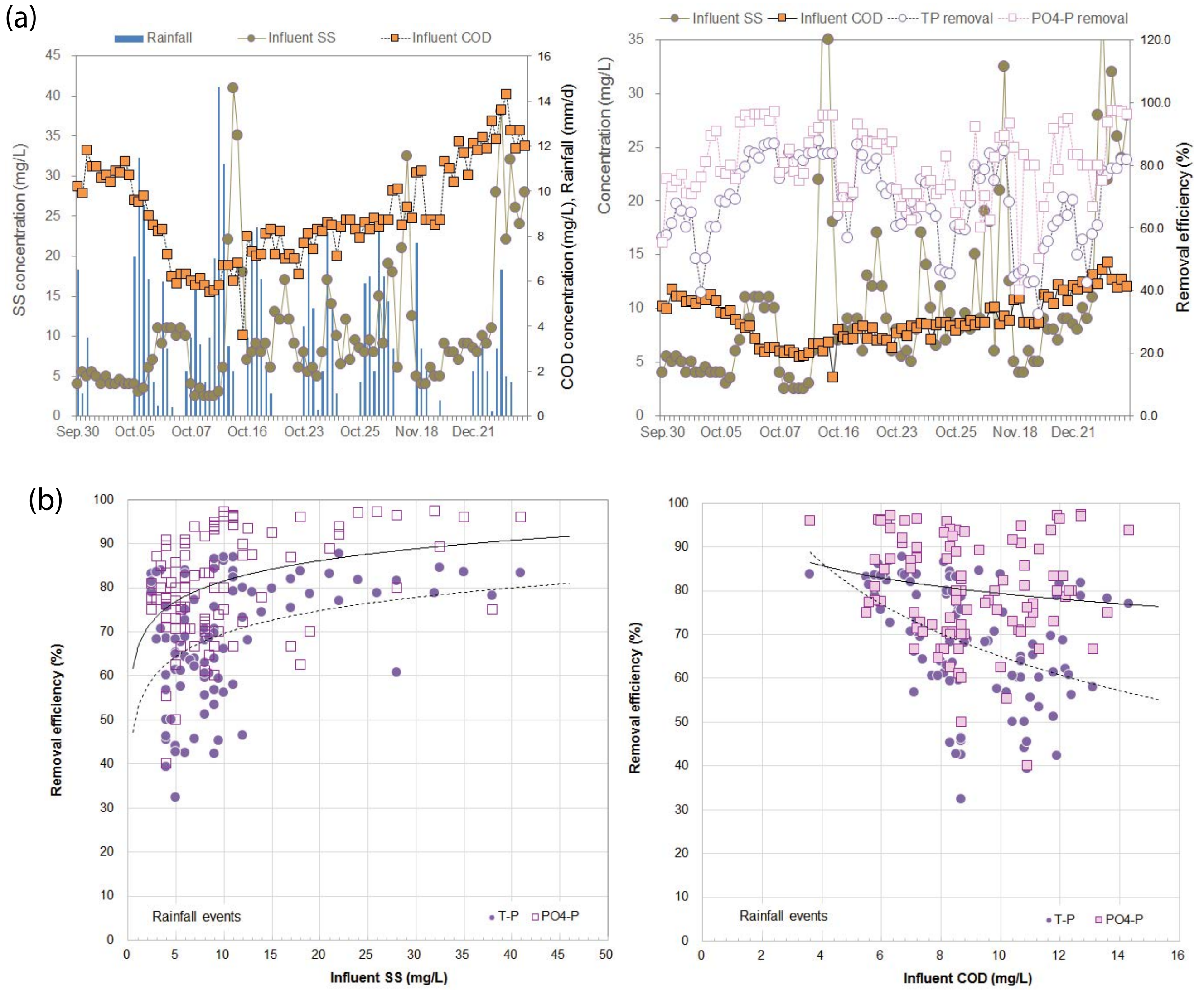

Fig. 6. Variation in P removal efficiency with water quality during rainfall events. (a) P removal efficiency and water quality of influent for rainfall events and (b) P removal efficiency vs. influent SS and COD concentrations.

fluctuated considerably because of the additional non-point source pollution on the 50 rainy days. The operating Al:P molar ratio range in the coagulation process of the PTPP was sufficiently high to satisfy the effluent TP concentration criterion (maximum of 0.1 mg/L) because the water quality of the influent was quite low (TP 0.060–0.192 mg/L, SS 2–18 mg/L). In comparing their operating Al:P ratios, it was difficult to detect any difference between the rainy days and the dry days. On the other hand, the practical stoichiometric molar ratio between added aluminum and removed P was in the range of 2–13:1 in the PTPP operation as shown in Fig. 8b.

In addition, the key reaction variable in the coagulation process is either the trivalent cation of aluminum ion or the surface formation of aluminum hydroxide. Based on the coagulant doses in the PTPP, Fig. 9 presents the operating mole [Al^{3+}] in terms of the influent pH, according to Johnson and Amirtharajah [22], and Amirtharajah and Mills' diagram [23]. The dots, indicating the coagulant dose, are located within the regimes of soluble aluminum species, indicating that the surface of the aluminum hydroxide provided properly for the physical adsorption reaction. For the rainy days, the dots shift to the left because of the lower influent pH, and there was no difference in the mole [Al^{3+}] between the rainy days and dry days.

The high Al:P molar ratio range of PTPP will lead to an increase in operation costs owing to the large amount of coagulant dose needed for treating the low P concentration of stream water. On the other hand, alum sludge as a resource for P removal can be applied to streams feeding water reservoir for eutrophication control [24]. In addition, the P-containing sludge produced from the PTPP can be used as a readily available material for fertilizer [25] and used for P recovery. However, the sludge of the PTPP may be economically infeasible for P recovery as P concentration of typical stream water is considerably lower as compared with the sewage or wastewater.

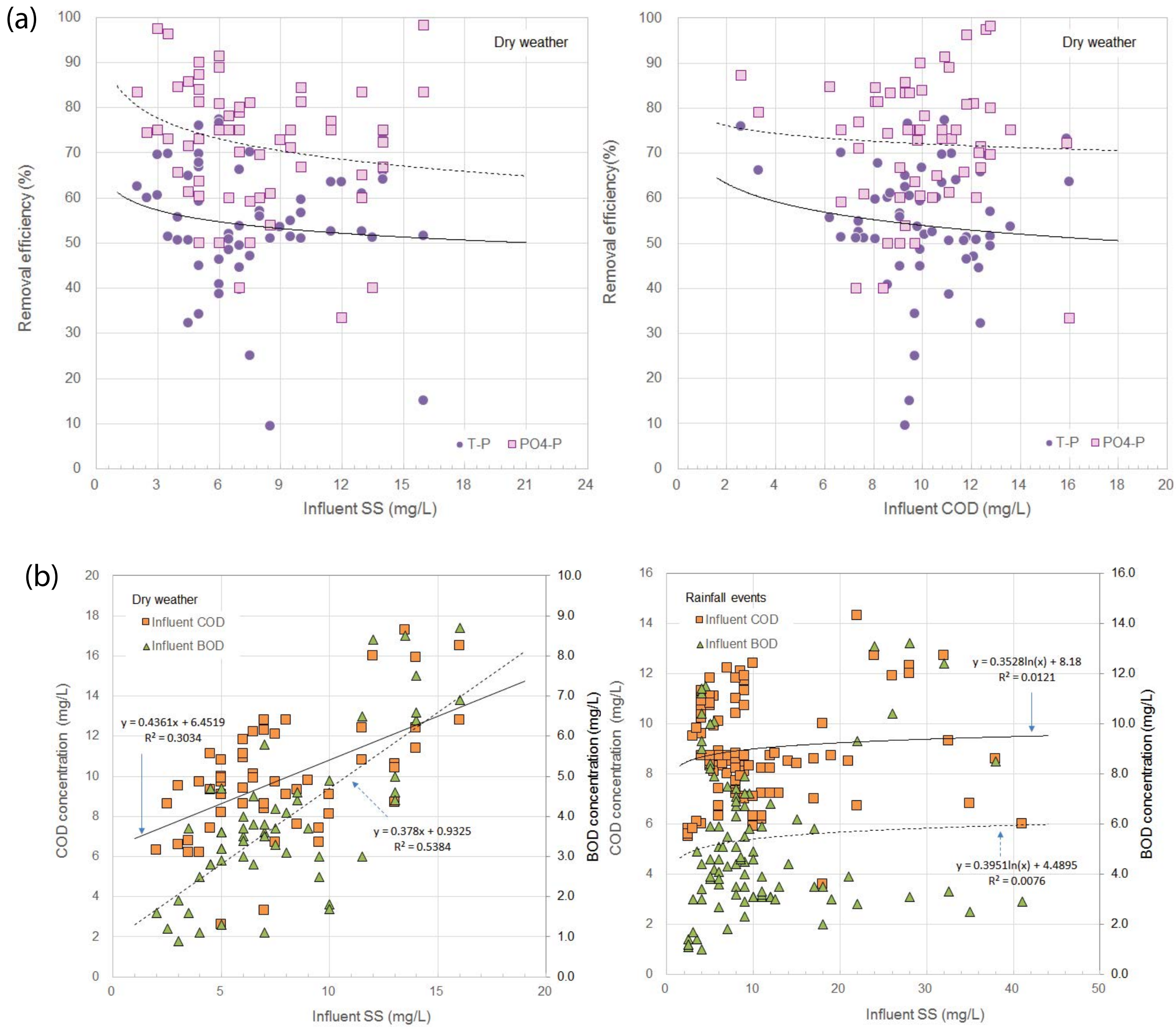

Fig. 7. Variation in P treatment efficiency and change in water quality for dry weather and rainfall events.

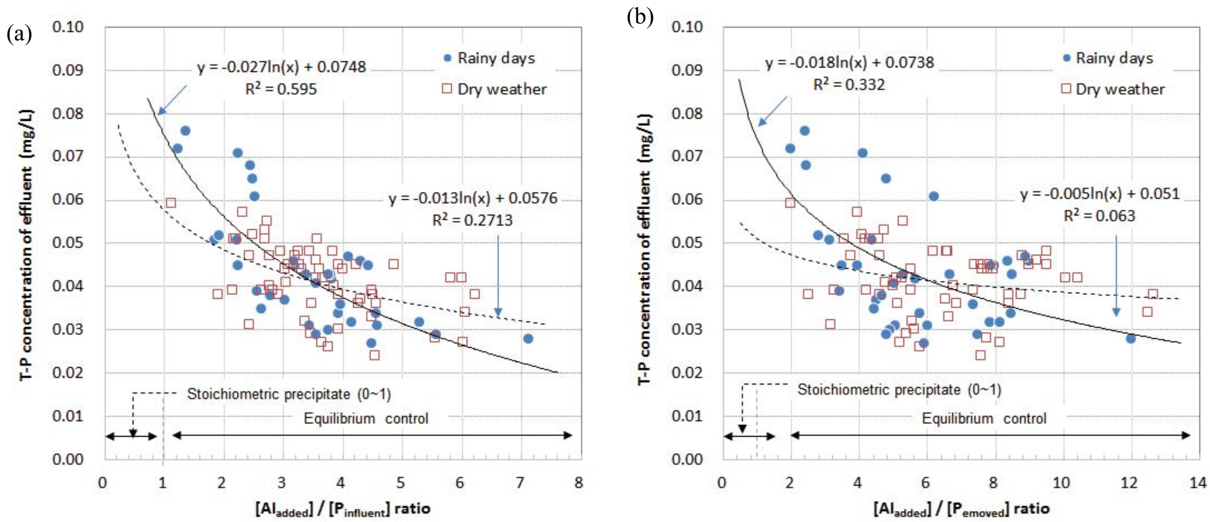

Fig. 8. Empirical values of molar ratios [Al]/[P] based on the PTPP operation data. (a) Molar ratios of added Al:influent P and (b) molar ratios of added Al:removed P.

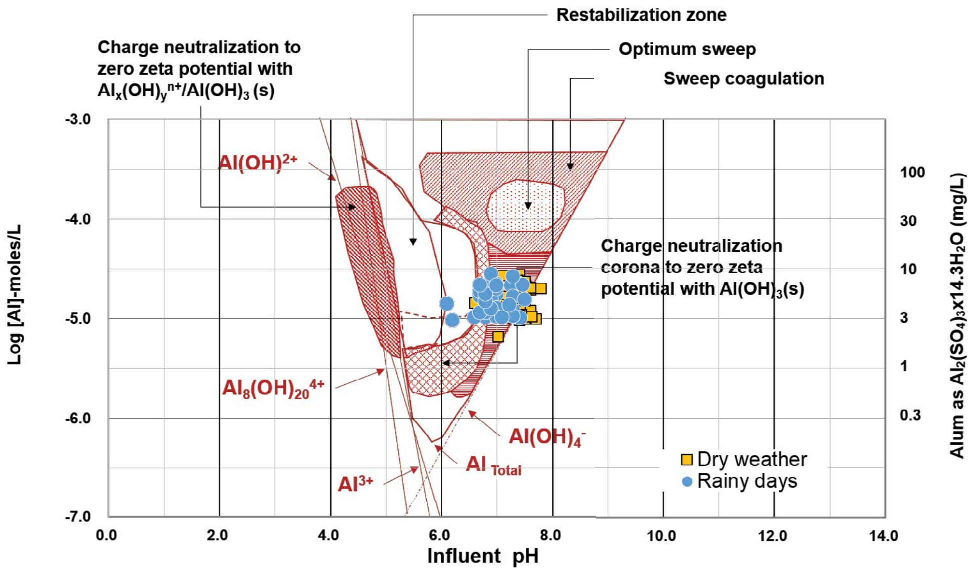

Fig. 9. Operated regime of coagulant dose in PTPP for P removal, based on Johnson and Amirtharajah [22], and Amirtharajah and Mills diagram [23].

4. Conclusions

To address the issue of eutrophication in the artificial lake, the Saemangeum Reservoir, a small-scale PTPP was installed and the treatment efficiency and P removal characteristics of a coagulation process to decrease P loadings in the stream water was studied. The results indicated that water quality for TP in the discharge water met the established criteria. TP removal efficiency was higher during the rainfall events compared with that during the entire study period, and increased with increasing rainfall intensity, because of the influent SS. Based on the relationship between SS and COD, the SS of the influent during dry weather was concluded to contain organic matter, unlike the influent SS during rainfall events. The crosscurrent results of this study lead us to conclude that the influent SS increased temporarily by rainfall enhances the P removal efficiency of the coagulation process, presumably because the SS originates from non-point source pollution.

The P removal efficiency during rainfall events increased with increasing rainfall intensity because of the influent SS, which was washed out from non-point source pollution by the rainfall. In contrast, increased influent COD during rainfall events, which is an indicator of the presence of organic matter, decreased the P removal efficiency of the PTPP. During dry weather, the P removal efficiency decreased with increasing SS as well as with increasing influent COD. Based on the relationship between SS and COD, the SS of the influent during dry weather was concluded to contain organic matter, unlike the influent SS during rainfall events. The crosscurrent results of this study lead us to conclude that the influent SS increased temporarily by rainfall enhances the P removal efficiency of the coagulation process, presumably because the SS originates from non-point source pollution.

The empirical molar ratios of Al:P vs. effluent-soluble TP varied in the range of 2–13:1 to reach minimal soluble P concentrations in the treated water. With regard to the mole [Al^{3+}] injected in water, there was no difference in the coagulant requirement between rainy days and dry weather.

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