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Estimation of Nutrient Elution and Removal on Sediment Surface of Clayey Canal Based on Hydraulic Model Experiments

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Abstract

A clayey canal tends to be selected over a concrete-lined canal to achieve water quality conservation in a land improvement project. Therefore, it is important to analyze quantitatively the interaction of nutrients on the sediment in a clayey canal. In this paper, the COD, nitrogen and phosphorus fluxes as well as elution and removal rates across/on the sediment surface were estimated based on hydraulic model experiments. The experiments were carried out for water under aerobic conditions at 30–32ºC (CASE 1) and 6–9ºC (CASE 2). In CASE 1, the net COD elution rate and the net phosphorus elution rate were 8.2 $mg{\cdot}m^{-2}{\cdot}day^{-1}$ and 11.5 $mg{\cdot}m^{-2}{\cdot}day^{-1}$, respectively. Nitrogen was removed by nitrification on the sediment surface so that the net removal rate which is composed of the denitrification rate, the settling rate and the elution rate was 15.1 $mg{\cdot}m^{-2}{\cdot}day^{-1}$. The rate constant in which the nitrogen removal is expressed as a first-order kinetic was 0.010 m/day. In CASE 2, the net COD elution rate and the net phosphorus elution rate were 9.9 $mg{\cdot}m^{-2}{\cdot}day^{-1}$ and 5.4 $mg{\cdot}m^{-2}{\cdot}day^{-1}$, respectively. The net nitrogen removal rate and its rate constant were 9.0 $mg{\cdot}m^{-2}{\cdot}day^{-1}$ and 0.0023 m/day, respectively. The rates of elution and removal increased remarkably with the temperature.

Discipline: Agricultural environment
Additional key words: water quality, denitrification, creek, chemical oxygen demand

Introduction

Since environmentally friendly implementation is required in a land improvement project, a clayey canal tends to be selected over a concrete-lined canal to achieve water quality conservation. Although it is expected that denitrification and decomposition of organic materials which may occur on the sediment surface, contribute to water purification, nutrient elution from the sediment may result in the deterioration of the water quality.

Numerous studies have been carried out to quantify nutrient processes across/on the water-sediment interface, although most were performed in wetland and lagoon waters[3].

The purpose of this study was to analyze the nutrient elution and removal rates to quantify the influence of a clayey canal on water quality, using hydraulic model experiments in which a sediment collected from a creek in the alluvial plain of the Chikugo-river was placed at the bottom.

Methods

As shown in Fig. 1, the hydraulic model consists of a rectangular tank, 200 cm long, 50 cm wide and 50 cm deep, which has a lid on it to prevent photosynthesis and the fall of dust into the water. Sediment collected from a creek in the alluvial plain of the Chikugo-river was put at the bottom of the tank, and water was poured continuously from the left weir into the tank and the outflow was collected in a bottle. The sediment was 21 cm thick. From the start of water-pouring to the beginning of the experiments, for 17 days, the tanks were allowed to stand

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for the sinking of suspended materials stirred up by initial water-pouring.

The experimental conditions are listed in Table 1. The experiments were carried out in 2 cases, at a high water temperature (CASE 1) and at a low water temperature (CASE 2). In every case, 2 RUNs were tested as follows: with sediment as mentioned above (RUN 1) and without sediment (RUN 2). RUN 2 is necessary for the estimation of the net effects of sediment on water quality and important to determine how freshly settled and easily decomposable organic materials on the sediment surface may affect the water quality, as Van Luijn et al.[5] suggested that such organic materials appeared to markedly influence the denitrification activity.

The water-pouring rate was controlled at 10 L/day, and the hydraulic retention time was 25 days. The poured water and outflow water collected in the bottle were analyzed for the concentrations of nitrate/nitrite nitrogen (NO_x-N), ammonia nitrogen (NH_4-N), total nitrogen (TN), inorganic phosphorus (PO_4-P), total phosphorus (TP) and chemical oxygen demand (COD) every 3 days, and the water temperature and the dissolved oxygen (DO) concentration of water were measured by electrodes continuously.

The properties of the pore water of the sediment are shown in Table 2.

Results and discussion

1. CASE 1

The DO concentration in the tanks changed within the range of 4–5 mg/L for RUN 1 and of 6–7 mg/L for RUN 2, and we observed an oxidized layer on the sediment surface after 10 days. Therefore, it appears that the experiments were carried out under aerobic conditions in both RUNs. The lower DO concentration in RUN 1 than that in RUN 2 was attributed to oxygen consumption on the sediment surface. The water temperature changed within the range of 30–32°C. The changes in the quality of the poured water and the tank water in CASE 1 are shown in Fig. 2.

Regarding the quality of poured water, there was a marked increase in the COD in the poured water from the beginning until it reached a value of 6.8 mg/L on the 28th day of the experiment. The TN concentration ranged from 1.9 to 2.6 mg/L and about 60 to 83% of nitrogen was in the NO_x-N form. The TP concentration was almost constant and very low, 0.08 to 0.26 mg/L.

Table 1. Experimental cases and conditions

Case		Run	
CASE 1	Water temperature: 30–32°C	RUN 1	With sediment
		RUN 2	Without sediment
CASE 2	Water temperature: 6–9°C	RUN 1	With sediment
		RUN 2	Without sediment

Table 2. Nutrient concentrations of the pore water of the sediment (mg/L)

	TN	TP	NH_4-N	NO_x-N	PO_4-P
CASE 1	2.53	2.97	0.91	0.60	3.10
CASE 2	–	–	0.19	0.25	4.19

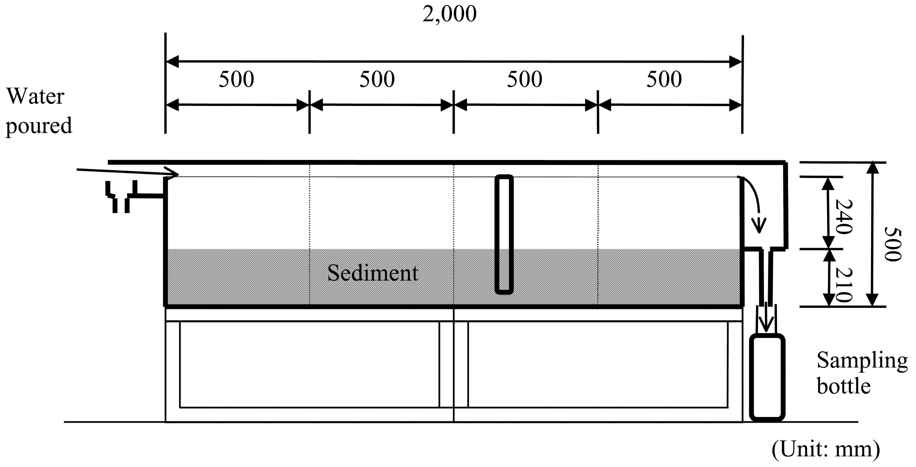


Fig. 1. Lateral view of the hydraulic model

In RUN 1, the COD began to rise on and after the 21st day, because of the rise of COD of the poured water and COD elution from the sediment. TN concentration and NO_3-N concentration gradually decreased by more than 1.0–1.5 mg/L during the experiment. Since the changes in the patterns of both TN and NO_x-N were parallel, most of the decrease in the concentration of nitrogen was attributed to the denitrification of NO_x-N. The NH_4-N concentration in the test tank was lower than that of the poured water, indicating that nitrification and denitrification proceeded remarkably throughout the experiment. The TP concentration and PO_4-P concentration began to rise on and after the 11th day, due to the phosphorus elution from the sediment.

In RUN 2, the water quality remained constant except for COD. The COD tended to increase with fluctuations throughout the experimental period. These characteristics were similar to those of poured water.

2. CASE 2

The experiments were carried out under aerobic conditions because the DO concentrations in the tanks were 6 to 7 mg/L for RUN 1 and 9 to 10 mg/L for RUN 2. An oxidized layer on the sediment surface could be observed after the 20th day, namely 10 days later than in CASE 1. The water temperature changed within the range of 6–9°C. The changes in the quality of the poured water and the tank water in CASE 2 are shown in Fig. 3.

The COD of the poured water was almost constant. Also the TN concentration of the poured water was constant, 2.7 to 2.9 mg/L and about 72 to 81% of nitrogen was in the NO_x-N form, while the TP concentration was very low.

In RUN 1, the NH_4-N concentration in the tank was lower than that of poured water, and the TN concentration and NO_3-N concentration gradually decreased during the experiment. Although these characteristics were similar to those in CASE 1, the rates of change were lower than those in CASE 1. Also, the rise of the TP concentration and PO_4-P concentration was 1/3 of that in CASE 1, and the rise of the COD was slow.

In RUN 2, the water quality was stable except for COD which tended to decrease with time throughout the experiment in contrast to CASE 1.

Estimation of elution and removal rates

The nutrient elution rate and removal rate can be estimated based on the nutrient mass balance in the tank. Assuming that $Q = Q_{in} = Q_{out}$, the mass balance during an experiment, from t_0 to t_e, is described by Equation (1) as follows:

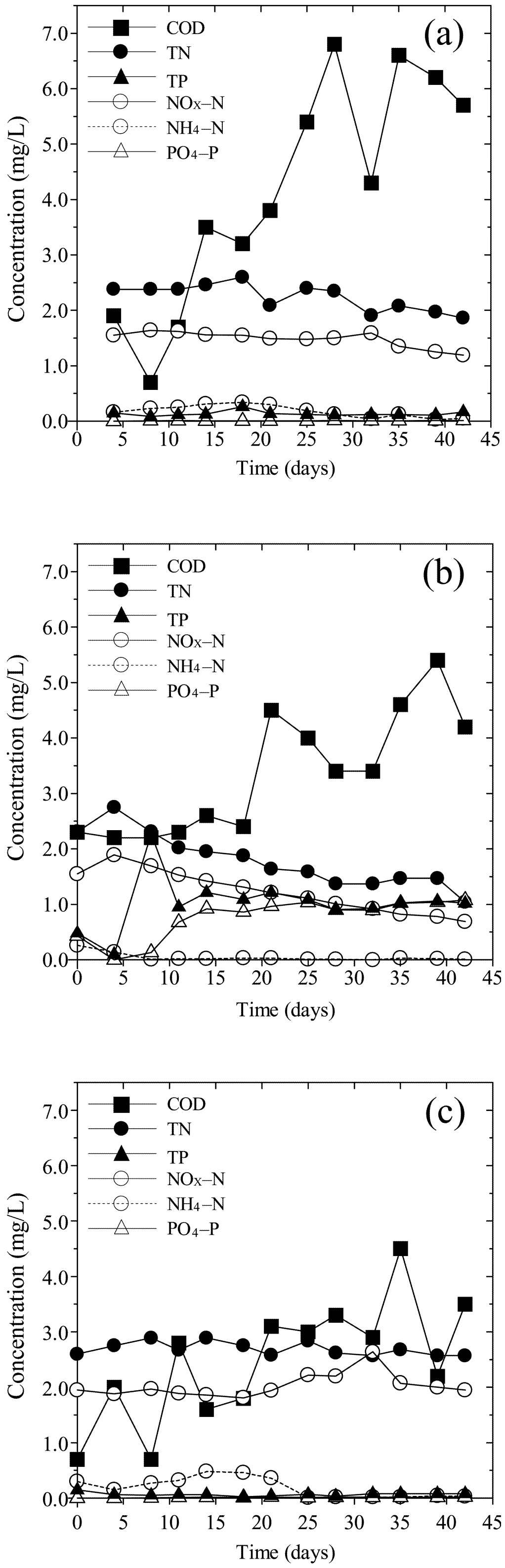


Fig. 2. Changes in water quality in CASE 1
(a): Poured water, (b): RUN 1,(c): RUN 2.

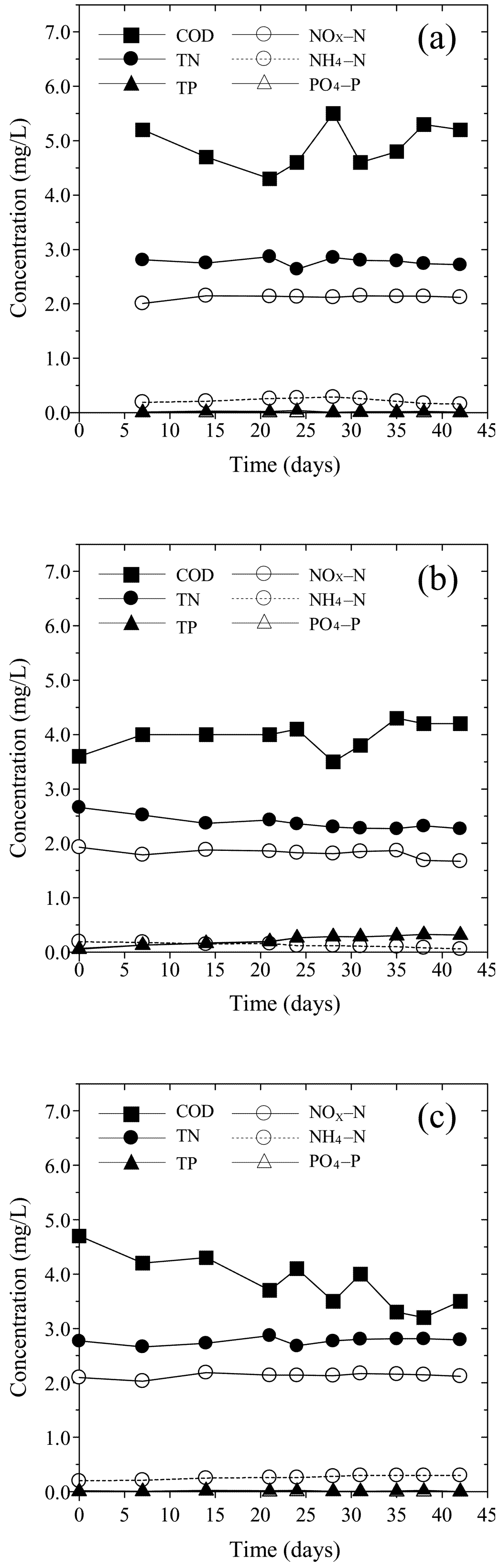


Fig. 3. Changes in water quality in CASE 2
(a): Poured water, (b): RUN 1,(c): RUN 2.

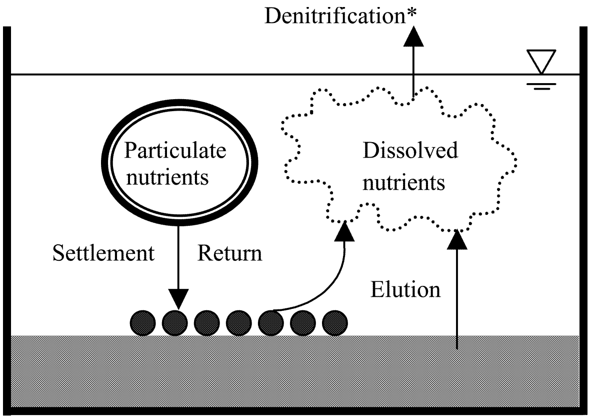
$$\frac{V}{h}\int_{t_0}^{t_e} E\,dt \;=\; V(C_e - C_0) + Q\int_{t_0}^{t_e} C - C_{in}\,dt \qquad (1)$$

where C is the nutrient concentration in the tank (mg/L), C_0 is the initial nutrient concentration in the tank (mg/L), C_e is the final nutrient concentration in the tank (mg/L), Q is the flow rate (m^3/day), E is the nutrient elution or removal rate ($g{\cdot}m^{-2}{\cdot}day^{-1}$), h is the water depth (m), V is the water volume, and suffixes for Q, *in* and *out*, denote poured water and outflow water, respectively.

In the tank, the nutrient balance appeared to result from bio-chemical reactions and physical reactions[1], such as elution from the sediment surface, denitrification of NO_x-N, nitrification of NH_4-N, settlement of particulate nutrients, and return of dissolved nutrients into water due to the decomposition of organic materials settled at the bottom. These processes are summarized in Fig. 4. Based on these data, nutrient elution and removal in the tank could be estimated.

1. Estimation in CASE 1

Nutrient mass balance in the experiments in CASE 1 calculated by Eq. (1) during the experiments is shown in Table 3. The COD balance was 3.2 $mg{\cdot}m^{-2}{\cdot}day^{-1}$ and –5.0 $mg{\cdot}m^{-2}{\cdot}day^{-1}$ for RUN 1 and RUN 2, respectively. Since COD includes particulate COD (p-COD) and dissolved COD (d-COD), the settlement of p-COD was the main factor for the decrease, while elution of d-COD from the sediment surface and return of decomposed p-COD at the bottom were the main factors for the increase. The COD balance estimated here indicates that the sum of the elution rate and the return rate was higher than the s-COD settling rate in RUN 1, and that the return rate was higher than the settling rate in RUN 2. These data indicate that the net elution rate was 8.2 $mg{\cdot}m^{-2}{\cdot}day^{-1}$.



* Only for nitrogen

Fig. 4. Processes of nutrient reactions in the tank

The TN balance for RUN 1 was –10.9 mg·m^{-2}·day^{-1} because the sum of the denitrification rate and the settling rate outweighed the sum of the elution rate and the return rate of nitrogen from the sediment surface. On the other hand for RUN 2, the TN mass balance in the water was 4.2 mg·m^{-2}·day^{-1}, which corresponds to the remainder of the subtraction of the settling rate of particulate nitrogen from the nitrogen return rate. These data indicate that the net nitrogen removal rate, which includes the denitrification rate, the settling rate and the elution rate, was 15.1 mg·m^{-2}·day^{-1}. Since the C:N ratio affects the nitrification rate, as indicated by Ingersoll and Baker[2], the denitrification here seems to be restricted mainly to the low rate.

In general, as the removal rate such as denitrification rate or settling rate is described by a first-order kinetic, the changes in the TN concentration in the tank are expressed by Eq. (2),

$$\frac{dN}{dt} = \frac{Q}{V}(N_{in} - N) + \frac{D - aN}{h} \qquad (2)$$

where N is the TN concentration (mg/L), N_{in} is the TN concentration of poured water (mg/L), D is the return rate of nitrogen from the settled organic materials on the sediment surface (mg·m^{-2}·day^{-1}), and a is the removal rate constant (m/day).

When N_{in}, D and a are constants, the solution of Eq. (2) is given by Eq. (3),

$$N = N_0 \exp\left(-\frac{Q}{V} - \frac{a}{h}\right) - \frac{N_{in}Qh + DV}{Qh + aV}\left[\exp\left(-\frac{Q}{V} - \frac{a}{h}\right) - 1\right] \qquad (3)$$

where N_0 is the initial TN concentration (mg/L).

Substituting the average recurrence rate estimated from RUN 2 during the estimation period into Eq. (3), we obtained a = 0.010 (m/day) by curve fitting as shown in Fig. 5. This rate constant value was approximately in agreement with the nitrogen removal rate in a paddy field reported by Tabuchi[4].

As the TP balance for RUN 1 and RUN 2 was 10.9 mg·m^{-2}·day^{-1} and –0.6 mg·m^{-2}·day^{-1}, respectively, the net phosphorus elution rate from the sediment was 11.5 mg·m^{-2}·day^{-1}. The PO_4-P balance was 10.7 mg·m^{-2}·day^{-1} for RUN 1 and was 0.1 mg·m^{-2}·day^{-1} for RUN 2. Based on these values, the net PO_4-P elution rate was 10.6 mg·m^{-2}·day^{-1}. Assuming that the PO_4-P balance for RUN 2 corresponds to the return rate of PO_4-P from the settled organic materials on the sediment surface, it is deduced that the proportion of returned phosphorus to settled phosphorus was 20.2%.

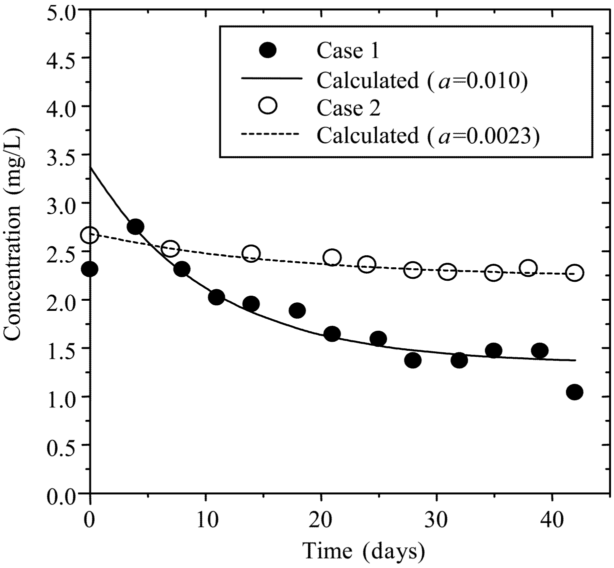


Fig. 5. Curve fitting to TN concentration changes by Eq. (3)

2. Estimation in CASE 2

Nutrient mass balance of the experiments in CASE 2 is shown in Table 4.

The COD balance of RUN 1 and RUN 2 was negative. It is thus reasonable to assume that the elution rate and the return rate which resulted from the decomposition of organic materials at the bottom were lower than those in CASE 1 and that the settling rate was higher than the sum of the elution rate and the return rate. The net COD elution from the sediment surface was estimated at 9.9 mg·m^{-2}·day^{-1}.

The TN balance for RUN 1 and RUN 2 was –9.4 mg·m^{-2}·day^{-1} and –0.4 mg·m^{-2}·day^{-1}, respectively. In RUN 2, it is considered that the settling rate of nitrogen was higher than the return rate as in the case of COD.

Table 3. Nutrient balance in CASE 1 (mg·m^{-2}·day^{-1})

	COD	TN	TP	IN*	PO_4-P
RUN 1	3.2	–10.9	10.9	–9.5	10.7
RUN 2	–5.0	4.2	–0.6	4.1	0.1
Net elution or removal rate	8.2	–15.1	11.5	–13.6	10.6

*$[NH_4+NO_x]$-N

Table 4. Nutrient balance in CASE 2 (mg·m^{-2}·day^{-1})

	COD	TN	TP	IN	PO_4-P
RUN 1	–15.8	–9.4	5.2	–9.2	5.5
RUN 2	–25.7	–0.4	–0.2	1.8	–0.0
Net elution or removal rate	9.9	–9.0	5.4	–11.0	5.5

These data indicate that the net removal rate was assumed to be 9.0 mg·m^{-2}·day^{-1}, a value which is approximately 60% of that in CASE 1. The removal rate constant calculated by Eq. (3) was 0.0023 m/day.

The TP balance for RUN 1 and RUN 2 was 5.2 mg·m^{-2}·day^{-1} and –0.2 mg·m^{-2}·day^{-1}, respectively. Therefore, the net phosphorus elution rate from the sediment was 5.4 mg·m^{-2}·day^{-1}, a value which is approximately half of that in CASE 1.

Conclusion

Based on these hydraulic model experiments, it was demonstrated that nitrogen is removed on the sediment even in water under aerobic conditions, and that COD and phosphorus in the water in the clayey canal are derived from the sediment. The removal rate and elution rate increased remarkably with the temperature.

As water quality in a canal results from interactions among nutrients, bacteria and plankton, an ecosystem model analysis should be conducted to determine the effect of a clayey canal on the water quality.

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