

Nitrogen and phosphorus interchange between sediments and overlying water of a wastewater retention pond¹

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Abstract

Nitrogen and P interchange between the sediments and the overlying water of a simulated retention pond used for wastewater treatment were evaluated under conditions of seasonal temperature fluctuations and varying physico-chemical conditions (exposing floodwater surface to daylight vs. dark and turbulent vs. quiescent floodwater). Natural sediment columns obtained from two types of field retention ponds were used. One type of retention pond consisted of calcareous clay loam sediment while the sediment of second retention pond contained organic soil. Nutrient interchange between sediments and the overlying water was measured once a month over a period of one year.

Nitrogen removal rates from floodwater were controlled by the initial floodwater NH_4^+ and NO_3^- concentration, rate of NH_4^+ diffusion from the sediments to the overlying water, ammonification in the sediments, NH_3 volatilization and nitrification at the sediment-water interface, and denitrification in the sediments. Under the conditions studied, NH_4^+ concentrations of the floodwater were in the range of 0.01 to 0.05 $\mu\text{g}/\text{ml}$, while NO_3^- concentrations were in the range of 0.27 to 0.78 $\mu\text{g}/\text{ml}$. Sediments with organic soil were found to be less effective in the removal of floodwater organic N, organic C and P, compared to the sediments with calcareous clay loam. Phosphorus exchange rates were dependent on the capacity of the sediment to adsorb or desorb P. Total P exchange rates were in the range of -1.04 to 0.34 $\text{mg P}/\text{m}^2$ day. Seasonal temperature fluctuations, turbulent vs. quiescent water conditions or exposing the floodwater surface to daylight or dark had very little effect on N and P exchange rates.

Introduction

Wetlands, flooded fields, retention and detention ponds have been studied by several researchers (Boyt *et al.* 1977; Beek *et al.* 1977a, b; Tilton & Kadlec 1979; Reddy *et al.* 1982a) as a possible wastewater treatment alternative. Wastewater N and P removal in these systems primarily occurs through physical, chemical, and biological processes functioning in the overlying water and underlying sediments. Nitrogen processes functioning include NH_3

volatilization (Stratton 1968) nitrification-denitrification (Reddy & Graetz 1981); and P processes include adsorption-desorption by the sediments and chemical precipitation (Nielsen 1974). A significant portion of wastewater N and P can also be removed through uptake by macrophytes and algae. Rate of N and P removal by these processes is influenced by the physico-chemical conditions that exist in the overlying water and in the underlying sediment. Some of these conditions are (1) dissolved O_2 in the water; (2) pH; (3) temperature; (4) residence time of water; (5) water depth; (6) mixing in the water column; and (7) presence of aquatic macrophytes and algae. In addition, under-

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lying sediments can function as a sink or source of N and P to the overlying water. This will depend on the interstitial N and P concentration of the sediments, and N and P regeneration rates in the sediments.

In central Florida, eight retention reservoirs (18 to 20 ha each) are currently in operation on the north shore of Lake Apopka to reduce nutrient levels of agricultural drainage effluent that has been discharged from the adjacent organic soils planted with vegetable crops (8 000 ha). These soils are poorly drained under natural conditions and artificial drainage is often necessary to maintain the water table at optimum level. Excess drainage discharge is pumped into the retention reservoirs and subsequently discharged into the lake. These retention reservoirs are necessary to reduce nutrient loads to the lake. Similar retention and detention ponds are also in use in other areas of Florida as a wastewater treatment alternative.

The purpose of this investigation was to evaluate the role of sediments in retention and detention reservoirs in functioning as a N and P source or sink to the overlying water under varying physico-chemical conditions. Natural sediment columns obtained from the experimental field retention reservoirs were used in the study.

Materials and methods

Undisturbed sediment columns were obtained from the existing experimental field retention reservoirs and flooded fields located near Lake Apopka by driving a PVC (polyvinyl chloride) pipe (12.7 cm OD) using a sledge hammer. Sediment column depth was 25 cm for reservoirs and 35 cm for flooded fields. The bottom portion of the intact sediment column was sealed to a PVC plate using silicone glue. The columns were then placed in a shallow pan containing melted paraffin wax to insure sealing. The reservoir sediments consisted of a calcareous marl layer while the flooded field bottom consisted of an organic soil (Lithic Medisaprists, euic hyperthermic). Selected characteristics of the sediment columns are shown in Table 1. Detailed description of the field experimental reservoirs and flooded fields is given by Reddy *et al.* (1982a). Agricultural drainage effluent used in the study was also obtained from the drainage canals

Table 1. Selected characteristics of the undisturbed sediment columns used in the study.

Parameter	Reservoirs	Flooded organic soil
Length, cm	20.0	35.0
Surface area, cm ²	78.5	78.5
Bulk density, g/cm ³	0.91	0.35
Water column, cm	20.0	20.0
Total C, %	6.6	45.1
Total N	0.61	3.5

surrounding organic soils planted to vegetable crops.

Experimental set-up used in this study was similar to the one described by Reddy & Graetz (1981). Triplicate sediment columns with 20 cm overlying drainage effluent were incubated under the following conditions: (1) overlying water surface exposed to daylight (open) with aeration (turbulent) and without aeration (quiescent); (2) overlying water surface exposed to dark (closed) with and without aeration.

All sediment columns were placed in a shaded greenhouse where temperatures were maintained at the same level as encountered outside the greenhouse by cross ventilation and using an electric fan. Temperatures in the greenhouse were continuously monitored by a recording thermometer. Drainage effluent obtained each month from the field was placed in each column to a depth of 20 cm and for a period of 30 days. At the end of 30-day equilibration, drainage effluent was replaced with fresh drainage effluent and similar procedure was repeated for a period of 12 months. Water samples at the start and at the end of equilibration were analyzed for NH_4^+ , NO_3^- , organic N, soluble ortho-P, total P, and organic C. Dissolved O_2 and pH of the water were also measured.

At the end of one year, sediment columns were sectioned into several depth increments and analyzed for water soluble NH_4^+ , NO_3^- , ortho-P, exchangeable NH_4^+ , and double acid extractable P.

Analytical methods

Ammonium N and NO_3^- in the water samples were determined by steam distillation followed by titration with standard acid (Bremner 1965). Organic N was determined by Kjeldahl digestion followed by steam distillation (Bremner 1965). Ortho-

Table 2. Dissolved oxygen and pH of the water column (expressed as an average of 12 months). Each value is an average of 72 observations taken during the study period.

Treatment	Reservoirs				Flooded organic soil			
	DO ($\mu\text{g}/\text{ml}$)		pH		DO ($\mu\text{g}/\text{ml}$)		pH	
	Mean	$\pm\text{SD}$	Mean	$\pm\text{SD}$	Mean	$\pm\text{SD}$	Mean	$\pm\text{SD}$
Light (open)								
Turbulent	7.8	± 1.4	8.5	± 0.2	6.8	± 1.9	8.4	± 0.5
Quiscent	4.4	± 1.5	8.1	± 0.3	3.4	± 1.3	8.0	± 0.3
Dark (closed)								
Turbulent	7.6	± 1.2	8.6	± 0.3	7.5	± 1.2	8.6	± 0.4
Quiscent	2.2	± 0.6	8.2	± 0.3	2.9	± 0.5	8.1	± 0.2

P was determined on water samples filtered through 0.2 μm filter paper, using a single reagent method (Murphy & Riley 1962). Total P was determined by persulfate digestion followed by the single reagent method. Organic C was analyzed on an auto analyzer (Technicon 1978).

A portion of the sectioned wet sediment was mixed with deionized water to obtain a sediment-water ratio of 1:4, and filtered through 0.2 μm filter paper after 30 min shaking. Filtered solutions were analyzed for NH_4^+ , NO_3^- , and ortho-P. A portion of the wet sediment was also extracted with 2 M KCl at a sediment to extraction solution ratio of 1:4. Filtered solutions were analyzed for NH_4^+ and NO_3^- . Another portion of the wet sediment was shaken for 30 min with a 0.05 N HCl + 0.025 N H_2SO_4 in a sediment to extraction solution ratio of 1:5 and filtered through 0.2 μm filter paper. Filtered solutions were analyzed for ortho-P by single reagent method.

Results and discussion

Dissolved O_2 concentration of the overlying floodwater was in the range of 6.8 to 7.8 $\mu\text{g}/\text{ml}$ under turbulent (aerated) floodwater and 2.2 to 4.4 $\mu\text{g}/\text{ml}$ under quiscent (no aeration) conditions (Table 2). pH of the water under both conditions was in the range of 8.0 to 8.6. Sediment characteristics did not influence the dissolved O_2 and pH of the water.

Ammonium concentration of the drainage water (wastewater) added to the sediment columns was in the range of 0.1 to 1.1 $\mu\text{g N}/\text{ml}$, while the NH_4^+ concentration of the water at the end of each 30-day incubation was less than 0.1 $\mu\text{g N}/\text{ml}$ (Table 3). Floodwater NH_4^+ and the NH_4^+ released from the sediment were rapidly depleted from the water during each 30-day equilibration period, probably due to active loss mechanisms (NH_3 volatilization and nitrification) functioning in the water column, as-

Table 3. Ammonium N and NO_3^- -N concentration of the water column (expressed as an average of 12 months and a total of 36 values). Standard deviations represent the variations among months.

Treatment	Reservoirs				Flooded organic soil			
	NH_4^+ -N		NO_3^- -N		NH_4^+ -N		NO_3^- -N	
	Mean	$\pm\text{SD}$	Mean	$\pm\text{SD}$	Mean	$\pm\text{SD}$	Mean	$\pm\text{SD}$
	$\mu\text{g}/\text{ml}$							
Light (open)								
Turbulent	0.02	± 0.02	0.65	± 0.39	0.02	± 0.02	0.78	± 0.32
Quiscent	0.05	± 0.11	0.43	± 0.25	0.03	± 0.03	0.60	± 0.22
Dark (closed)								
Turbulent	0.02	± 0.01	0.76	± 0.41	0.03	± 0.04	0.69	± 0.29
Quiscent	0.01	± 0.01	0.48	± 0.21	0.03	± 0.03	0.27	± 0.13
Influent								
Drainage water	0.66	± 0.31	0.58	± 0.44	0.66	± 0.31	0.58	± 0.44

sociated with the uptake by algae. Removal of NH_4^+ from the floodwater was approximately the same under all conditions (turbulent vs. quiescent, light vs. dark), with about >98% NH_4^+ removal during any 30-day equilibrium of the one-year study. Very little or no seasonal difference as a result of temperature fluctuations was observed in NH_4^+ removal from the water column.

Floodwater NO_3^- concentration was generally higher under turbulent floodwater conditions than quiescent floodwater conditions (Table 3). Under turbulent conditions, floodwater NO_3^- was increased by 8.4 to 29.2% for calcareous reservoir sediment and 18.7 to 29.8% for flooded organic soil. Increased NO_3^- levels in the water column were due to rapid nitrification of the floodwater NH_4^+ and the NH_4^+ diffused from underlying sediments. Under quiescent conditions, floodwater NO_3^- was decreased by 21.4 to 28.1% for reservoirs and +1.2 to 54.1% for the flooded organic soil. Initial NO_3^- added through drainage effluent was probably denitrified during the first few days of 30-day equilibrium. However, diffusion of NH_4^+ from the underlying sediments and subsequent nitrification elevated the NO_3^- levels of the floodwater. Removal of NO_3^- from the floodwater is controlled by the rate of uptake by algae and other aquatic organisms and denitrification in the underlying sediments. In studies reported elsewhere, it has been shown that very little or no denitrification occurs in the floodwater (Engler & Patrick 1974; Reddy *et al.* 1980) and rate of NO_3^- removal will then depend on the diffusion of NO_3^- from floodwater to underlying sediment. In our

study, both organic soil and reservoir sediment consisted of high organic matter (Table 1), indicating high potential for NO_3^- reduction (Reddy *et al.* 1982b).

Data in Table 4 show the mean organic N and organic C concentration of the overlying water. For floodwater with an underlying calcareous reservoir both organic N and organic C content of the water were decreased by about 11 to 30%, while for water with an underlying organic soil, reductions were in the range of +8 to 18%. Increased levels of organic N and organic C of the water with an underlying organic soil were probably due to (1) algal activity in the water exposed to daylight; and (2) diffusion of soluble organic N and organic C from the underlying sediments to the overlying water. Diffusion process probably contributed to the elevated levels of organic N and organic C in the water column incubated in the dark where no algal activity was observed. For both types of sediments, floodwater organic N and organic C contents were lower when incubated in the dark than the water exposed to daylight. This was probably due to the activity of algae in the water exposed to daylight. Differences between turbulent and quiescent floodwater conditions were not significant. Significant relationship was observed between organic N and organic C ($R^2 = 0.80^{**}$) concentrations of the floodwater. Average C/N ratio of the water was found to be 7.84 ± 0.74 .

Soluble ortho-P accounted for about $80 \pm 7\%$ of the total P (Table 5). At the end of each 30-day equilibration, P concentration of the water with an

Table 4. Organic N and organic C concentrations of the water column (expressed as an average of 12 months and a total of 36 values). Standard deviations represent the variation among months.

Treatment	Reservoirs				Flooded organic soil			
	Organic N		Organic C		Organic N		Organic C	
	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
	$\mu\text{g/ml}$							
Light (open)								
Turbulent	3.03	±1.58	22.5	±9.0	3.69	±1.46	27.7	±5.9
Quiescent	2.92	±0.65	19.2	±5.2	3.60	±0.64	27.2	±4.4
Dark (closed)								
Turbulent	2.41	±0.62	20.2	±5.2	3.16	±0.80	28.7	±8.3
Quiescent	2.50	±0.46	21.4	±7.1	3.18	±0.84	22.7	±7.6
Influent								
Drainage water	3.42	±0.99	27.6	±8.9	3.42	±0.99	27.6	±8.9

Table 5. Phosphorus concentration of the water column (expressed as an average of 12 months and a total of 36 values). Standard deviations represent the variation among months.

Treatment	Reservoirs				Flooded organic soil			
	Ortho-P		Total P		Ortho-P		Total P	
	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
	µg/ml							
Light (open)								
Turbulent	0.50	±0.25	0.64	±0.20	0.77	±0.21	0.98	±0.29
Quiscent	0.33	±0.21	0.39	±0.18	0.70	±0.31	0.98	±0.40
Dark (closed)								
Turbulent	0.37	±0.23	0.44	±0.26	0.56	±0.19	0.81	±0.21
Quiscent	0.43	±0.18	0.45	±0.13	0.49	±0.25	0.61	±0.27
Influent								
Drainage water	0.66	±0.53	0.87	±0.59	0.66	±0.53	0.87	±0.59

underlying organic soil was generally higher than the water with an underlying calcareous reservoir sediment. Floodwater P concentration was reduced by 26 to 55% in the water with calcareous reservoir sediment, indicating that sediments were functioning as a sink for the floodwater P. Organic soils functioned as a poor sink for floodwater P with about 7 to 30% reduction in the water columns incubated in the dark, while floodwater P concentration increased by 9 to 13% in the water columns exposed to daylight. Total P exchange rates between reservoir sediment and the overlying water were in the range of -1.04 to -0.60 mg P/m² day (negative values represent the disappearance of P from the water), while the exchange rates of -0.46 to 0.35 mg P/m² day were observed for flooded organic soil.

Data on water soluble and total (water soluble + exchangeable) NH₄⁺ distribution in the sediment profile are shown in Figs. 1 and 2. Turbulent or quiscent conditions in the floodwater and exposing the floodwater surface to daylight or dark did not contribute to any significant differences in the sediment NH₄⁺ concentration. However, two sediment types showed distinct differences in NH₄⁺ concentration. Water soluble NH₄⁺ concentration of the reservoir sediment was in the range of 5 to 37 µg N/g of soil, while total NH₄⁺ was in the range of 7 to 70 µg N/g of soil. In flooded organic soil, NH₄⁺ concentration was in the range of 5 to 155 µg N/g of soil for water soluble NH₄⁺, and 30 to 276 µg N/g of soil for total NH₄⁺. Low NH₄⁺ concentrations were observed in the surface layers of the sediments,

indicating movement of NH₄⁺ from the sediments to the overlying water. Decrease in NH₄⁺ concentration was more striking for organic soil than the calcareous reservoir sediment. Continuous depletion of NH₄⁺ from the floodwater as a result of NH₃

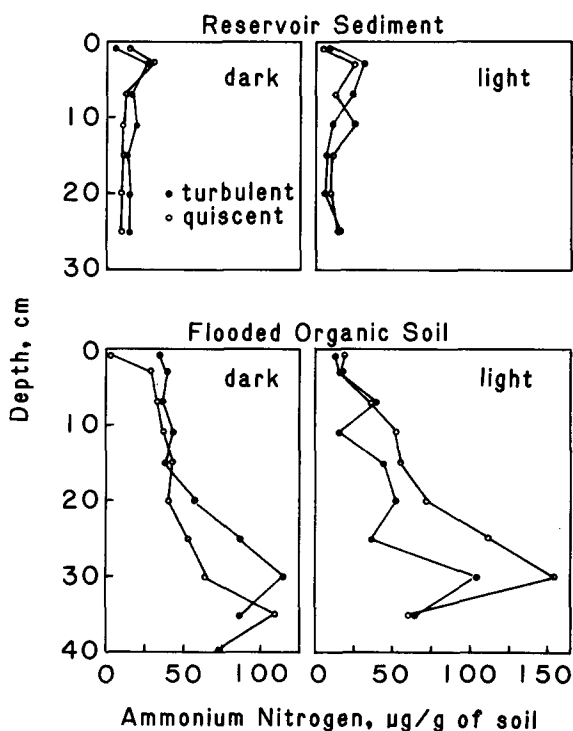


Fig. 1. Distribution of water-soluble ammonium nitrogen in the soil profile at the end of one year study period.

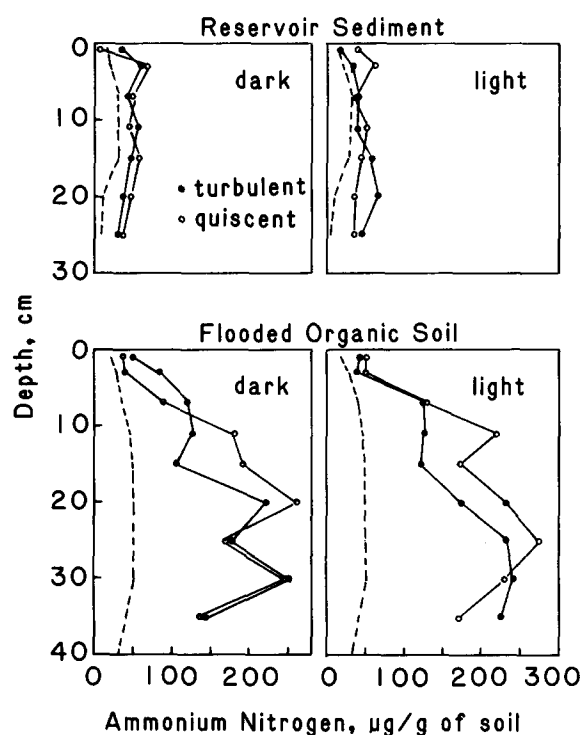


Fig. 2. Distribution of extractable ammonium nitrogen (water soluble + exchangeable) in the soil profile at the end of one year study period. (Dotted line shows initial concentration of $\text{NH}_4^+\text{-N}$).

volatilization, nitrification, and algal uptake, created a concentration gradient across the sediment-water interface and resulted in the movement NH_4^+ from the sediments to the overlying water. A steady rate of organic N mineralization replenished the NH_4^+ in the sediments. Amount of N mineralized in the flooded organic soil was about $66 \mu\text{g}/\text{cm}^3$ of soil ($231 \text{ kg N}/\text{ha yr}$) and loss of NH_4^+ as a result of diffusion accounted for about 25% of the NH_4^+ mineralized ($57 \text{ kg N}/\text{ha yr}$). Mineralization rates were estimated by using the NH_4^+ concentrations at 30 cm depth, where upward NH_4^+ diffusion was minimal and by assuming a constant rate of mineralization (Reddy *et al.* 1976) throughout the sediment profile. It was not possible to make similar estimates for reservoir sediments, primarily due to shallow sediment depth which has resulted in the diffusion of NH_4^+ from lower depths. In addition to NH_4^+ loss, mineralization of organic N during one year study, increased the NH_4^+ levels by about 48 to 59% for reservoir sediment and 174 to 251% for flooded organic soil, respectively.

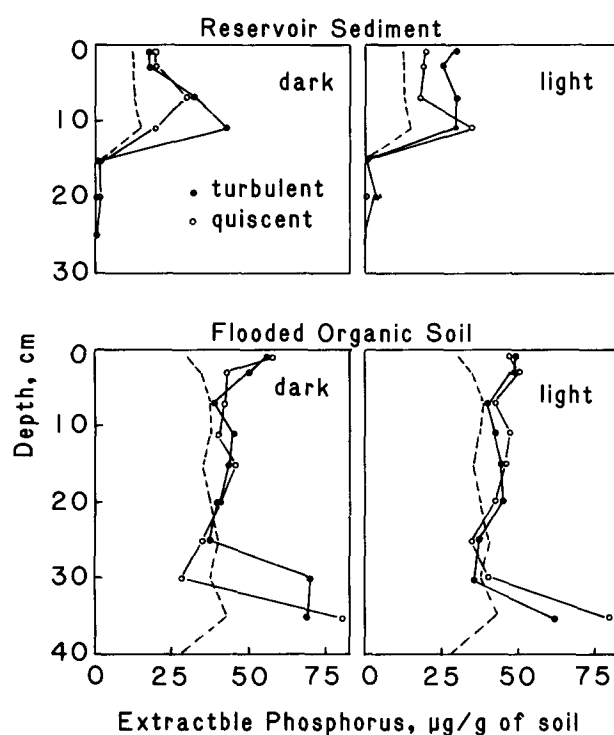


Fig. 3. Distribution of dilute acid (0.05 N HCl + 0.025 N H_2SO_4) extractable phosphorus in the soil profile at the end of one year study period. (Dotted line shows initial concentration of available P).

Distribution of available P in the sediment profile (Fig. 3) was approximately the same under all conditions studied (turbulent floodwater vs. quiescent floodwater, light vs. dark). For both sediment types, P levels were low in the upper sediment layers compared to lower depths of sediment. For reservoir sediment, maximum P concentration (20 to $35 \mu\text{g P/g}$ of soil) was observed between 10–15 cm depth. Below 15 cm depth, P concentrations were less than $0.25 \mu\text{g/g}$ of soil, primarily due to low available P in the sediments. Reservoir sediment consists of a calcareous clay loam up to 15 cm depth, followed by limestone below 15 cm. At the beginning of the experiment, available P concentration was fairly uniform in the upper 15 cm of the reservoir sediment. However, at the end of one year study, although available P concentration increased, a significant amount of P was lost from the surface sediment layer, primarily due to diffusion into the floodwater. Similar trends were also observed in the flooded organic soil with significant amount of upward P movement from the sediment

to the overlying water. Based on P concentrations at lower depths, amount of P made available as a result of mineralization of organic P and solubilization of inorganic P was calculated (Reddy *et al.* 1976) to be about $8.5 \mu\text{g P/cm}^3$ of soil (29.8 kg P/ha yr) for organic soil and $15 \mu\text{g P/cm}^3$ of soil (22.5 kg P/ha yr) for reservoir sediment, respectively. Upward diffusion of P into overlying water accounted for about 39 and 34% of the total available P, respectively, for organic soil and reservoir sediment.

In Florida, detention ponds are commonly used for reducing the nutrient levels of agricultural drainage effluents, sewage effluents, and discharges from animal waste operations. For example, eight retention ponds ($\cong 20$ ha each) are in operation on the north shore of Lake Apopka (central Florida) to reduce nutrient levels of agricultural drainage effluents. Underlying sediments in some of these ponds consist of calcareous clay loam, while other ponds have organic soil bottoms. In both the systems, underlying sediments played a significant role in functioning as a source or sink of N and P to the overlying wastewater. The results presented in this study have shown that both types of retention ponds (sediments containing calcareous clay loam or organic soil) functioned effectively for inorganic N removal under light or dark, and turbulent or quiescent floodwater conditions. However, ponds with underlying organic soil were found to be less effective in organic N, organic C, and P removal from water, compared to the ponds with calcareous clay loam sediment. Seasonal temperature fluctuations, varying O_2 concentrations in the water or exposure of floodwater surface to light or dark had very little influence on the nutrient removal capacity of the system. Major factor controlling the nutrient removal from the overlying water was the characteristics of the underlying sediment. For example, continuous upward flux of N and P from the organic sediments to the overlying water resulted in a decreased nutrient removal efficiency.

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