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A FOUR-YEAR MASS BALANCE FOR A NATURAL WETLAND SYSTEM RECEIVING DOMESTIC WASTEWATER

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ABSTRACT

In order to clarify the natural purification potential of a natural wetland having free-flowing water, we performed a four-year study on such a wetland system which had been receiving for 12 years the domestic wastewater discharged from a residential area comprised of 45 households. The wetland's removal rate of organic matter throughout the four years ranged from 80% for COD to 95% for BOD, whereas the corresponding nitrogen removal rate was comparatively lower. Results indicate that NH_4-N release from the bottom sediment and repression of nitrification are the main factors responsible for the wetland's low removal rate of nitrogen during winter. The wetland purification performance even in winter was determined as follows (g m^{-2} d^{-1}): 2.2 BOD, 0.81 COD, 1.1 TOC, 0.10 T-N, and 0.023 T-P.

KEYWORDS

Wetlands; reed; BOD removal; nitrogen removal; phosphorus removal; mass balance; nitrification; denitrification; nitrogen release.

INTRODUCTION

Potential utilization of wetland systems as a natural water purification process has drawn the attention of several wastewater treatment research and development groups (Gersberg *et al.*, 1986; Reed *et al.*, 1987; U.S. EPA, 1988; Hosomi, 1990), yet only a few such practical wastewater treatment applications exist (Brix *et al.*, 1989; Findlater *et al.*, 1990; Lienard *et al.*, 1990; Watson *et al.*, 1990). Additionally, few investigations have focused on clarifying the purification potential, long-term treatment performance, or optimum wastewater loading conditions and structure of wetland systems (Haberl and Perfler, 1990). In fact, no extensive, long-term studies have specifically evaluated wastewater treatment in a wetland system having free-flowing surface water.

The present paper reports survey results which define the water purification potential of such a wetland system to treat domestic wastewater discharged from a small Japanese community in Japan over a four-year period (March 1986–February 1990). This wetland was non-cropping farm land (originally a rice paddy field) rampant with emergent aquatic plants consisting mainly of reeds and cattails. Non-treated graywater, i.e., domestic wastewater excluding night soil (human excrement), flowed into the wetland through small channels constructed in the residential areas.

One major concern regarding the use of a wetland system as a natural water purification treatment process is that biological activity (e.g., that from microorganisms) is degraded during the cold winter season, although it remains high during the warm summer season. Consequently, this survey considered year-round wastewater treatment performance.

ANALYZED WETLAND SYSTEM

The analyzed wetland is located at Yasato-machi, Ibaragi Prefecture, Japan. Graywater has been discharged into the above-described wetland for 12 years from two nearby residential areas, the first one having 25 households and the second 20.

It was initially difficult to establish a mass balance for this wetland due to it being located in a ravine and collecting ground water seepage and effluent from adjacent upstream paddy fields. To mitigate this drawback and obtain a more precise mass balance, as well as to prevent short circuit flow in order to improve the water purification function, a civil construction project was undertaken in the summer of 1986. The subsequent modifications consisted of dike construction which divided the wetland into four zones to better utilize the available area. Dikes and drainage canals were also constructed around it to divert the inflow of upstream drainage. The examined zones are shown in Fig. 1, where graywater discharged from the first residential area enters at inflow position St. 1, while discharge from the second area directly enters the wetland through polyvinyl piping at a position located between the intermediate point St. 2 and outflow point St. 3.

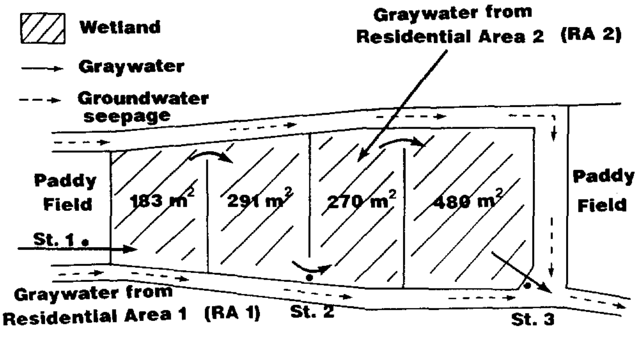

Fig. 1. Diagram of studied wetland area after dike construction.

MATERIALS AND METHODS

Prior to the modifications, flow rate measurements and composite samples were taken on an hourly basis at St. 1 and St. 3 (Fig. 1). Immediately after the modifications, corresponding sampling and flow rate measurements were additionally taken at St. 2. Water quality was determined in accordance with the methods specified in Table 1 (Japan Sewage Works Association, 1985; Hosomi and Sudo, 1986a). In addition, effluent from valley water (i.e., seepage water) and upstream paddy fields were also sampled to clarify the wetland's mass balance. A representative number of samples were analyzed by ion exchange chromatography and inductively coupled plasma (ICP) emission spectral analysis to determine the concentrations of major soluble ions such as chloride and sodium.

In June 1986, sediment core samples were collected at the inflow area (the central part of the first zone shown in Fig. 1), intermediate area (near St. 2), and outflow area (near St. 3) to estimate the nutrient exchange rate between the wetland's bottom sediment and overlying water. Sample locations were selected where aquatic plants such as reeds were not present. The core samples were analyzed by the laboratory sediment core method (Hosomi and Sudo, 1986b). We also employed the acetylene block method to determine the denitrification rate. Briefly, this method uses nitrate and acetylene additions to the overlying water of a sediment core sample, followed by incubation in the dark at 20°C for 2 days (Hosomi and Sudo, 1992). The resultant changes in the nitrous oxide (N_2O) concentration in the gas phase of the core's overlying water is then sampled via the head space method and measured with an electron capture detector (ECD) gas chromatography. Because the denitrification rate was determined using nitrate additions, we treat this measured value as the denitrification potential.

TABLE 1. Employed Methods for Chemical Analysis of Wetland Water and Discharged Wastewater

Item	Method
BOD	5-day BOD using azide modification of the iodometric method*
COD	Acid-potassium-permanganate method at 100°C*
TOC	TOC analyzer*
DO	Azide modification of the iodometric method*
NH_4-N	Automated phenate method**
NO_2+NO_3-N (NO_x-N)	Automated cadmium reduction method**
PO_4-P	Automated ascorbic method**
T-N, T-P	Simultaneous determination of T-N and T-P concentration using the persulfate digestion method**
SS	Glass-fiber filter method*

* Japan Sewage Works Association (1985).
** Hosomi and Sudo (1986a).

RESULTS AND DISCUSSION

Inflow load

The inflow load of graywater at St. 1, discharged from residential area 1 (RA 1) , was determined from composite samples prepared from the hourly collected samples and hourly measured flow rates taken before and after the modifications. A per capita load of graywater was then calculated using this total inflow load and the population of RA 1 (Table 2). No statistical significance (P>0.05) was found in the per capita load of RA 1 among the four seasons and, with the exception of SS, the resultant coefficient of variance (CV) ranged from 20 to 30% for all measured pollutants (29 samples).

TABLE 2. Per Capita Load of Graywater Discharged from RA 1

Season*	Water	BOD	COD	TOC	SS	T-N	T-P
	(l·cap^{-1}·d^{-1})			(g·cap^{-1}·d^{-1})			
Spring (3)	179	19.7	7.36	7.96	9.4	1.43	0.224
Summer (7)	264	19.4	9.53	8.92	18.2	1.76	0.244
Autumn (18)	199	15.6	6.41	9.63	4.9	1.11	0.192
Winter (3)	217	15.2	6.57	8.37	5.2	1.38	0.211
Average	216	16.7	7.25	9.17	8.5	1.33	0.210
CV(%)**	22	25	32	30	107	32	32

* Parentheses indicate sample number.
** CV: coefficient of variance.

Behavior of pollutants

Figure 2 shows variations in T-N/T-P concentrations and flow rate at St. 1–3 from December 17–18, 1986. The outflow rate at St. 3 consists of the graywater discharged from RA 1 via St. 2, as well as the graywater directly discharged from RA 2. Note the inflow rate at St. 1 fluctuated more widely than the flow rates at St. 2 and St. 3.

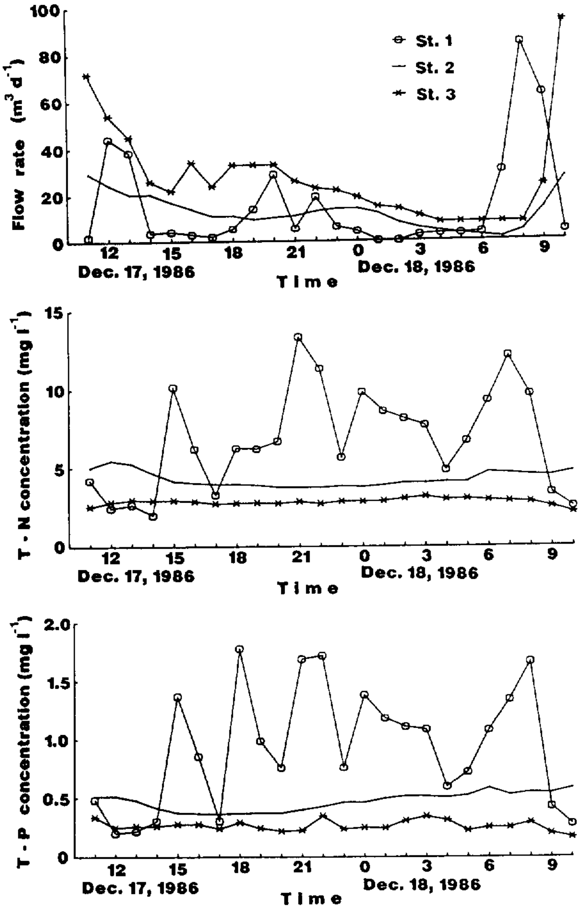

Fig. 2. Variations in flow rate and T-N/T-P concentrations at St. 1–3 from December 17–18, 1986.

The hourly T-N concentration at St. 1 ranged from 1.95–13.4 mg l^{-1} (ave. 6.82 mg l^{-1}, CV 48%), at St. 2 from 3.74–5.45 mg l^{-1} (ave. 4.27 mg l^{-1}, CV 12%), and at St. 3 from 2.10-3.14 mg l^{-1} (ave. 2.78 mg l^{-1}, CV 7.5%). Obviously both the T-N concentration and CV value decreased as the discharge crossed the wetland. The hourly T-P concentration showed a similar trend, in which the CV value significantly decreased from St. 1 to St. 2, while being fairly constant for St. 2 and St. 3. It should be noted that this marked decrease occurred in spite of the graywater discharge from RA 2 (Fig. 1).

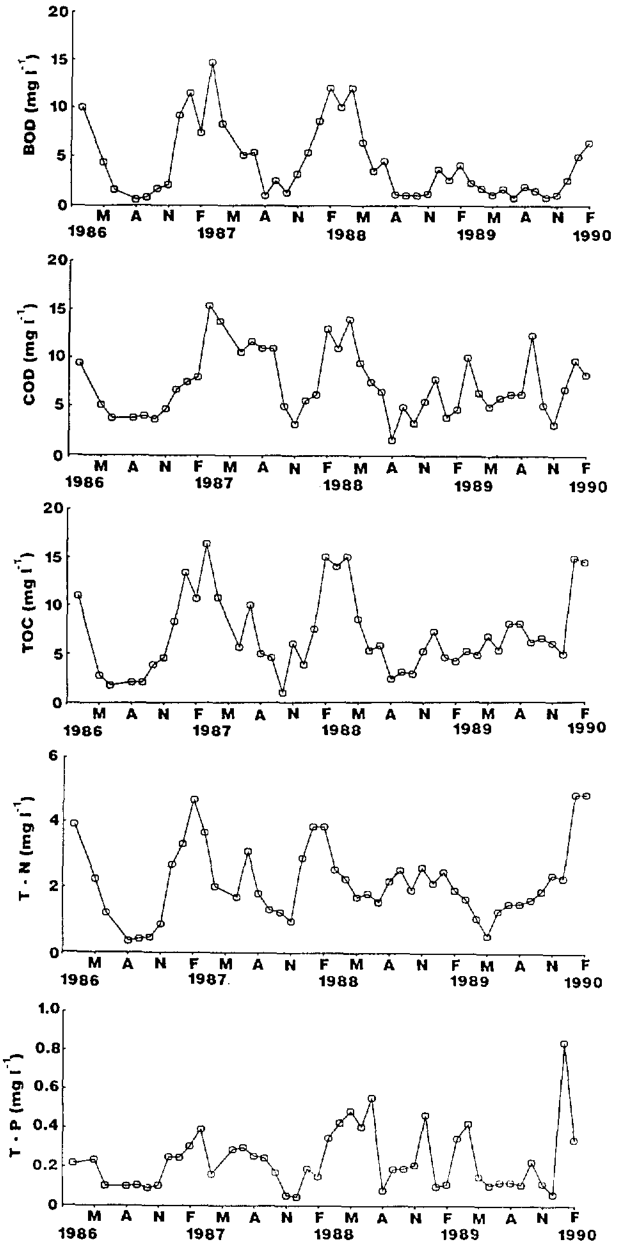

Fig. 3. Seasonal variations in the BOD, COD, T-N and T-P effluent concentrations (St. 3).

Seasonal effects on pollutant effluent concentrations

Figure 3 shows seasonal variations in BOD, COD, TOC, T-N, and T-P concentrations at St. 3 from March 1986 to February 1990. The BOD, COD, TOC, and T-N concentrations generally showed seasonal variations in which they increased from winter to early spring; a period during which aquatic plants such as reeds died and the water temperature decreased, e.g., less than 5°C in February. In particular, the T-N effluent concentration increased to nearly its influent level. This phenomenon is probably a result of the fact that cattails that died in the autumn did so in such a manner which enabled sunlight to reach the water surface; thus increasing the photosynthetic production of algae attached to the surface of underwater leaves and stems. The aggressive activity of toads in early spring and their agitation of the bottom is also thought to have accelerated the nitrogen release from the bottom sediment. No clear seasonal variation in T-P concentration was observed.

Mass balance models

Before modifications (March 1986–July 1986). Prior to the civil construction modifications, the wetland most surely accepted valley water and paddy field effluent from upstream, as well as groundwater from nearby mulberry fields and forests. Consequently, a mass balance could not be clearly determined during this period based on sampling results from St. 1 and St. 3. If the inflow load from sources other than graywater is taken as the difference between the flow rates at St. 1 and St. 3, then a representative water quality must be determined. Since valley water coming from the upstream side of the wetland was probably groundwater runoff, this was considered to be the major source of inflow other than graywater. Based on this assumption, an ion balance was determined for Na^+, Cl^-, SO_4^{2-}, and K^+. These ions were selected because their quantity is only slightly affected by absorption into plants and oxidation decomposition. Figure 4 indicates the results, where INPUT/OUTPUT designates the ratio of inflow and outflow quantities. The mass balance becomes more accurate as this ratio approaches 1, and as clearly shown, all of these ions have ratios close to 1. Similar results were also obtained in June 1986; hence supporting the hypothesis that valley water can be considered representative of the inflow other than graywater.

Figure 5 shows a mass balance of BOD, COD, T-N, and T-P before the modification work when the wetland was rampant with reeds and cattails, being derived by a method similar to that described above. Although BOD removal was 90% or greater, COD and T-N removal were only about 60%.

Four-year mass balance. Table 3 summarizes the average influent and effluent concentrations and removal rate of various pollutants from March 1986 to February 1990 (including the period before the modifications). The per capita load of inflow graywater (Table 2) from RA 1 was assumed to be applicable to RA 2. Accordingly, the sum of the inflow load from RA 1 and RA 2 was taken as the average total inflow load. Note the average effluent concentrations are substantially lower than those of the influent ones. Since the BOD removal rate was 95% and that for COD and TOC more than 80%, this wetland system demonstrates relatively good treatment performance. In contrast, however, the T-N removal rate was only 67%. These results equate to the following annual average purification performance values (g m^{-2} d^{-1}): 2.3 BOD, 0.85 COD, 1.1 TOC, 0.13 T-N, and 0.024 T-P. During the winter period (January to March) when the wetland surface may be covered with ice, the corresponding purification performance was 2.2 BOD, 0.81 COD, 1.1 TOC, 0.10 T-N, and 0.023 T-P, where only the T-N value is markedly different from the annual average. From May 1986 to February 1987, the average removal rate of SS was 85% and the average SS purification capacity 1.0 g m^{-2} d^{-1}.

Nitrogen behavior

The behavior of nitrogen within the wetland system was investigated in response to the finding that its nitrogen purification capacity is poor compared to that for other pollutants. Figure 6 compares the influent and effluent nitrogen loads for March and June 1986, where the quantity of particulate nitrogen (PN) in the influent is markedly reduced in March, while the influent dissolved organic nitrogen (DON) and NO_2+NO_3-N (NO_x-N) amounts are also reduced. In contrast, NH_4-N correspondingly increased. During June, influent PN and DON were reduced similarly to the trend shown in March, although NH -N contrastingly showed a decrease and NOx-N an increase. In March a portion of the wetland was frozen and the effluent water temperature remained at about 1°C, whereas in June it was about 20°C. The low water temperature in March appears to have suppressed nitrification. In addition, the sedimentation of PN, the conversion of DON into inorganic compounds, and the denitrification and release of NH_4-N from the bottom sediment were predominant. In June the predominant processes appear to be sedimentation of PN, conversion of DON into inorganic compounds, nitrification, denitrification, and release of the NH_4-N from the bottom sediment.

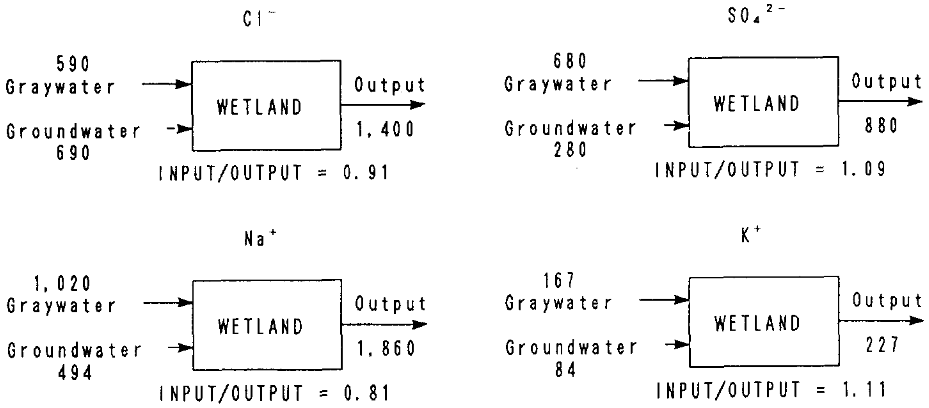

Fig. 4. Mass balance of Cl^-, SO_4^{2-}, Na^+, and K^+ (g d^{-1}) in the wetland on May 13–14, 1986.

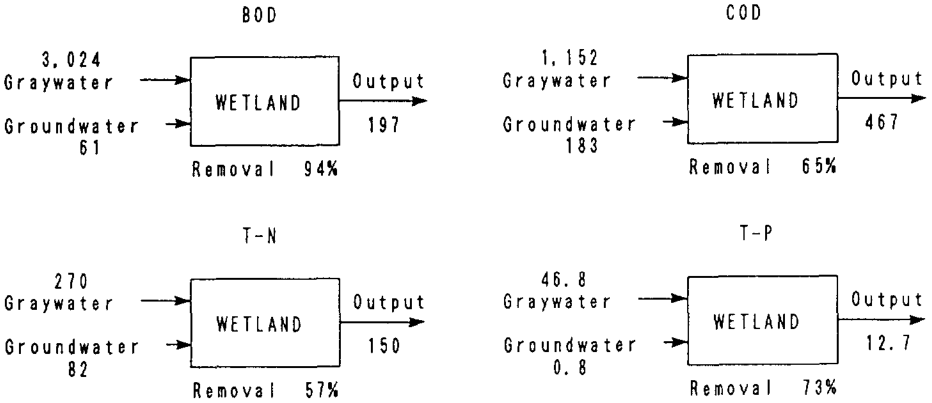

Fig. 5. Mass balance of BOD, COD, Te-N, and T-P (g d^{-1}) in the wetland on June 23–24, 1986.

TABLE 3 Average Influent and Effluent Water Quality and Removal Rate (%) in the Wetland from March 1986 to February 1990

Item		Influent	Effluent	Removal (%)
Flow rate	($m^3 \cdot d^{-1}$)	38.9	35.9	--
Pollutant	($mg \cdot l^{-1}$)			
BOD		77.3	4.3	95
COD		33.6	7.3	80
TOC		42.5	7.0	85
T-N		6.2	2.2	67
T-P		0.97	0.24	77

The nutrient release flux from the bottom sediment was determined using sediment core samples, where Table 4 summarizes the results. The release of PO_4-P from the bottom sediment only occurred in the wetland's upstream area, with negative values mean that occurring in its intermediate and downstream areas. The negative values mean that phosphorus in the overlying water was adsorbed into the bottom sediment. The release flux of NH_4-N ranged between 79 to 234 mg m^{-2} d^{-1}, which relatively corresponds to about half the inflow loads of nitrogen in the graywater. (i.e., 197 mg m^{-2} d^{-1} based on the entire wetland area). Since the magnitude of denitrification activity for the wetland was nearly equal to the NH_4-N release flux, significant denitrification is expected if wastewater containing NO_3-N is introduced and/or nitrification proceeds.

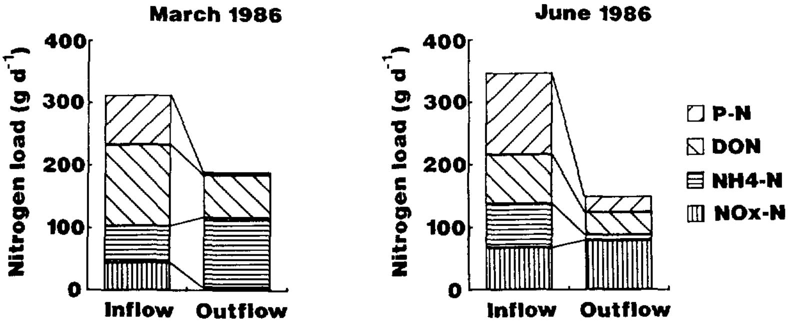

Fig. 6. Inflow and outflow nitrogen loads in the wetland.

TABLE 4. Nutrient Exchange Fluxes and Denitrification Activity in the Water–Sediment System*

Sampling Station Location	Flux ($mg \cdot m^{-2} \cdot d^{-1}$)		
	PO_4-P release	NH_4-N release	Denitrification activity
Inflow area (by St. 1)	4.4	234	223
Intermediate area (by St. 2)	-7.9	115	74
Outflow area (by St. 3)	-3.8	79	76

* The sediment core samples taken in June 1986 were aerobically incubated in the dark at 20℃. The nutrient exchange flux was then determined using the increase or decrease in the nutrient concentrations in the water phase. Denitrification activity was determined by the increase in the N_2O concentration in the water phase using the acetylene block method following NO_3-N and acetylenen addition to the water phase.

Based on these results, we conclude that the nitrogen purification performance in wetlands is degraded during winter because the NH_4-N which is converted into inorganic compounds, included in the inflow graywater, and released from the bottom sediment, is discharged from the wetland without nitrification. This behavior indicates that during the winter season, nitrification is the controlling process for nitrogen removal.

Nutrient uptake by macrophytes

Wetland aquatic plants are known to contribute to the removal of nutrients from incoming wastewater via nutrient absorption taking place during their growth period. Reeds and cattails are the dominant aquatic plants found in the surveyed wetland. Reeds found in coastal area of Lake Kasumigaura and Lake Suwa have nitrogen and phosphorus contents of 1.46–3.41% and 0.17–0.38%, respectively, while cattails in these areas have corresponding contents of 1.23–1.87% and 0.16–0.24%. These contents vary with season and location, being high at the initial growth stage in April, and then being reduced to about half this level by the end of May. When these plants begin to die in October, the nitrogen and phosphorus contents respectively drop to less than 0.5 and 0.02% (Watanabe and Sakurai, 1988; Sakurai, 1988). An experiment using cultured, reed-bed reactors showed that in October different carbon, nitrogen, and phosphorus contents were present in different parts of a plant (Hosomi, unpublished data), e.g., a stem/leaves content as follows: carbon 3.5%/4.2%; nitrogen 0.7%/2.8%; and phosphorus 0.09%/0.21%. The standing crop of reeds in the coastal area of Lake Kasumigaura is approximately 700–3600 g m^{-2}, while that corresponding to cattails is approximately 400–1000 g m^{-2}. In comparison, the values for the surveyed wetland were from 1500–3000 g m^{-2} depending on the sampled area.

Figure 7 shows the mass balance for carbon, nitrogen, and phosphorus, where the effects of aquatic plants are included. The plants' average daily rates of production of carbon and nitrogen and phosphorus uptake are also plotted. These results were calculated from Table 3 using a 2000-g m^{-2} standing crop determined by surveys, and by assuming that the contents of carbon, nitrogen, and phosphorus are 4.2%, 1.5%, and 0.15% in reference to available literature (Sakurai, 1988). Since 2300 mg m^{-2} d^{-1} of carbon was fixed in the plants, the "apparent" removal rate of 1145 mg m^{-2} d^{-1}, determined by difference between the influent and effluent carbon loads, is obviously underestimated. The reason for this is that harvesting and off-site disposal of aquatic plants did not take place for more than twelve years; thus the carbon load to the wetland should definitely exceed 1350 mg m^{-2} d^{-1}.

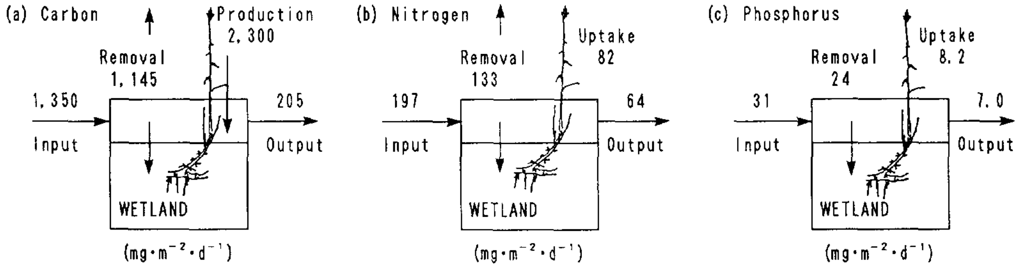

Fig. 7. Mass balance of carbon, nitrogen, and phosphorus in the wetland from March 1986 to February 1990.

Nitrogen is removed from discharged wastewater via deposition of PN in the bottom sediment. Following this accumulation and subsequent biological nitrification, denitrification occurs in the bottom sediment and in the biofilms formed on the stem surfaces of plants. The nitrogen removal rate was 133 mg m^{-2} d^{-1} and the nitrogen uptake rate was 82 mg m^{-2} d^{-1}, values which are approximately 60% of the corresponding nitrogen removal rate. Since phosphorus is only removed from the water by the deposition and accumulation in bottom sediment, its removal rate was 24 mg m^{-2} d^{-1} and the phosphorus uptake rate 8.2 mg m^{-2} d^{-1}, corresponding to approximately 30% of the phosphorus removal rate. Since no harvesting occurred, the nutrients in the aquatic plants accumulated in the wetland after the aquatic plants died, some of which then dissolved into solution. The importance of this finding is that removal of nutrients by plant absorption does not contribute to nutrient removal, unless the aquatic plants are periodically cleared. In addition, the total amount of nutrients absorbed by the plants is not necessarily recycled back into the water, but instead are removed from the water and gradually accumulate in the bottom sediment.

CONCLUSIONS

A four-year study was performed to estimate the natural purification potential of a small, slightly modified, natural wetland located in Japan. This wetland system had free-flowing water and received non-treated domestic wastewater for 12 years from a residential area comprised of 45 households. Nutrient concentrations and the magnitude of their variation were found to be reduced along the flow direction. The estimated removal rate of organic matter was high, ranging from 80% for COD to 95% for BOD, whereas the corresponding nitrogen removal rate was comparatively lower. It is believed that NH_4-N release from the bottom sediment and repression of nitrification were the main factors responsible for the low removal rate of nitrogen during winter. The wetland purification performance even in winter was as follows (g m^{-2} d^{-1}): 2.2 BOD, 0.81 COD, 1.1 TOC, 0.10 T-N, and 0.023 T-P.

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