Effects of sediment phosphorus release associated with the density current on water quality of a subtropical and deep reservoir in Taiwan

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Abstract It was found that the increase of sediment P release in the anoxic state associated with the density current initiated by the cold front in the winter was the cause of the deterioration of the water quality of the subtropical, noncalcareous and deep reservoir, Feitsui Reservoir, in recent years. A mathematical model including the analytical solutions of the transport of the density current combined with a simple 2-layered water quality model has been established, describing the hydrodynamics and the water quality variation of the reservoir well. The continued sediment release of P in the anoxic state (from October to March) is an important P source and should be carefully assessed and controlled to reduce the impact of the internal loading of P incorporated with the density current on the water quality in future years.

Keywords Density current; phosphorus; sediment; subtropical reservoir; water quality model

Introduction

Sediment phosphorus (P) has been considered an important source for the eutrophication of freshwater or marine water systems lately (Ulrich, 1997; Petterson, 1998; Diaz, 2001). When the bottom water is devoid of DO, the sediment P is easily released into the overlying water due to high solubility of P species. In deep quiescent water, the rate of the transport of TP from the lower layer to the surface water is slow, depending upon the momentum of the flow created by the temperature difference between the lower and upper layers or by the inflow of the density current from upstream intruding into the lower layer to cause vertical circulation. Vertical circulation has been found ventilating the deep ocean and supplying the oxygen content of the bottom waters (Ingall and Jahnke, 1997). In freshwater, Ford and Johnson (1986) also found the cold, oxygenated inflow, the density current from Lake Ouachota, AR, maintained an oxic hypolimnion in the downstream Lake Hamilton. The formation of the density current depends on the morphology and hydrology of the water body. A deep and meandering reservoir is suggested to have a vertical circulation occur. The total phosphorus (TP) released from the sediments could be easily carried to the surface water and taken up by algae. A subtropical and deep reservoir in Taiwan, Feitsui Reservoir, is under the threats of hydrological change and deterioration of the water quality lately. In this paper, the properties of the sediments, the variation of the water quality and the hydrodynamics of Feitsui Reservoir were investigated. We hope that through this study, the mechanism by which the water quality is influenced by the internal cycle of P incorporated with the hydrological variation could be better understood.

Methods

Study site

Feitsui Reservoir (24° 9′N, 121º 6′E), located in Taipei County and completed in 1987, is an important water resource for more than 5,000,000 people in Taiwan (Figure 1). It has a surface area of 10.24 km^2 and a mean depth of 39.68 m with a maximum depth of 113.5 m near the Dam (S-5). With about 20 km in length, the mainstream is of meandering morphology. The average bed slope is 0.3%. The reservoir is in an area of subtropical climate. The averaged annual air temperature is 22°C. The mean annual precipitation of the watershed is approximately 3,765 mm. In addition to the stormwater carried by typhoons in the summer and autumn seasons, there are also abundant rainfalls in the winter coming with the cold fronts brought about by the northeast monsoon.

Sediment sample collection and analysis

The sediment cores were sampled at five sites (S-1–S-5) (Figure 1) in the reservoir from January 2000 to December 2001 with a free fall gravity corer with an inner core diameter of 4 cm. Immediately after sampling, the sediment cores were analyzed on-site for pH of the overlying water and the oxidation-reduction potential (ORP) at the depth of 5cm below the sediment-water interface. Upon returning to the lab, the overlying water was removed by siphon and the top 10 cm of sediment was extruded and recovered into a large plastic container for analysis. Porewater was analyzed for dissolved total phosphorus (DTP), dissolved reactive phosphorus (DRP) and dissolved total iron (D-Fe) (*Standard Methods*, 1995). DTP after digestion and DRP were determined using the ascorbic acid technique (colorimetric method). D-Fe was measured by atomic absorption spectroscopy. To identify the predominant P mineral phases controlling the processes of sediment P release, a procedure proposed by Hieltjes and Lijklema (1980) with modification was adapted for fractionation of the phosphorus. Water samples were collected at the Dam site from the epilimnion and the hypolimnion monthly during 1991–2001 (Feitsui Reservoir Administration Bureau, 1991–2001). The measured TP, water temperature and DO were selected to discuss the trends of the water quality.

Results and discussion

Trends of water quality

The statistics of the long term TP, water temperature and DO at the Dam site of Feitsui Reservoir from 1991 to 2001 were performed and are shown in Figure 2 (a)–(c). Before 1996, the TP of the epilimnion was kept lower than that of the hypolimnion (Figure 2 (a)). The average long-term concentration of TP of the epilimnion was about 10~20 μg/L, under the oligotrophic to mesotrophic level. However since 1996, the concentration of TP of the epilimnion at the Dam site started to increase with fluctuation. It was over 40 μg/L in the winter period (January to March) and exceeded the eutrophication level according to the OECD criteria. Since there was no obvious increase of the external load of TP during this

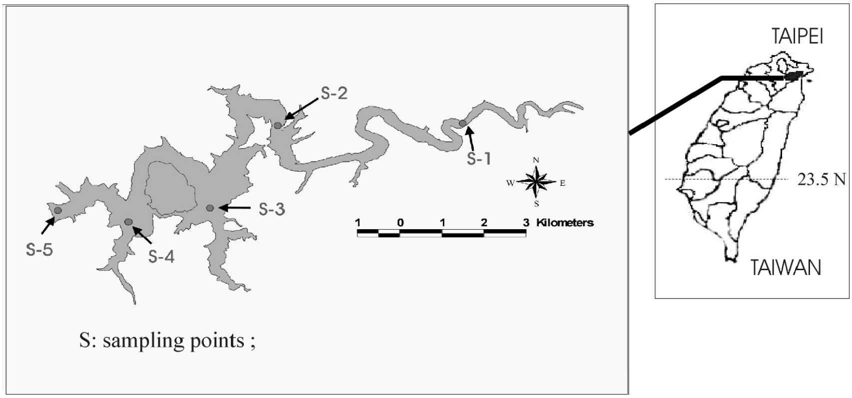


Figure 1 Location of Feitsui Reservoir and the sediment sampling sites

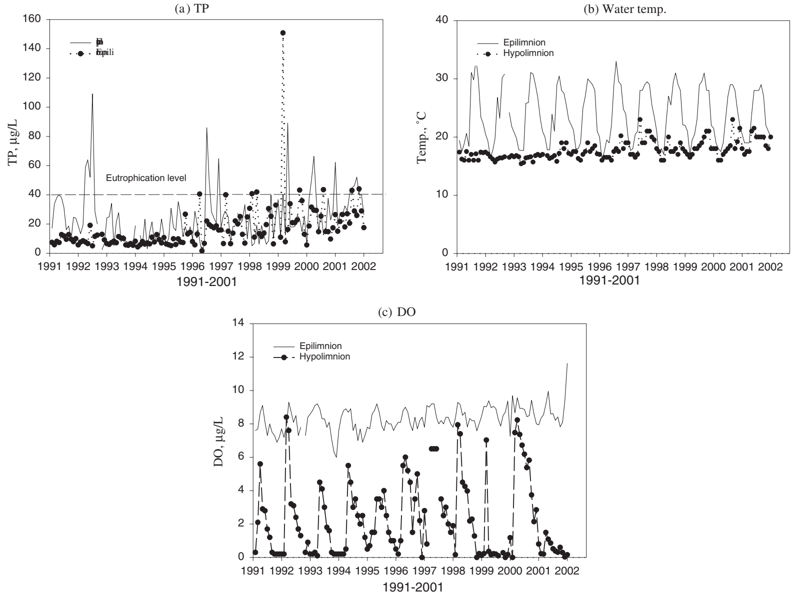
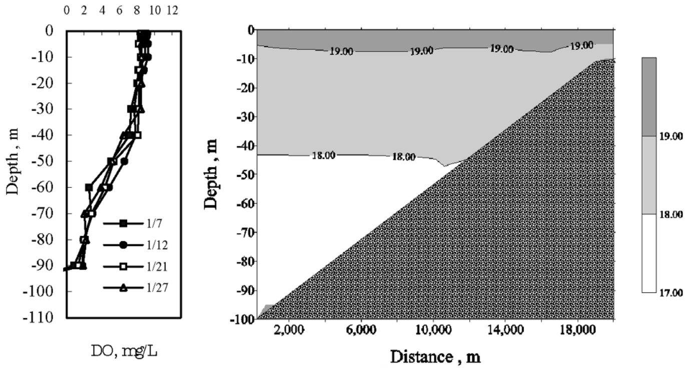


Figure 2 Time series of the water quality at the Dam site during 1991–2001: (a) TP, (b) water temperature and (c) DO. There were observed increased concentrations of TP in the epilimnion up to 40 μg/L, the eutrophication level according to the OECD criteria in the winter period since 1996. The sampling depths of the epilimnion and the hypolimnion were 1m below the surface water and 1m higher than the sediment water interface, respectively

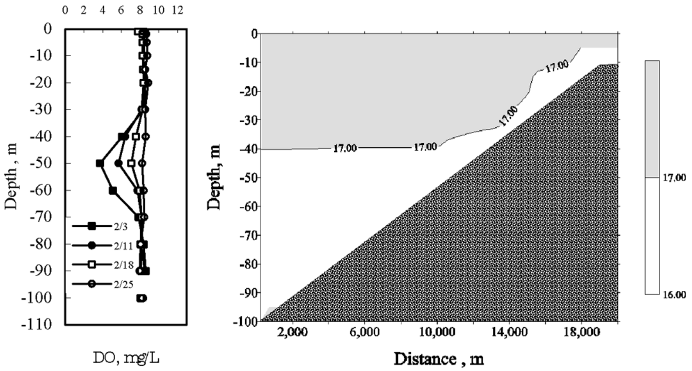
period as investigated, the abnormal increase of TP was suspected to be due to the internal load of the reservoir.

The magnitude of water mixing in the reservoir was strongly dependent upon the water temperature difference between the lower and upper layers and the amounts of inflow. For most lakes in the temperate zone, this is the so-called overturn and often happens in the spring or autumn period when the thermocline of the reservoir disappears. In this subtropical and deep reservoir, we discovered that when the TP in the epilimnion increased, it was also the time the cold front came. The cold front was always associated with abundant rainwater, which was typical weather at this watershed in winter. The time series of water temperature at the Dam site (Figure 2 (b)) indicated that at this period, the water temperature in the epilimnion was approaching that in the hypolimnion, which implied that the thermocline of this deep reservoir had disappeared and caused the water mixing. The water temperature of the upstream was close to the air temperature, about 10–13°C as recorded, which was also lower than the water temperature of the hypolimnion. The water temperature of the hypolimnion was maintained at 16–19°C during the whole year because of the stratification of this deep reservoir. Therefore, if the river water is denser than the surface water, the negative buoyancy causes the inflows to plunge beneath the reservoir water, becoming an underflow (Martin and McCutcheon, 1999). In this study, the statistics of DO at the Dam site from 1991–2001 (Figure 2(c)) and the vertical profiles of DO at the Dam site in the winter period (in January and February 2000) (Figure 3 (a) and (b)) can support the existence of a density current.

Figure 2(c) shows the time series of DO during these ten years. If we take the dissolved oxygen in the hypolimnion as an indicator, there exists a yearly cycle of DO in the hypolimnion. In about October the DO of the bottom water would have been decreased to 1 mg/L or zero due to the sediment oxygen demand, and maintained till the increase of DO the following year.



(a) January 2000



(b) February 2000

Figure 3 The vertical profiles of DO (left side) at the Dam site and the contours of water temperature (°C) (right side) in the flow regime of the reservoir before (a) and after (b) the cold front. Figure 3 (a) was in January 2000 and (b) was in February 2000

The vertical distribution of DO (Figure 3 (a) and (b)) indicates that after the density current came, the bottom water with low DO originally in January had been raised to the middle layer of the reservoir in February. Meanwhile, the DO in the bottom layer was increased to 8 mg/L, the same as that of the upper layer. The contour of water temperature of the whole flow regime of the reservoir shows that after the cold front in February (Figure 3 (b)), the stability of the flow regime was disrupted. Now it is a typical 2-layered reservoir.

According to the trends of the water quality of Feitsui Reservoir investigated, we suggest that there are some problems should be considered: (1) the frequency of the abrupt increase of TP in the epilimnion in these years; (2) the increasing average water temperature in the hypolimnion; (3) the longer duration of the period of time when DO dropped to zero; (4) the increasing loading of the sediment P. We are not sure that these are correlated with the global warming effect but it does imply that the hydrological cycle is under change. The influence of sediment phosphorus release on the water quality has been enhanced and should be taken into account.

Hydrodynamics of the reservoir

Density current. Analytical solutions for the location and depth of the plunge point and underflow in the reservoir were developed. Figure 4 is the schematic diagram of a mathematical model including the analytical solutions of the transport of the density current combined with a 2-layered water quality model. According to the hydrological data collected (Feitsui Reservoir Administration Bureau, 2001), the location of the plunge point of the density current in February 2000 was estimated by assuming the Froude number of the

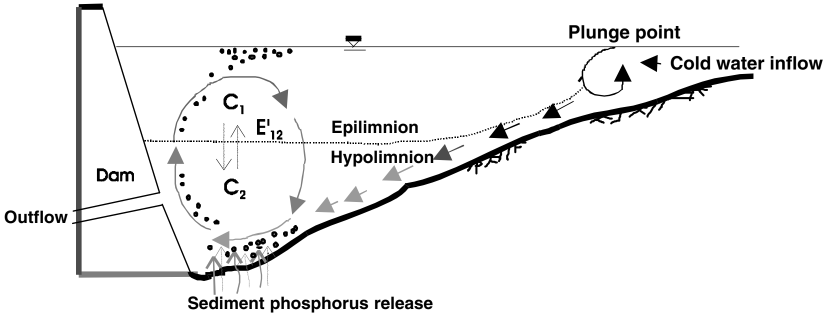


Figure 4 Schematic diagram of the density current occurring in the reservoir and the conceptual 2-layered water quality model

interflow (F_i) equal to the Froude number at the location of the plunge (F_p) (Martin and McCutcheon, 1999),

$$F_i^2 = \frac{u^2}{g\frac{|\Delta\rho|}{\rho}h_0} = F_P{}^2 \tag{1}$$

where u is inflow velocity, g is gravitational acceleration, h_0 is the hydraulic depth of the inflow, ρ is density of the inflow and $|\Delta\rho|$ is the density difference between the inflow and surface waters of the reservoir. The Froude number, F_p, can be expressed based on the conservation of energy and theory of the 2-layered flows in stratified water bodies (Martin and McCutcheon, 1999),

$$F_P{}^2 = 2.05\left(1 + \frac{f_i}{f_b}\right)^{-1}\left(\frac{S_0}{S_b}\right)^{0.478} \tag{2}$$

where f_b is the bed friction, f_i is the interfacial friction coefficient, and S_0 is the bed slope of the reservoir. The calculation results indicate that F_p is 0.77. The depth of the plunge point is 10.53 m. The plunge point is just behind the sampling site S-1, Wan-tan, as Figure 1 shows. The mixing and entrainment after the flow plunges result from the bottom shear across the surface of the underflow. The formulae used in the calculation of the entrainment coefficient, E, and the depth of the underflow are given below (Martin and McCutcheon, 1999),

$$E = \frac{1}{2}C_k C_D{}^{3/2} F_p^2 \tag{3}$$

$$h_u = \frac{6E}{5}X + h_{u0} \tag{4}$$

where C_k is approximately 3.2 (Hebbert *et al.*, 1979) and C_d is the bottom drag coefficient. The calculation results show that the greatest depth that the underflow could reach is about 83 m, almost equivalent to the depth of the sampling site, S-3, Hokengtze, about 8 km from the upstream. Although the underflow is well oxygenated and may improve bottom water quality, it can also push forward the bottom water with rich P into the downward regions of the reservoir. A 2-layered water quality model was applied to predict the concentration of TP of the reservoir.

Two-layered water quality model. Consider that in the reservoir, as shown in Figure 4, the hypolimnion receives the incoming loads of the density current with flow, Q_p, and

Table 1 Parameters specified in the 2-layered water quality model simulations

Parameter	Value	Unit
Outflow, Q_{OUT}	24	cm/s
Volume of the epilimnion, V_1	5.36×10^6	m^3
Volume of the hypolimnion, V_2	2.98×10^6	m^3
Interfacial area between layer1 and 2, A_{12}	7.29×10^4	m^2
Mixing length (equivalent to the distance from the centroid of layer 1 to the centroid of layer 2), Z_{12}	50.0	m
Bulk vertical dispersion coefficient, E'_{12}	3.28	m^3/s
Surface area at sediment-water interface, A_s	6.29×10^4	m^2
Sediment DTP flux , $q^{\dagger}$	2.2×10^{-7a}	kg/m^2 day
Decay rate constant due to algal uptake or debris settling in layer 1 and layer 2, k_1	0.05	day^{-1}
Inflow carried by density current, Q_p	277.28	cm/s
Concentration of TP in inflow, C_3	5.0	μg/L

† The value of flux, q, is entered by input of the estimated value in Jan. 2000 in Table 3

concentration of TP, C_0, and the sediment flux release of P, q, but is also mixed with the epilimnion. The withdrawal point of the reservoir is about 60 m in depth in the epilimnion. Under a steady state condition, the mass balance for the epilimnion (seg. 1) and the hypolimnion (seg. 2) is given by Eq. (5) and Eq. (6),

$$V_1 \frac{dC_1}{dt} = E'_{12}(C_2 - C_1) - V_1 k_1 C_1 = 0 \tag{5}$$

$$V_2 \frac{dC_2}{dt} = q \cdot A_S + Q_P \cdot C_0 + E'_{12}(C_1 - C_2) - V_2 k_1 C_2 = 0 \tag{6}$$

where the bulk vertical dispersion coefficient, E'_{12}, is given by (Martin and McCutcheon, 1999),

$$E'_{12} = \frac{V_2 Z_{12}}{A_{12} t} \ln\left[\frac{T_{21} - \overline{T_1}}{T_{22} - \overline{T_1}}\right] \tag{7}$$

The parameters used in the Eqs (5)–(7) and the values of them are tabulated in Table 1. The simulation results indicate that the simulated TP of the hypolimnion and epilimnion are 50.8 and 29.0 μg/L, respectively. They are very close to the observed values, 50.5 μg/L for the hypolimnion and 31.0 μg/L for the epilimnion. Although the concentration of TP of the epilimnion in February 2000 was still below the eutrophication level, 40 μg/L, it confirmed the contribution of TP in the hypolimnion that increased the concentration of TP of the epilimnion through the vertical mixing of water. The accumulation of TP in the bottom layer and the release of sediment P need to be assessed further.

Sediment properties investigation

The fractionation result of sediment phosphorus indicated that except for the residual P, organic P (25.3%) and Fe, Mn or Al-bound P (non-apatite P) (30.1%), which are larger than Ca-bound P (apatite P, 11.9%) and the exchangeable P (0.7%), are the two dominant phosphorus groups in the sediments. The geology of the watershed environment was verified with noncalcareous bedrocks. The mobility of phosphorus in the deep sediment is driven by the change of pH and oxidation-reduction potential (ORP) (Moore and Reddy, 1994). According to the results of the field study (Table 2.), with lowest ORP (–205 mV) and pH value (4.5) in the sediment in June 2000, the DTP (2.52 mg/L) and D-Fe (62.85 mg/L) show the highest concentrations among all. The dissociation of this rich non-apatite P in the

Table 2 The average chemical composition of the sediments in Feitsui Reservoir during 2000–2001

Constituent	01/00	06/00	09/00	05/01	08/01	12/01
DTP, mg/L	1.05	2.52	2.03	1.60	1.93	0.78
DRP, mg/L	0.38	0.46	0.52	0.79	0.53	0.29
D-Fe, mg/L	3.86	62.85	49.53	15.86	61.96	–
pH value	6.7	4.5	5.8	6.2	7.0	6.8
ORP, mV	–85.7	–205.4	–180.8	–195.0	–143.2	–123.5

Table 3 The estimated DTP fluxes at the Dam site

Sampling date	DTP, μg/cm^2 day		Bottom DO, mg/L
	(1)[a]	(2)[b]	
07-Jan-00	0.022	0.020	0
21-Jun-00	0.126	–0.014	6.18
29-Sep-00	0.053	0.042	1.19

a. Method (1) estimated the flux using Fick's law by input of the diffusion coefficient of P in the water as 3.6 × 10^6 cm^2/s at 20°C (Krom and Berner, 1980)

b. Method (2) estimated the flux by tracing the accumulation of the overlying water DTP conc. just above the sediment

sediment in an anoxic state, where the ORP and pH values are both low, was suggested as the main pathway of solid inorganic P into the porewater.

The P flux from the sediments is strongly affected by the overlying water DO because of the large sorption capacity of ferric oxyhydroxide particles for phosphate at the oxidized layer (Mortimer, 1941, 1942; Holdren and Armstrong, 1980; Buffle *et al.*, 1989). Assuming that sediment P release is the only P source of the overlying water during the sampling time, the release rate of the DTP from the sediment could be estimated by tracing the concentration accumulation of the overlying water just above the sediment. Another approach to predict the sediment fluxes is based on Fick's Law. We used both techniques to estimate the DTP flux of the reservoir. Table 3 shows that the estimated fluxes using method (2) for the anoxic state in January and September are larger than for the oxic state in June. The high DO in June was obviously the barrier inhibiting the transport of the large amount of DTP in the porewater. It also indicated that method (1), using Fick's law without considering the chemical behavior, might overestimate the DTP flux for the oxic state. We can conclude that the chemical potential of the sediment phosphorus is high when in an anoxic state in winter.

Conclusions

In summary, with noncalcareous geological formation and subtropical climate in the watershed, rich sediment phosphorus incorporated with the density current occurring in winter was the important nutrient source influencing the water quality. In terms of the contribution to the nutrient loading, not only the human activities but also the natural hydrological cycle should be carefully assessed.

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