DETERMINATION OF TROPHIC STATE AND TESTING OF PHOSPHORUS MODEL IN THE KI HEUNG RESERVOIR

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Abstract: The relationship between areal total phosphorus (TP) and areal hydraulic loading was identified and used as defining the trophic state of the reservoir And three simple, conceptual TP models were tested against the measured in-reservoir TP concentration The analyses were based on water quality data measured in the Ki Heung reservoir for two years. The results showed that Ki Heung reservoir has undergone eutrophic state, and Dillon's and Vollenweider's TP models were in close agreement with the measured annual mean TP concentration. However. the OECD's model underestimated the measured annual mean TP concentration in the Ki Heung reservoir. A discussion is given for the hypothetical application of TP loading plot which might be useful for establishing the TP control program in the reservoirs/lakes.

Key Words: eutrophication, phosphorus model, phosphorus loading plot. Ki Heung reservoir

1. INTRODUCTION

This paper is concerned with the eutrophication analysis using the hydrologic and water quality data monitored for 2 years in the Ki Heung reservoir. The phenomena of eutrophication has been a worldwide problem in the considerable number of reservoirs, lakes, rivers and coastal water, and extensively studied in the past as summarized by Sakamoto (1996). Eutrophication is the excessive growth of aquatic plants that can result in significant deleterious effects on the desirable water uses. One of the main causes of eutrophication is the excessive level of nutrients such as nitrogen and phosphorus imported into a water body from many sources.

In order to manage and control the water quality of reservoir effectively, it is necessary to identify the trophic state and to evaluate the nutrient levels of water body. Thus, the present paper is intended to determine the trophic state and to test a simple conceptual models which can predict the total phosphorus (TP) levels in the reservoir. The approach is based on some simplifying assumptions that phosphorus is a limiting nutrient controlling the growth of aquatic plants, and temporal variations in inflow/outflow and in-reservoir TP concentration are neglected on an annual basis.

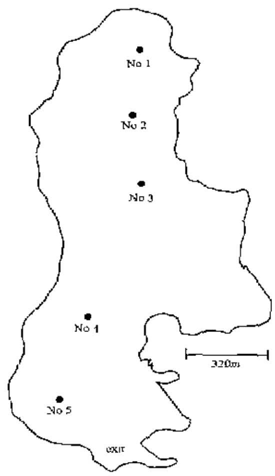

Fig. 1. Water Quality Sampling Points in the Ki Heung Reservoir

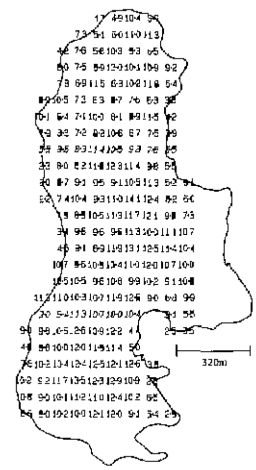

Fig. 2. Water Depth Distribution (m) Measured in the Ki Heung Reservoir

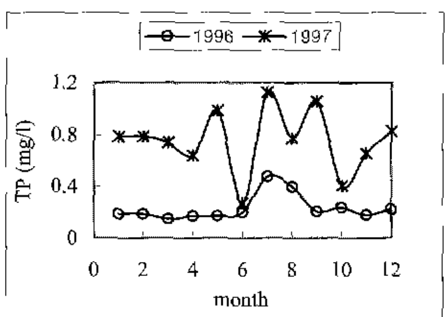

Fig. 3. Monthly Mean inflow TP Concentration

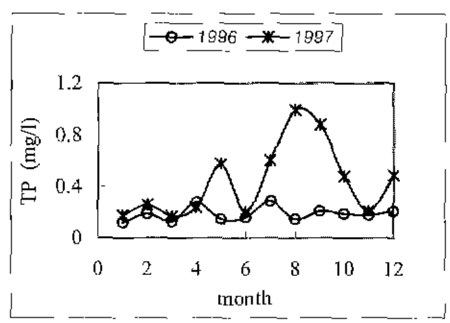

Fig. 4. Monthly Mean Outflow TP Concentration

2. STUDY SITE AND DATA COLLECTION

This study is based on the data collected in the Ki Heung reservoir during 2 years from 1996 through 1997. The Ki Heung reservoir is located in the headwaters of O-San stream and in the vicinity of Kyung Hee university which lies to the west of Yong-In city in Kyonggi province. The Ki Heung reservoir with the drainage area of about 52.5 ㎢ regulated by the operating gate supplies agricultural water for the downstream area. Fig. 1 shows five sampling locations for water quality measurements. At each location, the sampling was made at an interval of 2 m in depth. As shown in Fig. 2, water depth distribution was measured using the boat equipped with Global Positioning System (GPS) and water depth meter in order to identify the physical geometry of the reservoir.

Fig. 3 and Fig. 4 show the monthly mean inflow and outflow concentration of TP. The inflow concentration was measured at the sampling point located at 400 m upstream of the No. 1 sampling point, and the outflow concentration was sampled at the exit location of the reservoir.

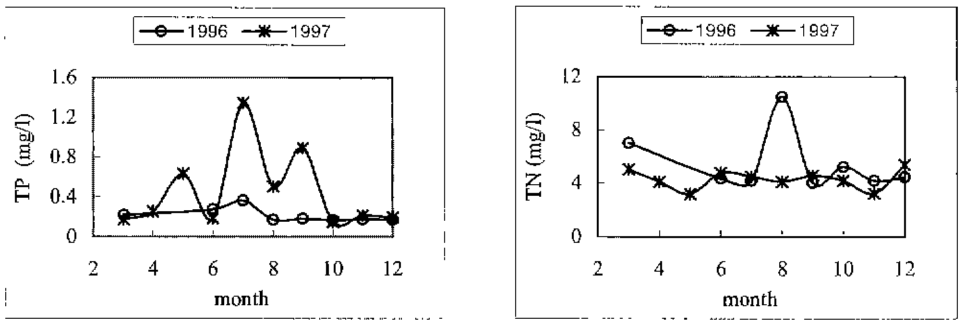

Fig. 5. Monthly Mean In-reservoir Concentration of TP and TN

The monthly mean in-reservoir concentrations of TP and TN are shown in the Fig. 5. These in-reservoir concentrations are estimated by spatially averaging the TP and TN concentrations measured at five sampling locations (No.1 through No.5 in Fig. 1). Fig. 6 indicates the monthly mean water stage of the reservoir where the water level in the reservoir generally decreases during the irrigation season and returns to the full water level during winter.

3. ANALYSES AND RESULTS

3.1 Physical and Hydrologic Characteristics

It is necessary to define the physical and hydrologic characteristics of the reservoir for the eutrophication analyses. The volume, surface area, inflow/outflow discharge, and detention time of the reservoir are the main physical characteristics to be identified. Table 1 shows the physical characteristics identified for 1996 and 1997. The annual mean water levels of the reservoir were averaged using the monthly mean water levels of the reservoir shown in Fig. 6. The annual average volume and surface area of the reservoir corresponding to the annual average water level were estimated through the spatial integration using water depth distribution data of the reservoir shown in the Fig. 2. The annual water level in 1996 and 1997 appears to be almost identical, so that the annual mean volume and surface area of the reservoir were assumed to be the same for both years.

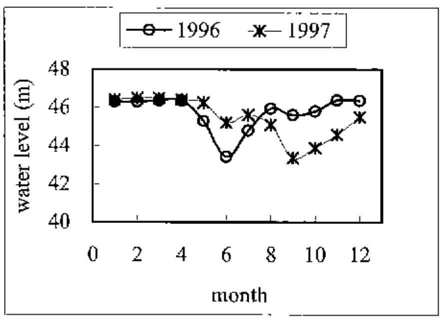

Fig. 6. Monthly Mean Water Level Changes

Since the continuous inflow and outflow records flowing into and out of the Ki Heung reservoir were not available, the annual mean discharge into the reservoir was estimated on the basis of water balance relation. The long-term water balance equation is given by

$$Q = P - E \tag{1}$$

where Q is inflow discharge, P is precipitation, E is evaporation. In this study the change in storage is assumed to be negligible on a yearly basis, and the spatial variations in precipitation and evaporation are also negligible and assumed

Table 1. Physical Characteristics of the Ki Heung Reservoir

Year	Water level (m)	Volume (m^3)	Surface area (m^2)	Inflow discharge (m^3/yr)
1996	45.3	11,348,908	1,554,808	10,803,278
1997	45.5	11,348,908	1,554,808	33,428,238

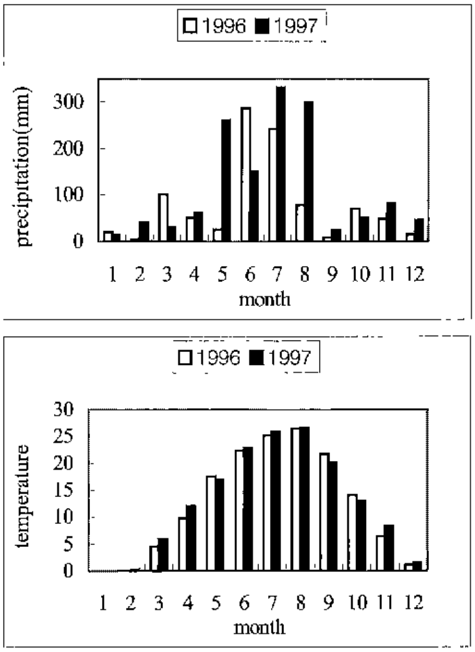

Fig. 7. Monthly Precipitation and Temperature(℃) Record

to be uniformly distributed within the drainage basin. As shown in Fig. 7, the monthly mean precipitation and temperature data in 1996 and 1997 have been measured at Su Weon climatological station located in the vicinity of the Ki Heung reservoir. The annual evaporation component in Eq. (1) was calculated by summing the monthly mean evaporation determined by Thornthwaite method. In Thornthwaite method, the potential evapotranspiration calculated on a monthly basis is given in Shaw (1994) as:

$$E_m = 16 N_m \left(\frac{10 T_m}{I} \right)^a \quad \text{(mm)} \tag{2}$$

where m indicates the month, N_m is the monthly adjustment factor related to daylight hours, T_m is the monthly average temperature (℃). The heat index I and constant a are given as follows:

$$I = \sum_{m=1}^{12} \left(\frac{T_m}{5}\right)^{1.5} \tag{3}$$

$$a = 6.7 \times 10^{-7} I^3 - 7.7 \times 10^{-5} I^2 + 1.8 \times 10^{-2} I + 0.49 \tag{4}$$

In Eq. (2), the monthly adjustment factor N_m depends on the location and is estimated on the basis of 37.5° north latitude at Su Weon climatological station. Table 2 reveals the estimated overall water balance for each year. The annual evaporation for two years are the same order of magnitude and the monthly evaporation distribution shown in Fig. 8 are similar between 1996 and 1997 because the monthly air temperature distribution is also similar each other as seen in Fig. 7. The annual inflow discharge in

Table 2. The Estimated Water Balance

Year	Precipitation (mm/yr/m^2)	Evaporation (mm/yr/m^2)	Runoff (mm/yr/m^2)	Inflow discharge (m^3/yr)
1996	952.1	746.3	205.8	10,803,278
1997	1394.3	757.6	636.7	33,428,238

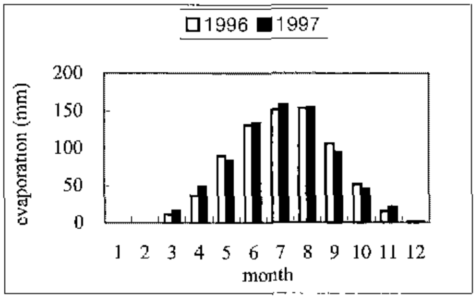

Fig. 8. The Estimated Monthly Mean Evaporation

Fig. 7. The annual inflow discharge in Table 2 can be calculated by the product of annual runoff per unit area by the drainage area of 52 ㎢ contributing to the Ki Heung reservoir.

3.2 Phosphorus Loading Plot and TP Models

In this section the trophic state of the reservoir was determined by constructing TP loading plot which can be derived on the basis of mass balance of TP. The simple TP models can be formulated by the mass balance equation with the following assumptions: (1) The reservoir is completely mixed. (2) The inflow/outflow and lake concentrations are steady state as annual average condition. (3) The phosphorus is a limiting factor controlling the growth of plant biomass. (4) TP is used as a measure of trophic status. The completely mixed reservoir system neglects the temperature stratification. This assumption approximately holds for the Ki Heung reservoir as shown in Fig. 9 where exhibits the monthly mean temperature profile measured in June and December. Except for the profile in June 1997, the temperature profile is almost uniform and, therefore, the temperature stratification can be neglected.

The assumption of phosphorus limitation implies that phosphorus is the nutrient that limits the plant biomass growth in the reservoir and all

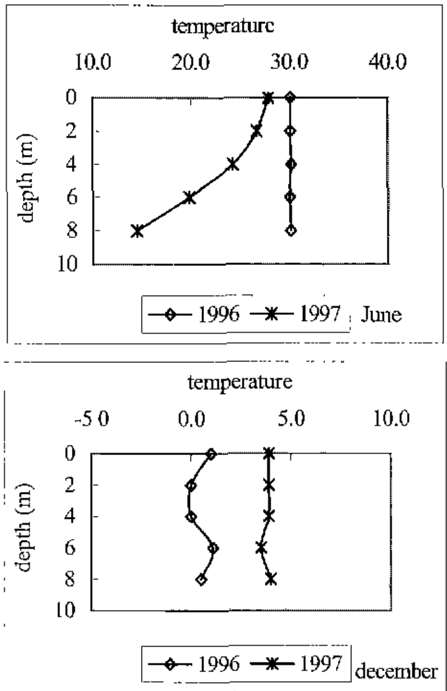

Fig. 9. The Temperature Profile in June and December

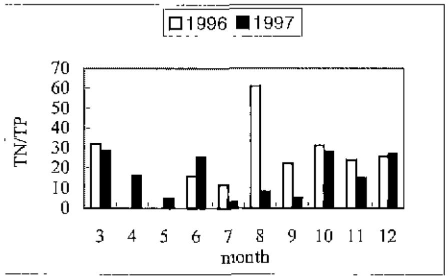

Fig. 10. Monthly-Averaged TN/TP Ratios

other nutritional requirements for the growth of the plant biomass are satisfied. The validity for this assumption of phosphorus-limited systems might be judged on the basis of TN/TP ratio in the reservoir. Thomann and Mueller (1987) suggest that TN/TP ratios of 20 or greater generally reflect the phosphorus-limited systems. Fig. 10 shows the monthly-averaged TN/TP ratios for the Ki Heung reservoir, in which the annual mean TN/TP ratio, determined from the monthly mean ratios, appears to be about 21. Hence, it is reasonable to assume that phosphorus is a limiting nutrient for the growth of the plant biomass such as phytoplankton.

The mass balance equation for TP is given by

$$V\frac{dP}{dt} = W - \upsilon_S A_S P - QP \qquad (5)$$

where V = the volume of the reservoir [L^3], P = total phosphorus concentration in the reservoir [M/L^3], W = input phosphorus mass loading [M/T], Q = outflow discharge [L^3/T], A_s = surface area of the reservoir [L^2], υ_s = the net settling velocity that represents the combined effects of settling and re-suspension [L/T]. If TP concentration in the reservoir is invariant with time $(\frac{dP}{dt} = 0)$, then the Eq. (5) becomes

$$P = \frac{W}{Q + \upsilon_S A_S} \qquad (6)$$

Using the concept of areal TP loading rate $L = \frac{W}{A_s}$ [$M/L^2/T$] and areal hydraulic loading rate $q = \frac{Q}{A_s}$ [L/T], the Eq. (6) is expressed as

$$P = \frac{L}{q + \upsilon_S} \qquad (7)$$

Vollenweider (1975) determined empirically the value of 10 m/yr as the net settling velocity. Thus, Eq. (7) is written as

$$P = \frac{L}{q + 10} \qquad (8)$$

To determine the trophic status of the lake, the objective levels of TP set by Vollenweider

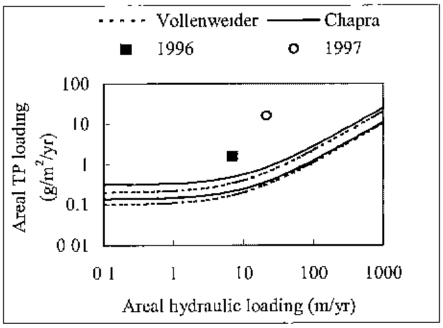

Fig. 11. TP Loading Plot. The Higher Lines Represent the Excessive Level and the Lower Lines Represent the Acceptable Level in each Case

(1975) are as follows:

P=0.01 mg/l for acceptable TP level

P=0.02 mg/l for excessive TP level

The 'acceptable level' represents the upper level of oligotrophic condition while 'excessive level' represents the lower level of eutrophic condition. By substituting these objective TP levels into Eq. (8), the TP loading rates can be given as a function of areal hydraulic loading.

L= 0 01 (q+10)) for acceptable loading (9a)

L= 0 02 (q+10) for excessive loading (9b)

Chapra and Tarapchak (1976) proposed an alternate TP loading plot based on mass balance Eq. (7), the relationship between mean annual and spring TP concentration, the relationship between spring TP concentration and chlorophyll a. The resulting areal TP loading is expressed as both functions of chlorophyll a concentration and q.

$$L = 0.0055(chl\ \ a)^{0\ 69}(q + 1.24) \qquad (10)$$

In the derivation of Eq. (10), Chapra and Tarapchak defined the value of the net settling velocity as 12.4 m/yr. Chapra and Tarapchak (1976) selected the following chlorophyll *a* concentration (*chl a*) as objective level to determine the trophic state.

chl a = 2.75 μg/l for acceptable *chl a* level

chl a = 8.70 μg/l for excessive *chl a* level

Substitution of these corresponding *chl a* levels into Eq. (10) results in the following TP loading rates as a function of areal hydraulic loading *q*.

$$L = 0.011\ (q + 12.4) \quad \text{for acceptable loading} \quad (11a)$$

$$L = 0.025\ (q + 12.4) \quad \text{for excessive loading} \quad (11b)$$

The TP loading Eqs. 9(a), 9(b), 11(a), and 11(b) can be used to determine the trophic state of the reservoir when the field estimated *L* and *q* data are available. The TP loading plots for Eqs. (9) and (11) are shown in the Fig. 11 where the dots represent the relationship between *L* and *q* determined using data measured in the Ki Heung reservoir. Since the relationships between *L* and *q* for both years lie above the excessive level, the trophic state of Ki Heung reservoir turns out to be eutrophic.

3.3 Testing of TP Models

The TP model (Eq. (7)) can be used to estimate the annual mean TP concentration of the reservoir with the given *L*, *q*, and υ_s. However, a direct measurement of υ_s is generally difficult so that an alternate model can be formulated in terms of measurable variables. Dillon and Rigler (1975) derived the TP model using the concept of retention coefficient (*R*) as

$$P = \frac{L}{q}(1 - R) \quad (12)$$

The retention coefficient can be calculated as

$$R = (\text{inflow load - outflow load})/\text{inflow load} \quad (13)$$

Thus *R* represents the ratio of the amount of TP added to the amount of TP retained by the reservoir. The other TP model can be formulated using the relation of υ_s to the detention time of the reservoir t_d suggested by Vollenweider (1976) as

$$\upsilon_s = H\sqrt{\frac{1}{t_d}}$$

where *H* is the mean depth of the lake and $t_d = \frac{V}{Q}$. Substitution of this relation into Eq. (7) results in the following TP model.

$$P = \frac{L}{q(1 + \sqrt{t_d})} \quad (14)$$

The OECD model was developed by correlating this Vollenweider's model with the data collected from international monitoring surveys (OECD, 1982) as

$$P = 1.55\left(\frac{L}{q(1 + \sqrt{t_d})}\right)^{0.82} \quad (15)$$

In the Eq. (15), the units of areal TP loading *L* should be used as μg/l/yr. The correlation coefficient of 0.93 was found in the OECD study with 87 data points.

Fig. 12 compares the annual mean TP concentration calculated from three models with that measured in the reservoir. Table 3 summarizes the parameters used for the TP models. These parameter values were estimated using the field measurement data explained above. As shown in Fig. 12, Dillon's and Vollenweider's TP models approximately predict the annual

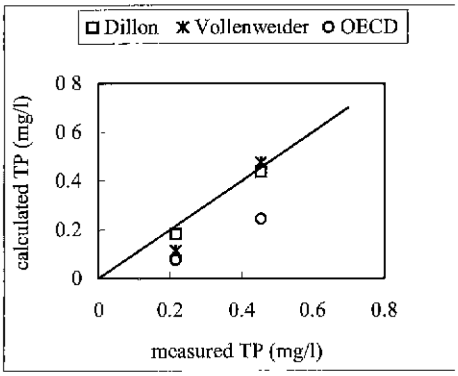

Fig. 12. Comparison Between Measured and Predicted TP Concentrations

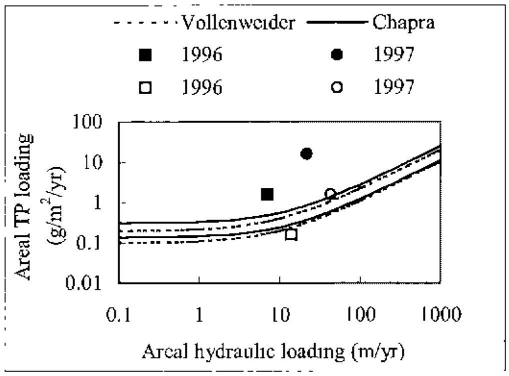

Fig. 13. Comparison Between the Existing and Controlled TP Loading Condition

mean TP concentration. And it appears that the predictability of Dillon's model is better than that of Vollenweider's model for this particular case. However, the OECD model highly underestimated the in-reservoir TP concentration in the Ki Heung reservoir. This result is consistent with that of Foy (1992) who also found that the OECD model underestimated the in-reservoir TP concentration in northern Irish lakes. According to Foy (1992), the steady state assumption in lakes with shorter detention time may be violated and results in lower estimation of in-lake TP concentration.

4. CONCLUSIONS AND DISCUSSION

In this paper the water quality measurements monitored for two years in the Ki Heung reservoir were analyzed to determine the trophic state of the reservoir and to test three simple conceptual models which is used for the evaluation of TP concentration. The major findings of this study are summarized as follows.

(1) The Ki Heung reservoir is proved to be eutrophic state on the basis of the TP loading plots of Vollenweider (1975) and Chapra and Tarapchak (1976).

(2) Two simple TP models of Dillon and Vollenweider closely predicted the annual mean TP concentration measured in the Ki Heung reservoir. And the predictive ability of Dillon's model is better than that of Vollenweider's model. However, the OECD's model highly underestimated the annual mean TP concentration of the Ki Heung reservoir.

(3) The two years average TN/TP ratio is estimated as about 21, so the Ki Heung reservoir might behave as the phosphorus limited system and nonpoint sources might be a dominant input loading source into the reservoir.

The TP loading plot illustrated in this paper is a useful tool for determining the trophic state of the reservoir and provides a clear visual inspec-

Table 3. The Field Determined L, R, q and t_d Values

Year	L (g/m^2·yr)	R	q (m/yr)	t_d (yr)
1996	1.6	0.2	6.95	1.05
1997	16.2	0.42	21.5	0.34

tion of how to control the TP loading and hydraulic loading required for achieving the desirable water quality levels. Fig. 13 exhibits the 'hypothetical' application of TP loading plot in managing the water quality of the reservoir. In the figure black dots represent the actual condition of areal TP loading and hydraulic loading in 1996 and 1997 while the open dots indicate the modified areal TP loading and areal hydraulic loading. The modified relationships were made by reducing the actual TP loading by 90% and by doubling areal hydraulic loading. As seen from the figure, this hypothetical control scheme modified the trophic state of the reservoir from eutrophic state to oligotrophic state for the case of 1996 and allowed to lie on the border line of eutrophic and mesotrophic state in 1997.

The most uncertain factor in the analyses might be the characteristics of inflow and outflow discharge in the reservoir. The inflow into the reservoir was assumed to be equal to the outflow discharge from the reservoir on a annual basis and was estimated on the basis of water balance equation and Thornthwaite's evaporation method. In future studies, the inflow / outflow discharge has to be measured continuously and the direct measurement data need to be incorporated in the analyses in order to give confidence about these findings. The approaches illustrated in this paper might serve as an efficient, economic tool for managing the eutrophication related water quality problems in the reservoir/lakes when the limited data and resources are available.

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