Ecosystem Modeling and Scenario Analysis of Water Quality Dynamics in an Agricultural Pond

Hour IX*, Kazuaki HIRAMATSU**, Masayoshi HARADA** and Makito MORI**

1. Introduction: For water quality conservation in agricultural areas, total nitrogen and total phosphorus are the most important water quality indices to be studied. Overloading of either nitrogen or phosphorus will result in an eutrophication condition which is the critical issue of water pollution, leading to a serious impact when such polluted water is later utilized as irrigation water for agriculture. The eutrophication phenomenon is due to both the shallow condition of the pond itself and the excessive nutrients of nitrogen and phosphorus caused by human activities. In this study, an ecosystem model was constructed for predicting the dynamics of water quality indices of nitrogen and phosphorus. The ecosystem model is composed of 5 water quality indices: a nitrogen oxide NO_x-N, an ammonia-nitrogen NH_4-N, an organic nitrogen Org-N, a phosphate-phosphorus PO_4-N and an organic phosphorus Org-P. The model was applied to an agricultural pond where concentrations of TN and TP are extraordinarily high. The effectiveness and validity of this model was firstly verified by comparisons between the observed and the simulated results. Subsequently, the scenario analysis was conducted to improve the water quality and to prevent the eutrophication.

2. Study Area: Toishigawara-ike is a eutrophic agricultural pond located in Sasaguri Town in Fukuoka Prefecture, Japan. Lying in a relatively flat and low area, Toishigawara-ike receives inflow water from the high-elevated forest as well as settlement areas adjacent to it. The pond plays an important role in providing irrigation water to the surrounding agricultural land with its total water storage capacity of approximately 2,200 m^3 . With an average depth of only about 2 m, the pond is regarded as a rather shallow water body.

3. Methodologies: A weekly water sampling process was conducted to specify the level of pollution and the fluctuating concentrations of nitrogen and phosphorus in both pond and inflow waters. Samples were retrieved directly from the field and taken to the laboratory to analyze the concentrations of NO_3-N, NO_2-N, NH_4-N, PO_4-P, TN, TP, chlorophyll-a and COD. Concentrations of Org-N and Org-P were determined by subtracting inorganic ion formations from TN and TP, respectively. Dissolved oxygen, water temperature, pH, electric conductivity and transparency were also measured on site. Furthermore, meteorological elements such as wind speed, air temperature, humidity and rainfall were continuously recorded at an interval of ten minutes by data logger. The discharge of inflow into the pond was measured in parallel with water sampling. As the water level of the pond remains constant, the amount of outflow water could be evaluated as the summation of inflow and rainfall volume running into the pond.

4. Ecosystem model: An ecosystem model (Chapra, 1997) was developed for predicting the daily variation of nitrogen (N) and phosphorus (P) in Toishigawara-ike. Org-N and Org-P consist of abiotic organism and phytoplankton. Referring to the model, the five targeted water quality indices of TN and TP are presented through the following equations:

$$\frac{dN}{dt}=\frac{q_{\text{in}}}{V}N_{\text{in}}+\frac{q_R}{V}N_R-\frac{q_{\text{out}}}{V}N+\alpha_N H-r_1\mu_N O-\alpha_D\frac{N}{h} \tag{1}$$

$$\frac{dH}{dt}=\frac{q_{\text{in}}}{V}H_{\text{in}}+\frac{q_R}{V}H_R-\frac{q_{\text{out}}}{V}H-\alpha_N H-(1-r_1)\mu_N O+\alpha_M O+\frac{E_H}{h} \tag{2}$$

$$\frac{dO}{dt}=\frac{q_{\text{in}}}{V}O_{\text{in}}+\frac{q_R}{V}O_R-\frac{q_{\text{out}}}{V}O+\mu_N O-\alpha_M O-\alpha_s\frac{O}{h} \tag{3}$$

$$\frac{dP}{dt}=\frac{q_{\text{in}}}{V}P_{\text{in}}+\frac{q_R}{V}P_R-\frac{q_{\text{out}}}{V}P+\beta_M Y-\mu_P Y+\frac{E_P}{h} \tag{4}$$

$$\frac{dY}{dt}=\frac{q_{\text{in}}}{V}Y_{\text{in}}+\frac{q_R}{V}Y_R-\frac{q_{\text{out}}}{V}Y-\beta_M Y+\mu_P Y-\beta_s\frac{Y}{h} \tag{5}$$

* Graduate School of Bioresource and Bioenvironmental Sciences, Kyushu University
** Faculty of Agriculture, Kyushu University
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In the equations, N, H, O, P, Y are concentrations of NO_x-N, NH_4-N, Org-N, PO_4-N, and Org-P respectively. V is volume of the pond, A is an area of the pond surface, h is a water depth defined as $h \equiv V/A$, q is the discharge running into or out of the pond. Subscripts of "in", "R", "out" denote inflow, rainfall and outflow, respectively. Parameters α_N, μ_N, α_D, α_M, E_H, α_s, β_M, μ_P, E_P are a nitrification rate, an intake rate of N by phytoplankton, a denitrification rate, a mineralization rate of Org-N to NH_4-N, an elution rate of N from bottom mud, a settling velocity of Org-N, a mineralization rate of Org-P to PO_4-P, an intake rate of P by phytoplankton, and an elution rate of P from bottom mud, respectively. $\beta_s (= \alpha_s)$ is a settling velocity of Org-P and r_1 is a distribution constant to NO_x-N and NH_4-N.

5. Scenario analysis: According to the observation, the concentrations of TN and TP in the pond were fluctuating closely related to ones of inflow. It would be considered that inflow load directly causes rich nutrient salt in the pond. Therefore, the reduction of inflow load seems to be the most effective measure in order to fulfill the Japanese water quality standard of TN for paddy rice and to suppress the progress of eutrophication. In order to acquire the measure for the water environmental conservation, the scenario analyses are conducted under the assumption that the inflow load of TN and TP via the inflow water is 80%, 60%, 40%, 20%, and finally 10% of the current situation.

6. Results and discussion: As shown in **Fig.1**, the calculated results of 5 indices of NO_x-N, NH_4-N, Org-N, PO_4-N and Org-P show very close values to the observed ones regardless of rainfall volume changes. This means that the ecosystem model used in this research could reproduce the matter cycle of nitrogen and phosphorus in Toishigawara-ike and can be sufficiently applied to evaluate and to predict the variations of water quality indices for the conservation and improvement of water environment. **Figure 1** also shows that TN is relatively high and around 4.0 mg/L in the pond. Meanwhile, TP is also high in both inflow load and pond water. TN concentration is increasing closely related to the increment of inflow water, which means inflow water is the main factor of TN accumulation. With regard to the scenario analysis shown in **Fig.2**, if 20% of the TN amount is loaded into the pond, the average concentration of TN in the pond will be reduced as low as the Japanese water quality standard of irrigation water for TN (less than 1 mg/L). Simultaneously, the concentration of TP is remarkably declining as well. Therefore, 80% reduction of the load in the inflow water should be the best solution for standard irrigation water.

7. Conclusion The time series approach using an ecosystem model was found to be useful. Some significant procedures have been successfully performed in this study. Those include a mathematical model of the pond ecosystem, a comparison between the calculated and the observed results, and a scenario analysis assuming 80% reduction of TN in the inflow load. This final conclusion is the most significant proposal to meet the water quality requirement for agricultural irrigation water.

References: Chapra, S. C. 1997 *Surface Water Quality Modeling*, WCB McGraw-Hill, 521-663.

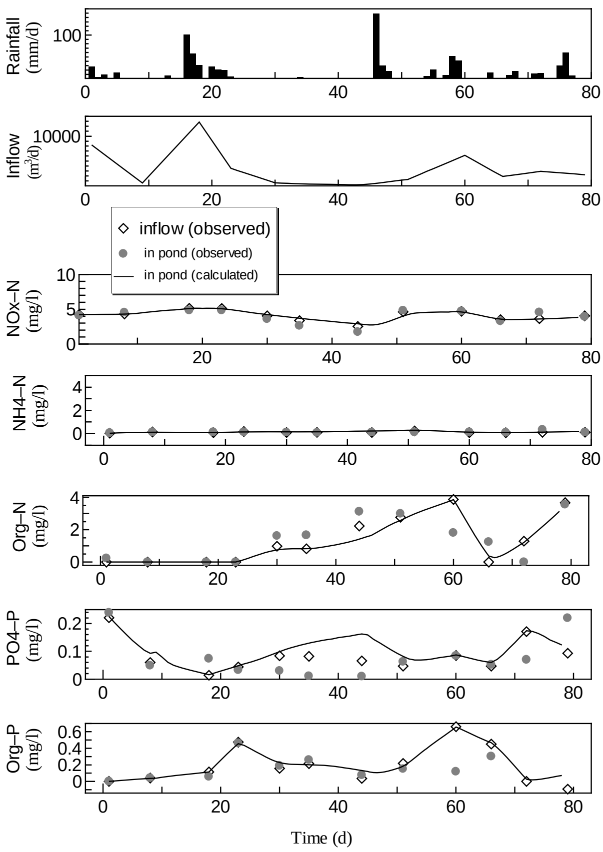

Fig.1 The observed and simulated result. (July 4 to September 20, 2006)

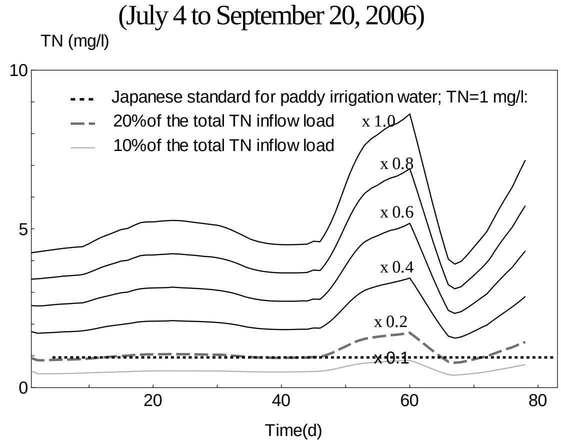

Fig.2 The results of scenario analysis. (July 4 to September 20, 2006)