Annual Journal of Hydraulic Engineering, JSCE, Vol.51, 2007, February

NUTRIENT-SEDIMENT LOADS FROM FOREST CATCHMENTS AND THEIR INFLUENCE ON LAKE AND RESERVOIR EUTROPHICATION

Kohji MICHIOKU

Fellow of JSCE, Dr. of Eng., Professor, Dept. of Civil Engineering, Kobe University
(1-1 Rokkodai, Nada, Kobe 657-8501, Japan)

Land-cover types in watersheds have a significant impact on water quantity and quality as well as on ecological cycles in lakes and reservoirs. Dependencies of substance loads from forest catchments on land-cover are discussed with a particular focus on nutrients and sediment. Ecological processes and the eutrophication mechanism in lakes and reservoirs are briefly reviewed. The relationship between water quality in lakes and reservoirs and the nutrient production from forest catchments is discussed. Algae bloom and the resultant eutrophication are predominantly controlled by a phosphorus load that is highly correlated with the sediment load. As forest-cover decreases in the catchment, the sediment and nutrient loads increase and eventually promote eutrophication in lakes and reservoirs. Since field data indicate that the clearing and collapse of forests result in a significant increase in the runoff rate and nutrient load, proper management of forests is one of the key issues for protecting the water environment.

Key Words : *water quality, eutrophication, nutrient loads, lake, reservoir, sediment yield, forest catchment, land-cover*

1. INTRODUCTION

Seasonal variations in discharge are generally significant in Japanese rivers and they have very large regime coefficients. Therefore, many reservoirs have been constructed for flood protection and water use in the last several decades. Since 67 percent of the country is covered by forest, water quantity and quality in lakes and reservoirs are greatly influenced by the substances produced in forest catchments. Nevertheless, little scientific knowledge is available with respect to the effects that water and substance loads from forests have on the water environment in downstream areas. In general, the water exchange rate and self-purification capability in lakes and reservoirs are much lower than in running waters. Therefore, even small changes in the balance of water and substances in watersheds accumulate in the system, with the possibility of having a marked impact on the ecosystem. This paper discusses the degree to which a forest catchment plays an important role in the ecological cycle in receiving waters. In addition, we will consider reservoir eutrophication from a basin-scale point of view.

2. LOADS FROM CATCHMENT AND EUTROPHICATION

Fig.1 schematically illustrates what happens in a reservoir. A catchment feeds water, nutrients, and inorganic and organic compounds to receiving waters. During warm seasons, nutrients fed from the catchment induce algae blooming in the photic zone. Although photosynthesis is a necessary activity in an ecological cycle, it may contaminate water when the nutrient load is too heavy for the receiving water's capacity. High concentrations of

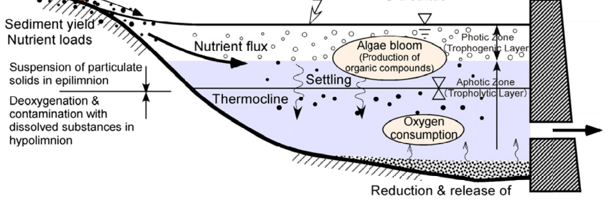

Fig.1 Ecological cycle in a eutrophic reservoir.

organic matter negatively impact the taste and smell of water, leading to a variety of technical problems in the water purification process. Long suspension of particulate organic matters makes water less transparent and eventually spoils a lake's appearance.

Organic compounds decompose in the course of settling, consuming a large amount of dissolved oxygen in the aphotic zone and making the hypolimnion anoxic. When the benthic layer in the hypolimnion is exposed to anaerobic water, dissolved substances such as ionic metals, organic compounds and nutrients are released from sediments through anoxic reduction. This is how the hypolimnetic water is contaminated.

In this way, pollutant loads from the catchment significantly affect the environment in receiving waters, especially in enclosed basins such as lakes and reservoirs.

3. COMPARISON OF NUTRIENT BALANCE BETWEEN NATURAL LAKE AND RESERVOIR

A variable α defined as

$$\alpha\,(1/\text{year}) = \frac{[\text{annual total discharge}\,(\text{m}^3/\text{year})]}{[\text{total storage capacity}\,(\text{m}^3)]}$$

is generally used as a parameter for indicating the average flushing rate of impounded water. The inverse of α, i.e. $\tau=1/\alpha$, is the theoretical filling time or the retention time of the water. A reservoir usually has a higher flushing rate or smaller retention time than a natural lake because of its engineering purposes. However, this fact does not necessarily mean that reservoirs have less possibility of eutrophication than natural lakes. By plotting the cumulative load of total phosphorus defined by

$$[\text{Cumulative load of P}\,(\%)] = \frac{[\text{Inflow flux of TP}]-[\text{Outflow flux of TP}]}{[\text{Inflow flux of TP}]}\times 100$$

against α, and comparing the results for a reservoir and natural lake as in Fig.2, a greater amount of TP is found to be stored in reservoirs than in lakes. This is attributed to differences in the thermal structure and fluid dynamics between lakes and reservoirs.

In general, concentration of chlorophyll-a or algae in inland waters is well correlated with the total phosphorus as plotted in Fig.3, an indication that the limiting nutrient for eutrophication is the phosphorus in most cases. Figs.2 and 3 lead to the conclusion that a reservoir is more likely to suffer from water quality problems than a natural lake. The discussion in the following sections will focus further on hydrological and ecological cycles in forest-covered catchment areas.

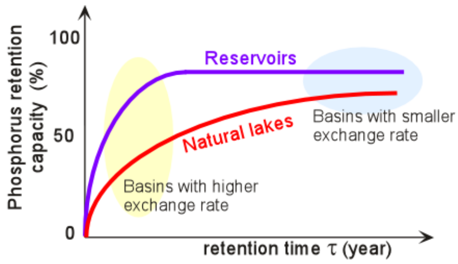

Fig.2 Phosphorus retention capacity versus retention time τ (rearrangement of dataset from 1))

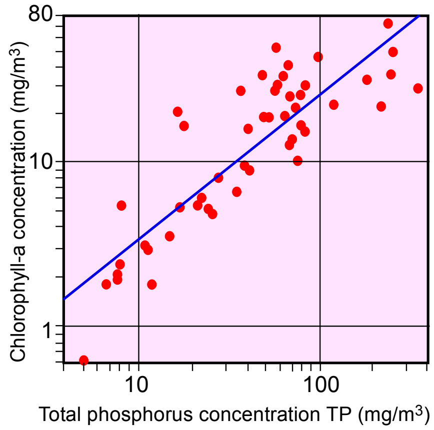

Fig.3 Correlation between concentrations of chlorophyll-a and total phosphorus[2].

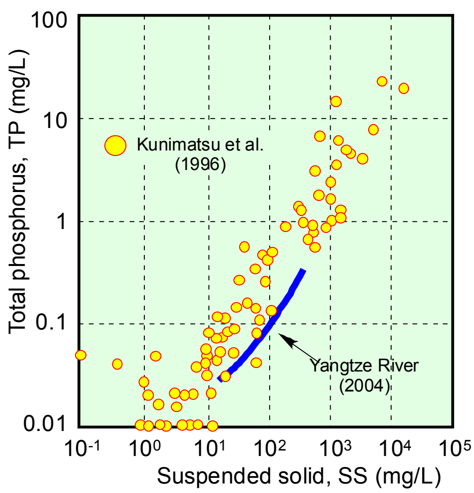

Fig.4 Total phosphorus TP versus suspended solids SS. Datasets from 3), 4) and 5) were rearranged by the author.

4. NUTRIENT-SEDIMENT LOADS FROM FOREST CATCHMENT

(1) Correlation between phosphorus and suspended solids

Phosphorus is strongly adsorbed to particles and most of it is transported with sediments.

Therefore, the concentration of phosphorus is expected to have a good correlation with suspended solids or turbidity. This is verified in Fig.4, where total phosphorus concentration TP is plotted against suspended solid concentration SS for catchments nationwide in Japan and in the Yangtze River basin[3), 4), 5)]. The figure demonstrates that the suspended solid or sediment can be used as passive tracers of phosphorus behavior.

(2) Effect of forest cover on nutrient-sediment loads

Since vegetation has a function to prevent soil erosion and suppress sediment production, clearing or damaging woodlands increases the sediment and nutrient loads from the catchment. When the receiving water is a lake or reservoir, the loss of forest-cover in the catchment accelerates eutrophication in the water. Fig.5 shows SS concentration in lakes plotted against the percentage of forest cover in the entire catchment area, where the solid and open circles correspond to datasets from Japanese and non-Japanese lakes, respectively. A negative correlation is confirmed in the data points, clearly indicating that loss of forest negatively impacts a lake's water quality. The concentration of suspended sediments in forest catchment streams is also plotted (indicated by the diamond symbol) and has the same tendency as the SS concentration in lakes.

Fig.6 shows the correlation between SS in lakes and the ratio of farmland area to lake volume. It is considered that, except in arid regions, farmland development is approximately equivalent to the loss of forest. The figure clearly shows that the amount of SS in lakes increases along with the increase of farmland cover or the decrease in a lake's storage capacity. In other words, greater nutrient loads occur in catchments with more extensive farmland development.

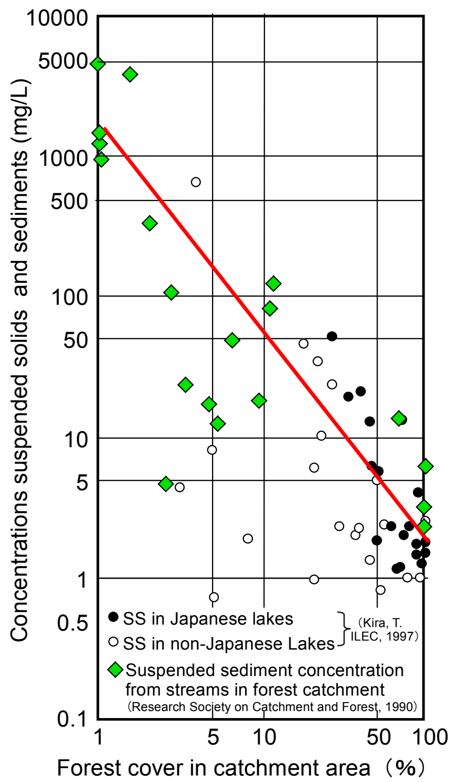

Fig.5 SS concentration in lakes plotted against percentage of forest cover in catchments. The concentration of suspended sediments in forest catchment streams is also plotted (diamond symbols). Datasets from 6) and 7) were rearranged by the author.

(3) Policy of returning farmland to forest

Due to the rapid growth of the market economy in China, huge areas of forest have been converted to farmlands as people seek cash income. As a result, woodlands have been cleared up to hills, farmlands have been heavily fertilized, the land surface has been damaged by livestock, soil erosion on steep hill-side slopes have yielded heavy sediment-nutrient loads, significant sedimentation and eutrophication have occurred in lakes and reservoirs, and severe flood disasters have taken place in downstream areas. Many cases of trouble

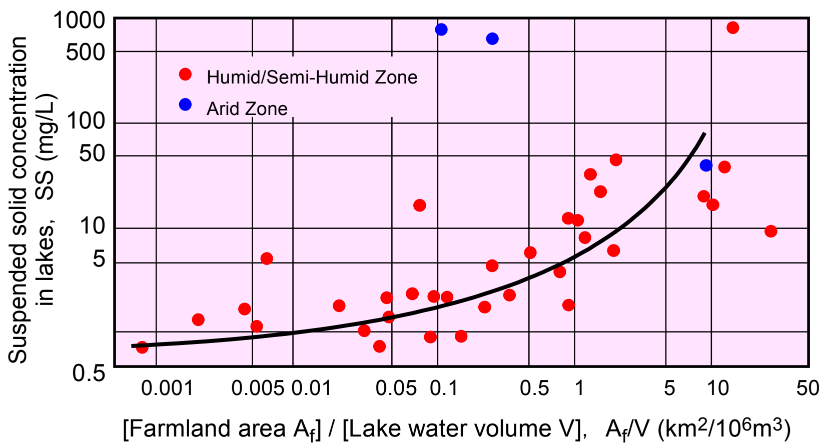

Fig.6 SS concentration versus ratio of farm land area to lake volume[6)].

of this nature have been reported in the Yangtze River Basin. As a countermeasure, the Chinese government has adopted a so-called "policy of returning farmland to forest" in which farmland is converted to forest in areas with a slope angle of greater than 25°. Fig.6 shows the policy's effect on decreasing sediment production. The data are from a numerical simulation conducted for scenarios of different thresholds of slope angles. The figure confirms that the policy is very effective in decreasing sediment production. In addition, stricter control of land-use over a wider area is recommended if further sediment control is necessary.

5. NUTRIENT LOAD DURING FLOOD EVENTS

The curves in Fig.7 are examples of the discharge duration in m^3/sec, the cumulative river discharge in m^3 and the cumulative phosphorus load in tons. The yearly mean discharge in this catchment is Q=9.6m^3/sec, which was exceeded for 155 days. For those 155 days, the cumulative discharge was 240 x 10^6 m^3, which represents approximately 80% of the annual total discharge. During the same period of time, the cumulative phosphorus load was 185 tons, which is equivalent to 88% of the total load. The graph demonstrates that water and nutrients are supplied from the catchment mostly during high discharge events. Therefore, it is important to accurately evaluate pollutant behavior during rainfall events in order to discuss the effects of land-use on the water environment in receiving waters.

6. CONCLUDING REMAKS

Basin scale management of river systems is a key issue that should be investigated further in the near future. Further study is urgently needed not only for flood protection and water use but also for the preservation of nature in river basins. Previous research in the literature gives an insight into the multifunctionality of forest catchments from an environmental point of view. In the future, more scientific activities focusing on this issue should be encouraged throughout Japan, too.

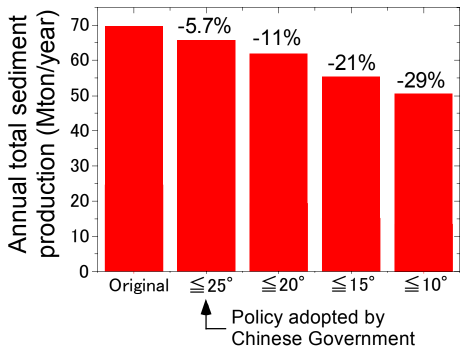

Fig.6 Effect of policy of returning farmland to forest (Chanqliang catchment in Yangtze River Basin)[8].

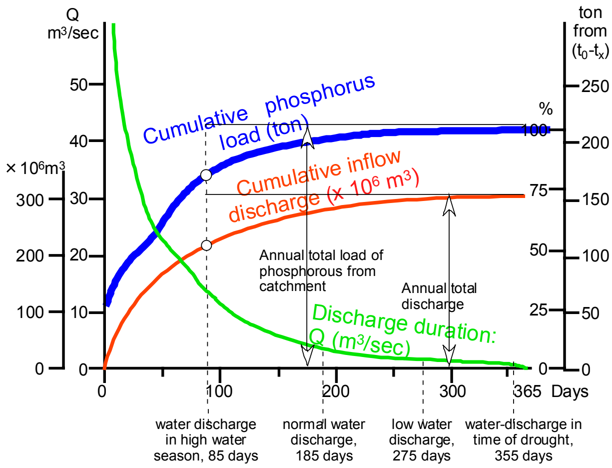

Fig.7 Phosphorus load and river discharge[9].

REFERENCES

1) Wetzel, R.G.: Limnology, 3rd Ed., Academic Press, 2001.

2) (For example) Arita, M. ed.: Environment in hydrosphere, Tokyo Denki-Daigaku Shuppankyoku, p.404, 1998 (in Japanese).

3) Kunimatsu, T.: "2. Self-purification performance of forest catchment", *Self-Purification in Nature*, Ed. by Kusuda, T., Gihodo Pub. Co. Ltd., p.242, 1996 (in Japanese).

4) Report of Special Research from the National Institute of Environmental Studies: Watershed Environment and Management Research Project, p.21, 2004 (in Japanese).

5) Murakami, S.: Toward sustainable water resources management in Yangtze River Basin. Proc. 17th AGEHR Symposium, 2005 (in Japanese).

6) Kira, T.: “7. Survey of the state of world lakes” in the Guidelines of Lake Management, Vol.8, The World's Lakes in Crisis, Ed. by Jorgensen, S.E. and Matsui, S., International Lake Environment Committee Foundation and UNEP, p.184, 1997.

7) Research Society on Catchment and Forest: Research on catchment and forest, Japan Forest Technology Association, p.46, 1990 (in Japanese).

8) APEIS-IEM: Technical Summary, p.12, http://www.ecoasia.org/APEIS/iem/pdf/TS_IEM.pdf, 2004.

9) Vollenweider, R.A.: “5. Assessment of mass balance” in the Guidelines of Lake Management, Vol.1, Principle of Lake Management, Ed. by Jorgensen, S.E. and Vollenweider, R.A., International Lake Environment Committee Foundation and UNEP, p.184, 1997.

(Received September 30, 2006)