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Scenario analysis for reduction of pollutant load discharged from a watershed by recycling of treated water for irrigation

Eisaku Shiratani[1,*], Yoshiyuki Munakata[2], Ikuo Yoshinaga[3], Tomijiro Kubota[1], Koji Hamada[1], Tadayoshi Hitomi[1]

1. National Institute for Rural Engineering, Tsukuba Science City 305-8609, Japan. E-mail: esh@affrc.go.jp
2. Kokusai Kogyo Co. Ltd., 2 Rokubancho, Chiyoda-ku, Tokyo 102-0085, Japan
3. National Agricultural Research Centre for Kyushu Okinawa Region, 2421 Koshi City, Kumamoto 861-1192, Japan

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Abstract

A model in which a river model was layered on a distributed model (double-layered model) was developed to analyse the transport of water and pollutants (nitrogen, phosphorus, and BOD as organic matter) in watersheds and rivers. The model was applied to the watershed of Abragafuchi Lake, Japan, where serious water pollution has occurred over three decades, and the applicability of the model was demonstrated. Scenarios of recycling of sewage treated-water into agriculture to reduce pollutant load discharged into the lake were analysed. The results showed that irrigating paddy fields with the sewage-treated water could contribute to conserving water and reducing pollutant load, with reduction rate in BOD, nitrogen, and phosphorus ranging from 6%–36%, 16%–46%, and 18%–51%, respectively. Particularly, the results indicated that, irrigating paddy fields with the treated water during non-cropping periods and the accompanying reduction in withdrawn water from the river were more effective in reducing pollutant loads discharged into the lake. Further study is required on the effect of recycled water on crop cultivation and soil conditions for safe implementation.

Key words: watershed management; paddy field; sewage treatment; water reuse

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Introduction

Recycling of wastewater and greywater generated from factories and households into agricultural use could not only save irrigation water but also reduce pollutant load in a basin, and is expected to contribute to preservation of the water environment (Angelakis et al., 2003). Several decades ago, when sewage-treatment had not popularised, sewage water drained untreated into canals had caused serious water pollution, and greywater was reused for paddy irrigation and excreta as manure in agriculture. By 2005, sewage-treatment serves approximately 70% of Japan's total population; water environments in rivers have been gradually improved but water pollution in lakes continues. At the same time, only less than 0.1% of treated water is recycled into agriculture in Japan. Consequently, 15 billion m^3 of treated water is drained to coastal areas, corresponding to approximately one-quarter of irrigation water withdrawn from rivers.

Like wetlands, paddy fields are known to purify irrigation water by biochemical decomposition, sedimentation, and denitrification in ponding water (Tabuchi, 2001). However, water purification is expected only when the pollution of irrigation water is at a certain level. Shiratani et al. (2006) reported that the nitrogen runoff through field drainages can be less than input nitrogen from irrigation and rainfall when the nitrogen concentration of irrigation water is higher than 1.6 mg/L; nonetheless, more than 90% of irrigation water collected from rivers and reservoirs is below that nitrogen concentration. On the other hand, concentrations of organic matter, nitrogen, and phosphorus in sewage-treated water are normally higher than those in rivers and reservoirs. When a paddy field is irrigated with the treated water, the irrigation water could probably be purified effectively.

In this article, we developed a watershed model which can simulate flow of water and pollutants in a watershed, and demonstrate scenario analysis of recycling sewage-treated water for agriculture to estimate the reduction of pollutant load discharged from a watershed.

1 Study area

The study area, Aburagafuchi Lake and its watershed (Fig. 1), is located in an alluvial plain on the coast of Mikawa Bay in central Japan. The maximum difference of elevation is less than 20 m. The area is fed by only the Meiji Irrigation Canal, which delivers water withdrawn from the Yahagi River throughout the year, and waters

* Corresponding author. E-mail: esh@affrc.go.jp

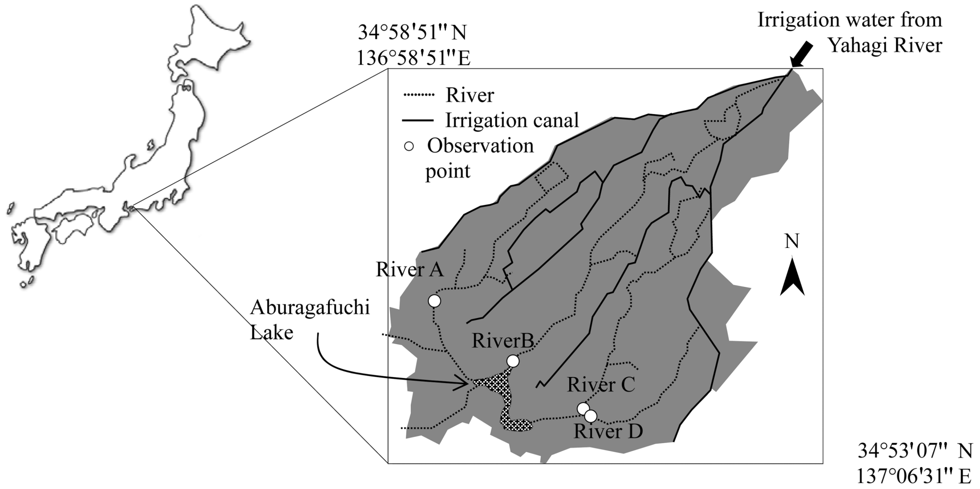

Fig. 1 Outline of study area (Aburagafuchi Lake and watershed, Aichi Prefecture, Japan).

used in agriculture, households, and factories, and rainfall are drained, gather into four rivers, and flow into the Lake. The outline of land use in the watershed is shown in Table 1. The watershed has an area of 6562 ha, of which agriculture use including paddy fields and upland fields accounts for approximately 68%; particularly, paddy fields account for 63%. Residential and commercial areas, including transportation use, account for approximately 25.9% of the watershed. The lake, which has a surface area of 64 ha and a mean depth of 3.0 m, lies in the lowest position in the area, and the water level is controlled by two drainage gates which drain the lake water in the event of flood and prevent the entry of seawater into the lake.

Table 1 Land use in the watershed

Land use	Area (m^2)	Percentage (%)
Paddy field	4148×10^4	63.2
Upland field	287×10^4	4.4
Orchard	56×10^4	0.9
Forest	22×10^4	0.3
Residential and commercial use	1698×10^4	25.9
Water area	162×10^4	2.5
Others	189×10^4	2.9
Total	6562×10^4	

The lake is polluted with organic matter, at around 10 mg/L at annual 75 percentile of chemical oxygen demand (COD_{Mn}) during this decade, and has been ranked as one of Japan's worst. Reducing pollutant load discharged into the lake has been the most important measure to improve the water environment. The rivers flowing into the lake are also contaminated with nutrients and organic matter, ranging from 5 to 10 mg/L of biochemical oxygen demand (BOD) on an annual average. As the public sewerage system serves only 2.8% of the population in the watershed (Table 2), pollution loads effused from households and factories are considered to be the keys to reduce pollutant load discharged into the lake.

Table 2 Number of people for each sewage treatment in the watershed

Treatment type	Number of people	Percentage (%)
Public sewerage system	2547	2.8
Night-soil treatment plant	19,545	61.5
Individual sewage treatment tank	12,966	14.2
Individual night-soil treatment tank	55,936	21.5
Total	90,994	

2 Analysis model

A model in which a river model is layered on a distributed model (double-layered model) as shown in Fig. 2 was developed for the analysis.

In the distributed model, the study watershed was divided into 6412 cells with a grid (each cell measuring 114.23 m from north to south and 92.45 m from east to west), and processes of the transport of water and pollutants (nitrogen, phosphorus, and organic matter) in the watershed were expressed.

In the river model, rivers were modelled by about 50 m long line segments connected with nodes on which flows of water and pollutant loads are calculated. The water and pollutants transported in the watershed were discharged into the nearest river, and modelled as flowing

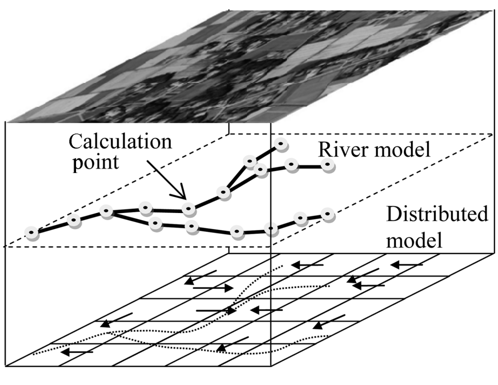

Fig. 2 Double-layered model formed by distributed model and river model.

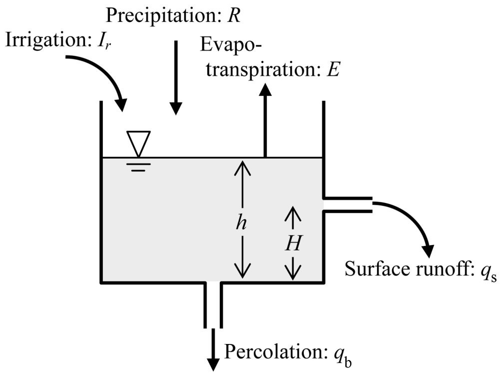

Fig. 3 Tank model to generate water flow.

down through the river and reacting biochemically by first-order kinetics.

2.1 Water generation

There are good examples in which a distributed model composed of a tank model in a cell could be useful to simulate nutrient transportation in an agricultural watershed (Kato et al., 2005; Munakata et al., 2006). A simple tank model (Fig. 3) which simulates water transport in the land was applied to each cell, and best applied parameters were derived for the specific land use. Water quantities of irrigation and discharge are calculated in the following manner.

When the tank model is adapted to a paddy field, the irrigation water is supplied to fill the gap between the ponding water depth of the previous day and the target water depth of the day, which is set based on the water management criterion developed by the local authority. Thus,

$$I_{r,i} = \begin{cases} h_{c,i} - h_{i-1}, & \text{if } h_{i-1} \leqslant h_{c,i} \\ 0, & \text{if } h_{i-1} > h_{c,i} \end{cases} \tag{1}$$

where, $I_{r,i}$ (m) is the irrigation on ith day, h_i (m) is the water depth on ith day, and $h_{c,i}$ (m) is the target water depth on ith day. The quantities of surface discharge and percolation are calculated by Eqs. (2) and (3), respectively.

$$q_{s,i} = \begin{cases} r_s A\,(h_{i-1} - H), & \text{if } h_{i-1} \geqslant H \\ 0, & \text{if } h_{i-1} < H \end{cases} \tag{2}$$

$$q_{b,i} = r_b A h_{i-1} \tag{3}$$

where, $q_{s,i}$ (m^3) is the surface runoff on ith day, $q_{b,i}$ (m^3) is the percolation on the ith day, A (m^2) is the area of a cell, H (m) is the threshold of surface runoff, and r_s and r_b are coefficients. Consequently, water depth of the day ith day is given by Eq. (4):

$$h_i = h_{i-1} + I_{r,i} + R_i - E_i - \frac{q_{s,i} + q_{b,i}}{A} \tag{4}$$

where, R_i (m) is the precipitation on ith day, and E_i (m) is the evapotranspiration on ith day.

Runoff water from a cell is given by the sum of surface runoff, percolation, and water from point sources, and is modeled to travel down the slope and flow into the nearest node (calculation point) set on the river model, accompanying pollutants generated in the cell.

2.2 Pollutant generation

Effluent of pollutants from a cell was calculated by a model in which pollutant dynamics were described in a simple manner according to land use and point sources pollution.

2.2.1 Forest

Pollutant load from a forest cell was calculated by the following Eq. (5), which is in practical use in Japan (e.g., Fujii et al., 2006).

$$L_i = \alpha_1 q_{s,i}^{\beta_1} \tag{5}$$

where, L_i (g) is the pollutant load on ith day, and α_1 and β_1 are coefficients.

2.2.2 Upland field

Considering that pollutant load effused from upland fields increases with surface runoff water, the following Eq. (6) was applied to upland field cells (Munakata et al., 2006).

$$L_i = L_U \left(1 + \alpha_2 \sqrt{q_{s,i}}\right) \tag{6}$$

where, L_U (g) is the unit pollutant load, and α_2 is coefficient.

2.2.3 Paddy field

Pollutant loads are supplied through irrigation, precipitation, and fertiliser, and undergo biochemical reaction in the paddy field. The model proposed by Shiratani et al. (2004) was used to express the pollutant load from a paddy field cell, with the model modified to apply to loads of phosphorus and organic matter.

$$L_i = C_{p,i-1}\,(q_{s,i} + q_{b,i}) \tag{7}$$

$$C_{p,i} = \frac{\{Ah_{i-1} - q_{s,i} - q_{b,i}\}\,C_{p,i-1}\exp(-\alpha_3/h_{i-1})}{Ah_i} + \frac{I_{r,i}C_{w,i} + R_iC_{r,i} + L_{f,i}}{h_i} + P \tag{8}$$

where, $C_{p,i}$ (mg/L) is the pollutant concentration of ponding water in paddy field, $C_{w,i}$ (mg/L) is the pollutant concentration of irrigation water, $C_{r,i}$ (mg/L) is the pollutant concentration of precipitation, $L_{f,i}$ (g/m^2) is the pollutant load by fertilisation, P (mg/L) is the production of organic matter, and α_3 (m) is the decrease rate coefficient of concentration. Because the production of organic matter in a paddy field is caused by algal growth, the following Eq. (9) can be used to calculate P in Eq. (8).

$$P = \alpha_4 C_{N,i}^{\beta_4} \tag{9}$$

where, $C_{N,i}$ (mg/L) is the nitrogen concentration of ponding water in paddy field, and α_4 and β_4 are coefficients.

2.2.4 Residential and commercial area

The characteristics of pollutant load in urban areas, where pollutants accumulate on roads and roofs during no rainy days, and runoff at rainfall time, was expressed by Wada (1981). Thus,

$$\text{Accumulation process: } S = S_0 e^{-\alpha_5 n} + \frac{S_\infty (1 - e^{-\alpha_5 n})}{1 - e^{-\alpha_5}} \quad (10)$$

$$\text{Runoff process: } L_i = \alpha_6 S^{\beta_6} q_s \quad (11)$$

where, S (g/m^2) is the accumulated load, S_0 (g/m^2) is the surviving load after previous rainfall, S_∞ (g/m^2) is the ultimately accumulated load, n (day) is the passage days from previous rainfall, and α_5, α_6, and β_6 are coefficients.

2.2.5 Point source

Effluent pollutant loads from point sources such as households and factories were calculated by multiplying unit water discharge (m^3/day) by the average concentration (mg/L).

2.3 Reaction in watershed and river

Pollutant loads generated in a cell were modelled as being transported by runoff water, and to reach the nearest node on the river model, decaying with distance from the cell to the node. Similarly, in the river model, the reached pollutant loads flow down the river into the lake, decaying with flow distance. The equation for the decaying loads is:

$$L' = L\exp(-ax) \quad (12)$$

where, L' (g) is the reached pollutant load, x (m) is the distance, and a is the decay rate constant.

3 Model validation

3.1 Data input

Land use was determined from LANDSAT images taken in 2000. Data for point sources such as population, sewer plants, and factories were provided by local governments, and the quantity of water discharged from each factory was estimated from its production volume. The pollutant loads from households given in Table 3, were cited from related publications (e.g., Japan Sewage Works Association, 1999).

Meteorological data such as rainfall, air temperature, and sunshine duration were provided by the automated meteorological data acquisition system (AMeDAS), and transevaporation was calculated by the Makkink's equation (Jacobs and de Bruin, 1998).

Table 3 Effluent pollutant loads from household per day

	BOD (g/capita)	Nitrogen (g/capita)	Phosphorus (g/capita)
Greywater	40.0	2.40	0.49
Individual sewage treatment tank	5.6	7.41	0.76
Individual night-soil treatment tank	0.9	6.50	0.75

The quantity of irrigation water supplied to the watershed by the Meiji Irrigation Canal was estimated from the quantity of water withdrawn at the headwork on the Yahagi River, and the water qualities of irrigation water were measured by the Aichi Prefectural office. Data for fertilisation were obtained from the criterion developed by the local authority.

3.2 Model calibration

The changes in water flow rate, BOD, nitrogen concentration (TN), and phosphorus concentration (TP) at the observation points on rivers in 1995 were simulated with the best fit parameters manually adjusted by least squares fit. The calculated results are shown in Figs. 4–7. The Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) which indicates how well the plot of observed versus calculated data fits the 1:1 line is summarized in Table 4. The Nash-Sutcliffe efficiency varied from 0.24 to 0.81. Considering that the values between 0.0 and 1.0 are generally viewed as acceptable levels of performance (Moriasi et al., 2007), it is fair to say that the model could simulate the water flow rate and BOD, TN and TP with satisfactory accuracy for application to the scenario analysis.

4 Scenario analysis

Scenarios for analysis and quantity of water and pollutant loads discharged from the watershed into the lake are shown in Table 5 and Fig. 8, respectively. The consequent amount of discharged water in every scenario was 0%–13% less than that in the present state. In addition, the discharged water decreased by 0%–2% even in scenarios (Scenario 2, 4, and 6) where the withdrawn water from

Table 4 Nash-Sutcliffe efficiency

	River A	River B	River C	River D
Water flow rate (m^3/sec)	0.81	0.26	0.51	0.46
BOD (mg/L)	0.71	0.32	0.30	0.24
TN (mg/L)	0.49	0.70	0.78	0.56
TP (mg/L)	0.54	0.65	0.45	0.57

Table 5 Scenario analyses

Analysis case	Analysis condition
Scenario 1	Irrigating paddy fields with sewage-treated-waters (recycle irrigation), and reducing water withdrawn from river corresponding to the recycle irrigation, throughout the year.
Scenario 2	Recycle irrigation, but no reducing water withdrawn from the river throughout the year.
Scenario 3	Recycle irrigation, and reducing water withdrawn from the river only during the cropping period (April–September).
Scenario 4	Recycle irrigation, but no reducing water withdrawn from the river only during the cropping period.
Scenario 5	Recycle irrigation, and reducing water withdrawn from the river only during the non-cropping period (October–March).
Scenario 6	Recycle irrigation, but no reducing water withdrawn from the river only during the non-cropping period.

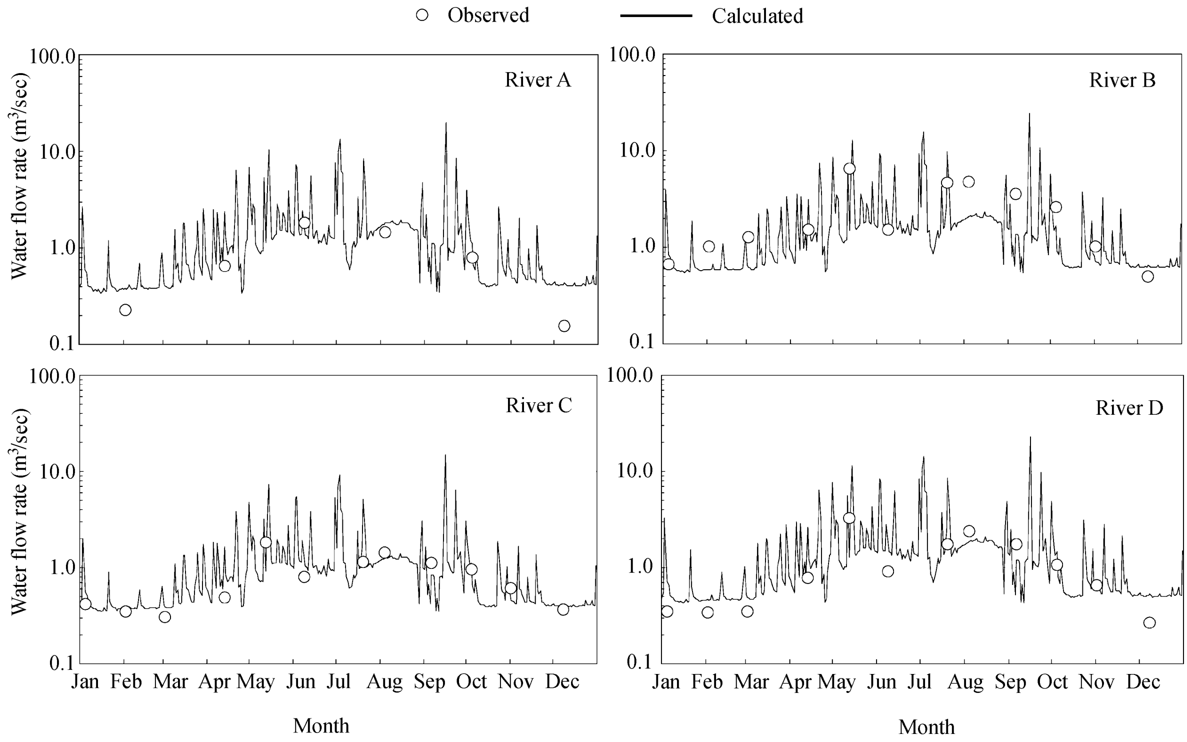

Fig. 4 Observed and calculated results of water flow rate at observation points on rivers A, B, C, and D.

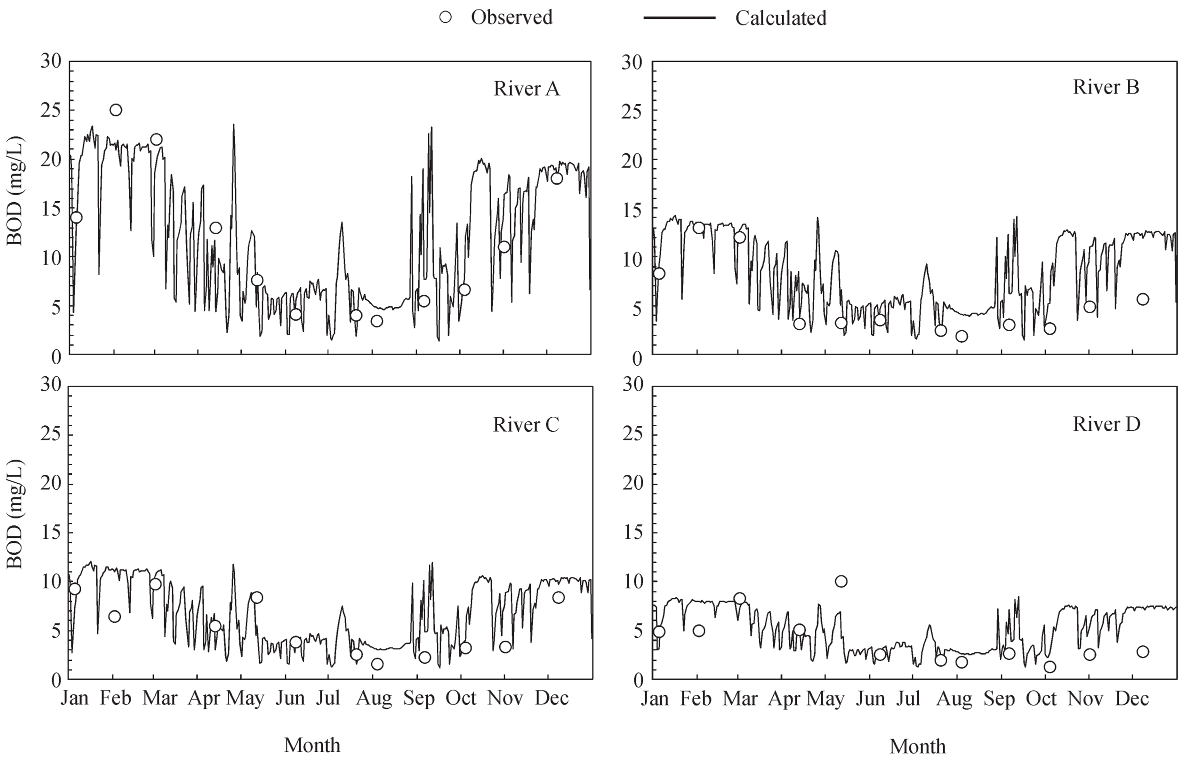

Fig. 5 Observed and calculated results of BOD at observation points on rivers A, B, C, and D.

the river was not reduced, because a portion of the sewage treated-water supplied to paddy fields was considered to be lost by evapotranspiration in the fields.

All pollutant loads decreased in every scenario, with reductions in BOD, nitrogen, and phosphorus ranging from 6%–36%, 16%–46%, and 18%–51%, respectively (Fig. 8). Especially, irrigating the paddy fields with treated water during the non-cropping period was more effective than irrigation during the cropping period; recycling treated water in the non-cropping period was 16%–21% more effective in BOD, 13%–15% in nitrogen, and 11%–12% in phosphorus, as compared with the reduction rate among

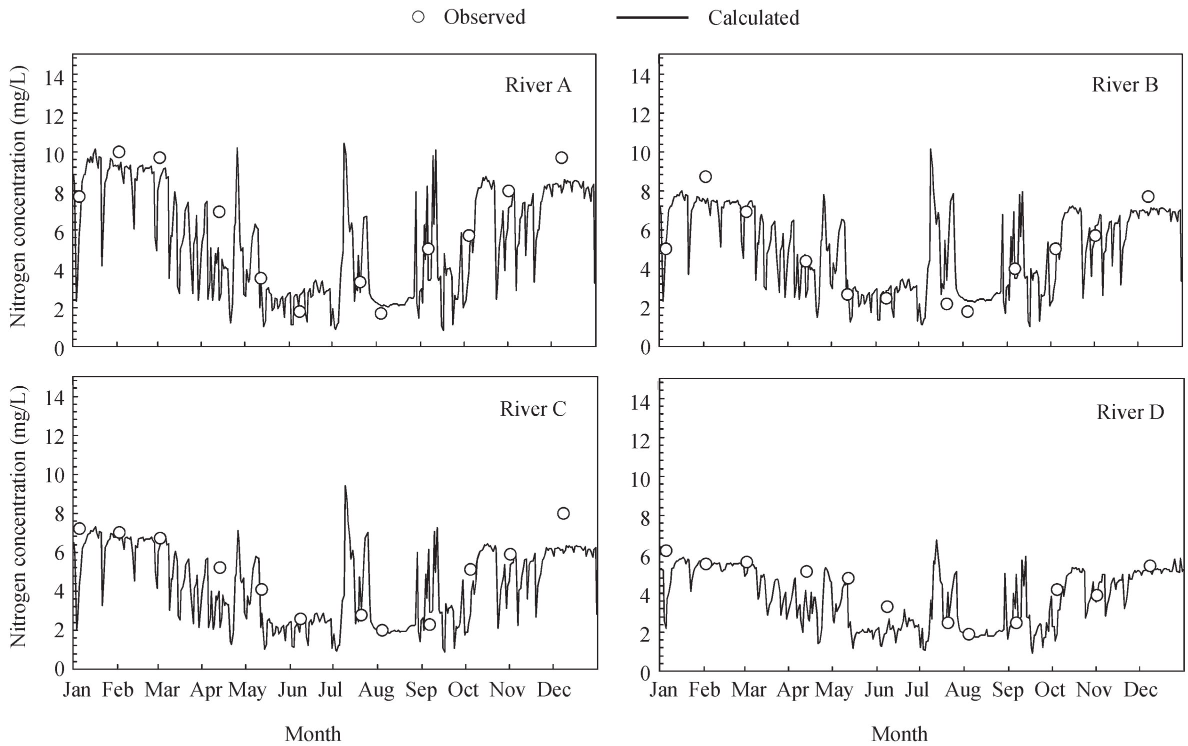

Fig. 6 Observed and calculated results of TN at observation points on rivers A, B, C, and D.

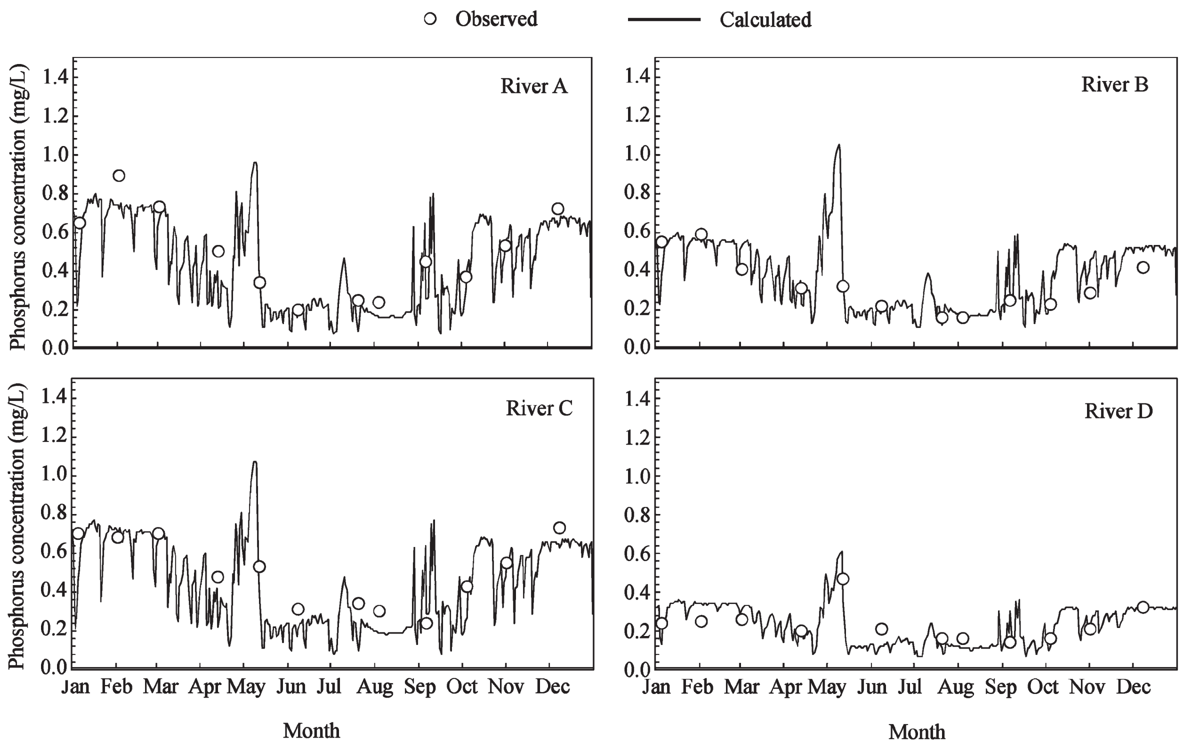

Fig. 7 Observed and calculated results of TP at observation points on rivers A, B, C, and D.

Scenarios 3–6. In addition, reducing the withdrawn water from the river corresponding to the amount of recycled treated-water for agriculture is much more effective in reducing pollutant loads. In the case where the paddy fields were irrigated with treated water and the water withdrawn from the river was reduced throughout the year, the pollutant loads discharged from the watershed decreased by 64%, 54%, and 49% in BOD, nitrogen, and phosphorus, respectively.

As is common knowledge, paddy fields function as wetlands, where BOD, nitrogen, and phosphorus are reduced through decomposition, denitrification, and settlement;

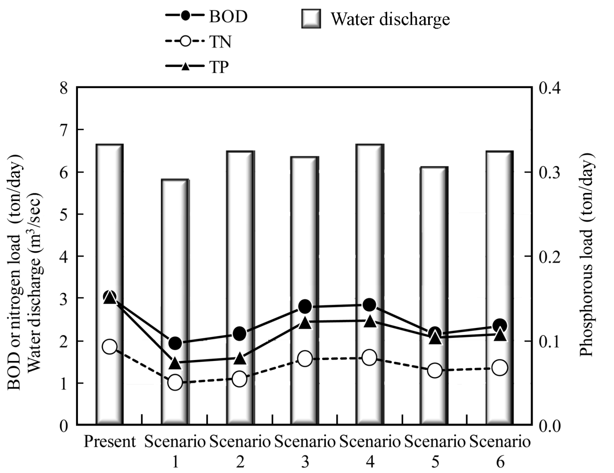

Fig. 8 Discharge of water and pollutant load from the watershed into the lake.

irrigating paddy fields with treated water during the non-cropping period is considered to enhance the effectiveness of water purification, because the precipitation rate is low and no fertiliser is applied to the fields.

5 Conclusions

A model in which a river model was layered on a distributed model was developed to analyse the transport of water and pollutants in watersheds and rivers. When applied to the Aburagafuchi Lake watershed, the model could simulate the water flow and water qualities in the rivers at good agreement.

With the model, scenarios of recycling sewage-treated water into agriculture to reduce pollutant load discharged into the lake were analysed. The results showed that irrigating paddy fields with the treated water could contribute to saving irrigation water and reducing pollutant load. Especially, irrigating paddy fields with the treated water during the non-cropping period was more effective in reducing pollutant loads discharged into the lake. In addition, reducing water withdrawn from the river corresponding to the recycle water could enhance the effectiveness.

On the other hand, the BOD and nutrient concentration of treated water could be too high for use as irrigation water. Although there are some paddy fields which are irrigated with treated water in Japan, further study is required on the effect on crop cultivation and soil conditions for safe implementation.

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