Impact of agricultural water management on lake water budget: a case study of Lake Ikeda, Japan

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Abstract Hydrological assessment of the effect of water utilization on a lake water budget is indispensable for proper water management. A model to estimate lake water level was developed for Lake Ikeda, Japan, and was applied to investigate the lake water budget and to examine the effect of agricultural water management on the lake water level. The calculated lake water levels agreed well with the measured levels for 1983–1999. The lake water level is generally highest from September to October and lowest in March, and is characterized by seasonal changes in the water budget components. Three simulations under hypothetical hydrological conditions revealed that river water supply in the agricultural water management system effectively compensates for the decrease in lake water levels caused by agricultural water use.

Key words freshwater resource; lake water budget; lake water level; water level simulation; water management; water use

INTRODUCTION

Shortage of available freshwater is one of the most important environmental issues in the world. Although lake water is a variable freshwater resource for various industries, inappropriate lake water management has caused deterioration of many lake environments. Water management that does not enhance sustainability leads to severe crises for many lakes; e.g. the Aral Sea and Lake Chad are in danger of disappearing (Ballatore & Muhandiki, 2002). To avoid such crises, hydrological assessment of the influence of water utilization on a lake water budget is indispensable for rational water allocation and proper water management.

The objectives of this study were to develop and verify a water level estimation model of Lake Ikeda as a freshwater resource for municipal and agricultural water uses, and to investigate the lake's water budget based on hydrometeorological data from 1983 to 1999. We also used the model to examine the effect of agricultural water management on the lake water level for a 17-year period.

STUDY SITE

Lake Ikeda is located in the southern part of Kagoshima prefecture, Japan (latitude 31°14′N, longitude 130°35′E), where mean air temperature is 18.3°C and average annual precipitation (1983–1999) is 1962 mm. It is a caldera lake formed by volcanic activity more than 5000 years ago and has no large inlet or outlet streams. The lake surface area is 10.62 km^2 and the catchment area is 12.34 km^2; its mean and maximum water depths are 125 and 233 m, respectively.

Freshwater from the lake is used as municipal and agricultural water in the surrounding area. Lake water has long been used as irrigation water, particularly since 1983, when the agricultural water management system was introduced by the Large-scale Upland Irrigation Project for a 6000-ha upland field. In the water management system, river water from the three river basins outside the lake catchment area has been transferred into the lake to compensate for the water loss; i.e. the lake water level has been artificially regulated with river water. Therefore, the lake's hydrological environment has changed considerably since 1983. However, the effects of agricultural water use and artificial water level regulation on the lake's hydrological environment had never before been assessed and the lake water budget had not been properly evaluated.

METHODS

Water level estimation model

The lake water budget can be expressed as:

$$\frac{dS}{dt} = I_p + I_i + I_s - O_l - O_e - O_t - O_a \tag{1}$$

where S is the lake water level, t is time, I_p is precipitation, I_i is inflow from the lake catchment area, I_s is river water supply, O_l is leakage from the lake bottom, O_e is lake evaporation, O_t is tap water use, and O_a is agricultural water use.

In this study, the model to calculate the daily water level of the lake was based on equation (1). Figure 1 shows the schematic diagram of the model to estimate the water level of Lake Ikeda. Lake evaporation is estimated by the one-dimensional model (Momii, 2003) in which thermal conduction of the lake water temperature and the lake heat budget are numerically computed. The model can give the vertical water temperature profile, where both the heat fluxes to and from the lake surface are in balance under the given meteorological conditions. The model parameters for a heat diffusion coefficient (based on Munk & Anderson, 1948) and a mass transfer coefficient including atmospheric stability parameters were calibrated by fitting with lake water temperatures measured in 2000 (Momii, 2003). The model without advected heat fluxes was validated by the Bowen ratio method with *in situ* data observed from August 2004 to September 2005 (Ito & Momii, 2007). In the heat budget analysis, shortwave and longwave radiation are estimated using meteorological data (air temperature, relative humidity, sunshine duration, and atmospheric pressure) obtained by the local meteorological observatory (Kondo & Xu, 1997).

Inflow from the lake catchment area is estimated by the tank model. Leakage from the lake bottom is estimated based on Darcy's law, in which the vertically averaged hydraulic conductance (Motz, 1998) and the head difference (Δh) between the lake water surface and a groundwater table outside the lake catchment area are considered.

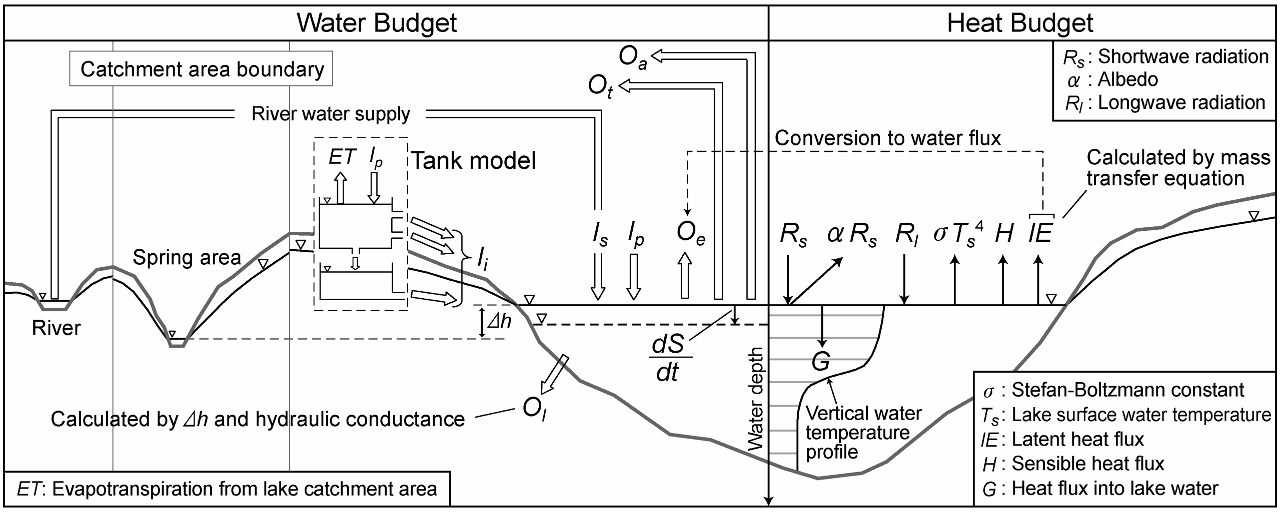

Fig. 1 Water level estimation model of Lake Ikeda.

The model parameters for inflow and leakage calculations were optimized by the Shuffled Complex Evolution (SCE-UA) method (Duan *et al*., 1992) with observed lake water levels for 1983–1985 (Ito *et al*., 2006). The optimized model parameters are employed in the water level calculation from 1986 to 1999 in the model verification. For precipitation, river water supply, tap water use, and agricultural water use, we used observed data from the local meteorological observatory and the land improvement district that manages the lake water level.

Water level simulations

To examine the effect of water use and water management on the lake water level, we analysed three simulation cases (Runs 1 to 3) with the model under hypothetical hydrological conditions for 1983–1999. Run 1 simulates natural conditions without human activity, i.e. no tap or agricultural water uses and no river water supply. Run 2 simulates conditions where lake water is used for tap water but not for agricultural water, and where river water is not supplied. Run 3 simulates conditions of tap and agricultural water uses and no river water supply.

RESULTS AND DISCUSSION

Model verification

The calculated and measured lake water levels of Lake Ikeda under real conditions for 1983–1999 fluctuated in the range of approx. 62–66 m a.m.s.l. (Fig. 2). The calculated lake water levels under the real conditions agreed well with the measured levels: R^2 and RMSE between calculated and measured lake water levels were 0.95 and 0.27 m, respectively. The monthly estimated evaporation rate also agreed well with the result obtained by the Bowen ratio method (R^2 = 0.85). Thus, the model is useful for evaluating the lake water budget.

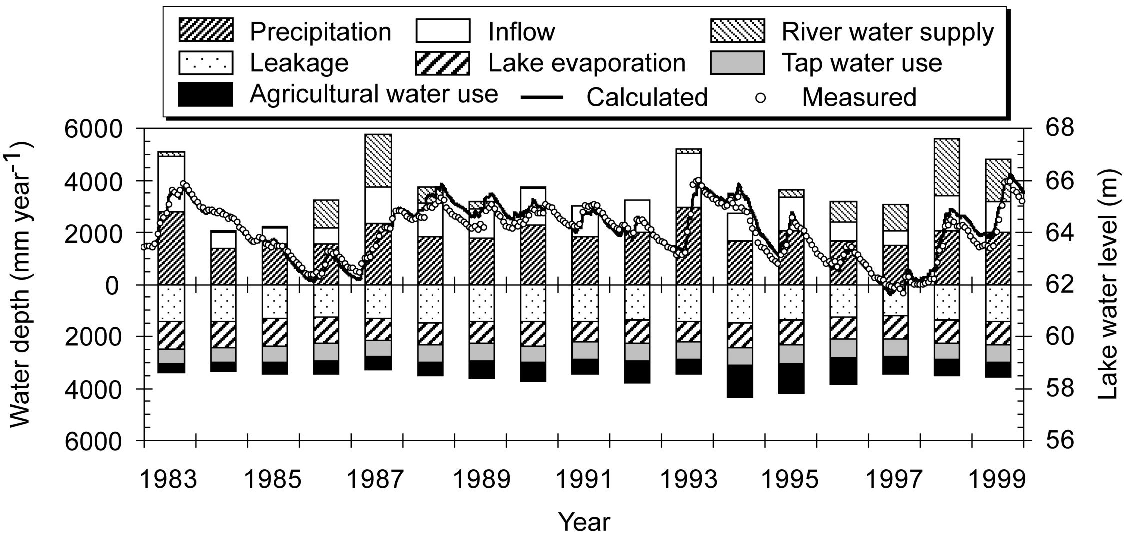

Fig. 2 Comparison of calculated and measured daily lake water levels and annual water budget of Lake Ikeda under real conditions for 1983–1999. The water budget components are expressed as the values converted into lake water depth.

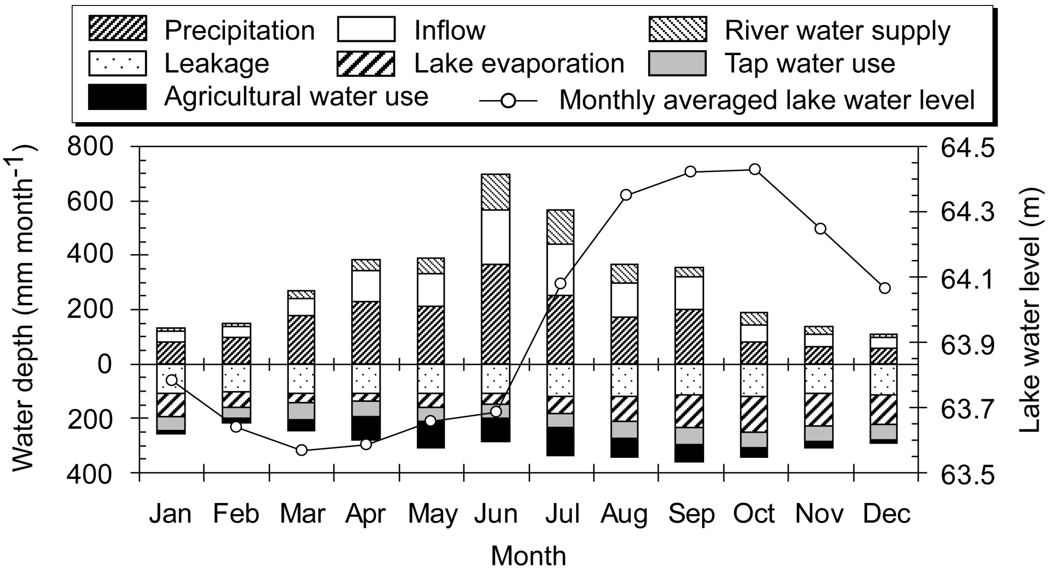

Fig. 3 Monthly averaged water budget and lake water level for 1983–1999.

Water budget of Lake Ikeda

In water budget components of the lake, annual variations in precipitation, inflow from the lake catchment area, river water supply, and agricultural water use are relatively large, while the other three components (leakage, evaporation, and tap water use) are roughly constant (Fig. 2). To illustrate the seasonal changes in the water budget components and the lake water level, their monthly averaged values for 1983–1999 are shown in Fig. 3. The three components of precipitation, inflow from the catchment area, and river water supply are principally large from June to July, corresponding to the rainy season in southern Japan. Evaporation from the lake surface is greatest in October and smallest in April; Lake Ikeda, a deep lake in a warm–temperate area, differs in this attribute from a deep lake in northern Japan. Lake water is frequently used as agricultural water from April to September. There are no marked seasonal changes in leakage or tap water use. The lake water level is generally highest from September to October, after the rainy season, and lowest in March, after the period when the amount of outflow exceeds inflow (Fig. 3).

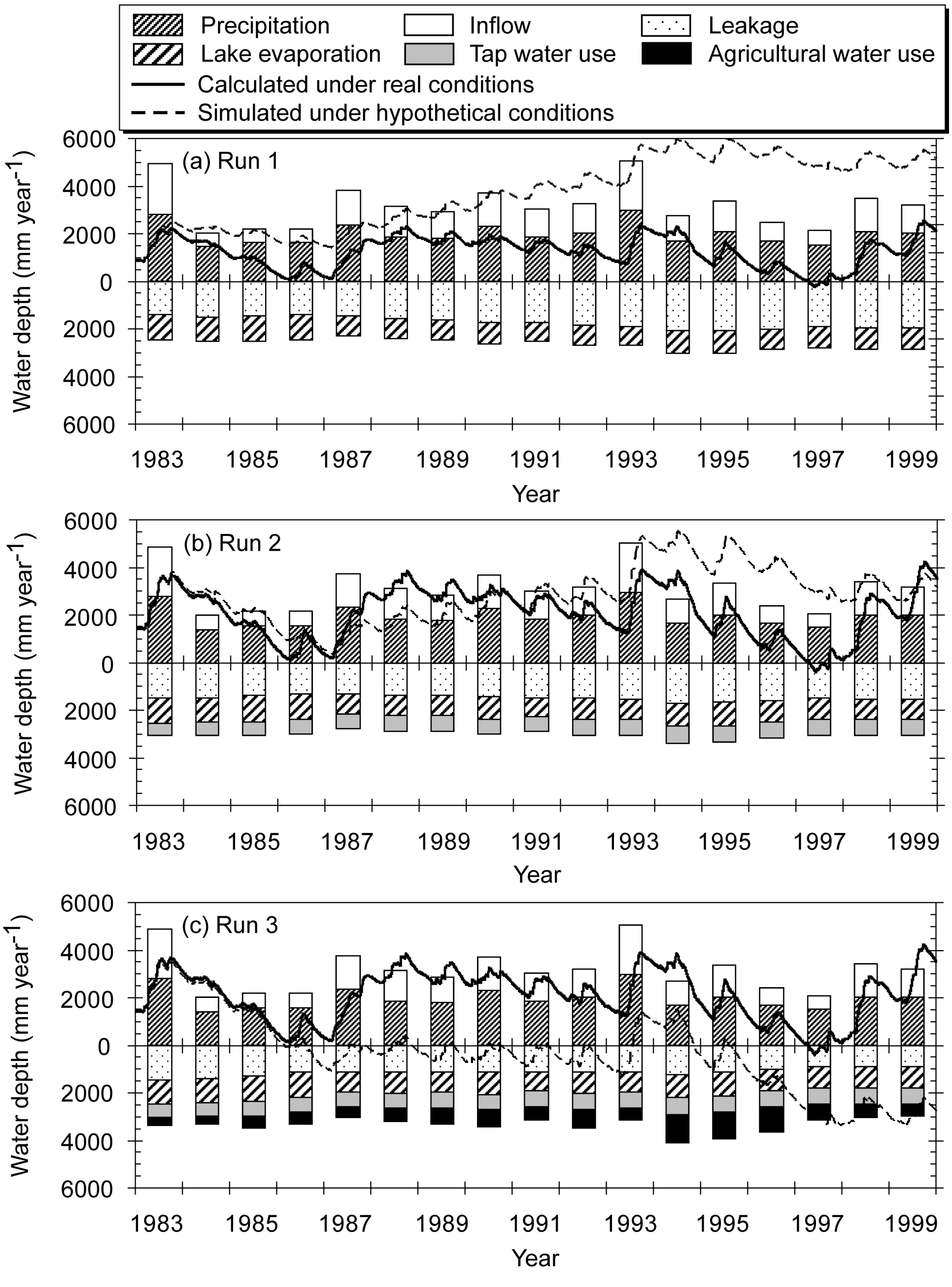

Fig. 4 Simulated daily lake water levels and annual water budget in: (a) Run 1 with no tap or agricultural water uses and no river water supply; (b) Run 2 with tap water use but neither agricultural water use nor river water supply; and (c) Run 3 with tap and agricultural water uses but no river water supply.

Inflow from Lake Ikeda's catchment area and leakage are mainly dominated by groundwater because the lake has no large inlet or outlet streams. Temporal variation in inflow was generally larger than that of leakage. A similar result was also reported by Krabbenhoft *et al*. (1990a,b) in analyses of groundwater exchange at Sparkling Lake, Wisconsin, USA. The estimated annual mean leakage in Lake Ikeda of 1.38 m year^{-1} was in the range of 0.12–4.27 m year^{-1} obtained at 11 karst lakes in Florida (Motz, 1998).

Water level variation under hypothetical conditions

Figure 4 shows simulated daily lake water levels and the annual water budget for Runs 1–3 under hypothetical hydrological conditions. Calculated lake water levels under actual conditions are the same as those illustrated in Fig. 2. The simulated lake water level under the natural conditions of Run 1 (Fig. 4(a)) gradually rose from 1983 to 1993 because there were no tap or agricultural water uses. After 1994, lake water level became constant due to lower precipitation in 1994, 1996, and 1997. In the model, leakage is calculated based on the head difference (Δh) between the lake water surface and the groundwater table. Therefore, a large amount of leakage is evident for 1994–1999 when the lake water level was relatively high.

In the case of Run 2 (Fig. 4(b)), the lake water use as tap water resulted in a decline of 3.3 m in the simulated mean water level compared to Run 1. However, the simulated water level, which fluctuated in the range of 62.3–67.5 m, was never lower than 62 m. This result indicates that there is no large decrease in the lake water when the only lake water use is as tap water, even if the lake water level is not artificially regulated with river water.

The results of Run 3 (Fig. 4(c)) indicated that the simulated lake water level gradually declined due to agricultural and tap water uses. The change in the simulated water level was not consistent with that calculated under the real conditions in 1986, 1987, 1998, and 1999, when river water supply was relatively large. Agricultural water use led to a decline of 3.2 m in the mean water level relative to Run 2. In contrast, river water supply produced a rise of 2.4 m in the mean water level relative to the real conditions. The results demonstrate that river water supply had a large effect on recovery of the lake water level in 1986, 1987, 1998, and 1999, and was effective in maintaining a stable lake water level.

CONCLUSIONS

A model to estimate lake water level was developed and tested for Lake Ikeda based on hydrometeorological data for 1983–1999. The model was applied to investigate the lake water budget and to examine the effect of agricultural water management on the lake water level.

In the model, lake evaporation was estimated through numerical analyses of the lake water temperature and the lake heat budget. Inflow from the lake catchment area and leakage from the lake bottom were estimated based on the tank model and Darcy's law, and the model parameters were optimized by the SCE-UA method. The calculated lake water levels agreed well with the measured levels for the 17-year period. Thus, the model is useful for evaluating the lake water budget.

Of the water budget components, annual variations in precipitation, inflow from the lake catchment area, river water supply, and agricultural water use were relatively large, while annual leakage, evaporation, and tap water use were roughly constant for 1983–1999. The 17-year result showed that the lake water level is generally highest from September to October and lowest in March.

Three simulations by the model revealed that river water supply in the agricultural water management system effectively compensates for the decrease in lake water levels caused by agricultural water use. Therefore, river water supply plays an important role in water management of Lake Ikeda as a freshwater resource.

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