Clarification of Temporal Variations in Water Temperature of Drainage Canals in a Paddy-Field District Implementing Cyclic Irrigation

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ABSTRACT
Cyclic irrigation, which is the reuse of drainage water as irrigation water, is practiced in paddy-field districts near Lake Biwa to conserve water quality. The water purification thus achieved, such as denitrification and adsorption of phosphorus to the sediment, is considered to depend significantly on storage capacity and water temperature of drainage canals. A paddy-field district where cyclic irrigation was being implemented was investigated and temporal variations in the vertical profiles of water temperature in the main drainage canal were measured during the period 2006 – 2008. In addition, a water temperature model for drainage canals was developed. Measurements confirmed that under cyclic irrigation, the temperature of drainage water was 2°C greater than that of the water in Lake Biwa, which is the original source of irrigation water. Although cyclic irrigation increased the suspended solids (SS) in the drainage canal, no significant relationship between water temperature and SS was observed. The results of simulation of water temperature in the drainage canal were improved by considering surplus irrigation water flowing into the drainage canal. It is suggested that operation of the irrigation pump and the inflow of surplus irrigation water has a more pronounced effect on water temperature than SS during the irrigation period.

Keywords: cyclic irrigation, drainage canal, water temperature

INTRODUCTION
The deterioration of water quality in enclosed water sources such as lakes and reservoirs is a serious worldwide problem at present. In particular, non-point source pollution is gaining attention within the scientific community. Paddy-field districts are representative non-point sources, and the effluent load from these districts has large impacts on downstream ecosystems. Problems such as eutrophication, algal blooms, and fresh water red tides have been attributed to such effluent load. Cyclic irrigation, i.e., the reuse of drainage water as irrigation water, is considered an effective measure for reducing the effluent load from paddy-field districts. The water purification realized by cyclic irrigation (e.g., Takeda and Fukushima, 2006; Hama et al., 2010) depends significantly on the hydraulic retention time of nutrients and the storage capacity of drainage canals. In particular, in low-lying paddy-field districts, which are so flat and do not have a steep slope, the storage capacity of drainage canals is higher than that of the canals in hilly and mountainous areas. The drainage canals in a low-lying area may trap nutrients and suspended solids and act as a sink for these materials. However, the drainage canal can also act as a source of effluent load during a non-rice cultivation period, when nutrient concentration in the overlying drainage water decreases.
Therefore, it is necessary to understand the dynamics of nutrients in the drainage canal in low-lying paddy-field districts for making water quality conservation measures more effective. In addition, the water temperature in the drainage canal strongly affects the physicochemical environmental processes involving nutrients and organic matter in the drainage canals. For instance, nitrification and denitrification processes, adsorption of phosphorus by particulate matters, precipitation of phosphorus, and aerobic decomposition of organic matter are all strongly affected by water temperature. Therefore, it is important to define the variation in water temperature accurately. The variation in water temperature in lakes, ponds, and rivers has been researched extensively through on-site field measurements (Ronan et al., 1998; Paaijmans et al., 2008) and through numerical simulations (Hondzo and Stefan, 1993; Younus et al., 2000). However, few studies have focused on the impact of water temperature in drainage canals in paddy-field districts.

The objective of this study is to understand the temporal variations in water temperature and to develop a simulation model for water temperature in a drainage canal in a paddy-field district where cyclic irrigation has been implemented for conserving water quality.

MATERIALS AND METHODS

Study Site

The study site is a low-lying paddy-field region located in Konohama District (Fig. 1), on the southeastern side of Lake Biwa, which is the largest lake in Japan. It is the most important water resource for Kinki region, which includes Osaka and Kyoto. The district covers about 1.5 km², of which more than 90% is used as paddy fields.

The drainage and irrigation canals are separated (Fig. 2). Industrial or domestic wastewatervfrom outside the study area does not enter the drainage and irrigation canals in the study area. The drainage system comprises a main and 14 lateral drainage canals. The main drainage canal is about 1.5 km long, less than 2 m deep, and 3 – 7 m wide. The main drainage canal runs from north to south through the district and has floodgates at both ends. Rainfall runoff from the paddy fields and surplus irrigation water from the irrigation canals flow into the main drainage canal via the lateral drainage canals. The

Fig. 1 - Outline of the study site.
floodgate at the northern end of the drainage canal was closed during our investigation period. Therefore, outflow of drainage water from the district was controlled by the operation of the southern floodgate.

Two types of irrigation practices, namely, lake water irrigation and cyclic irrigation are employed in the district. In lake water irrigation, water is pumped from Lake Biwa into the irrigation canals. In cyclic irrigation, drainage water in the main drainage canal is pumped and reused as irrigation water, and water flows from the lake to the drainage canal through the southern floodgate when the water level in the drainage canal decreases as a result of evapotranspiration. Two pump stations are located at the northern and southern ends of the main drainage canal. The irrigation period covers about four months, including a mid-summer drainage season of about 10 days. Cyclic irrigation is employed from the beginning of the irrigation period to the mid-summer drainage season (April to June, referred to as the cyclic irrigation period). About 80% of the total irrigation water used was taken from the main drainage canal during the cyclic irrigation period (Hama et al., 2010). After the mid-summer drainage season, lake water irrigation is employed until the end of the irrigation period (July to September, referred to as the lake water irrigation period). The period from the end of the irrigation period to the beginning of the next irrigation period is referred to as the non-irrigation period.

Measurement
Meteorological instruments for measuring rainfall (RT-5E, Ikeda-Keiki, Tokyo, Japan), air temperature (CS215L, Campbell Scientific, Inc., Logan, UT, USA), wind velocity (014A-L, Campbell Scientific, Inc.), relative humidity (CS215L, Campbell Scientific, Inc.), and solar radiation (short-wave radiation) (LP02-L, Campbell Scientific, Inc.) were installed in an open area at the southern pumping station. Water level and SS of the main drainage canal at both its ends were measured. Five water temperature gauges were set at increments of 25-cm depth from the surface (0.25 m, 0.50 m, 0.75 m, 1.00 m, and 1.25 m) at the southern end of the main drainage canal. However, in the study site, dredging operations were carried out in March 2006 and December 2008; hence, water temperature could not be measured during these periods. Water temperature data for Lake Biwa published by the Ministry of Land, Infrastructure, Transport and Tourism (2006 – 2008) were used to compare the main drainage canal and Lake Biwa. The point of measurement of the water temperature data for Lake Biwa is nearby the study site and at 2 m depth. Day length data were obtained from the Japan Meteorological Agency (2006 – 2008).
Model Description
In this study, we used a vertical one-dimensional model based on the heat energy budget (Jacobs et al., 2008; Hondzo and Stefan, 1993; Henderson-Sellers and Webster, 1991) to simulate water temperature in the main drainage canal:

\[
\frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left( K \frac{\partial T}{\partial z} \right) + \left( \frac{\partial I}{\partial z} \right) / c_{pw} \rho_w + Q_{in}
\]

(1)

where \( T \) is the water temperature of the main drainage canal (°C); \( t \) is the time (s); \( z \) is the depth (m); \( K \) is the vertical diffusion coefficient (m²/s); \( c_{pw} \) is the specific heat (J/g/°C); \( I \) is the incoming shortwave radiation (W/m²); \( \rho_w \) is the water density (g/m³), and \( Q_{in} \) is the heat influx caused by the inflow of irrigation water (°C/s). In this study, we assumed that water temperature in the main drainage canal does not change horizontally because water from lateral drainage canals flows into the main drainage canal every 200 m (Fig. 1).

Irrigation water that is not used to irrigate the paddy field is regarded as surplus and drains into the drainage canal. Therefore, the effect of the inflow of surplus water to the drainage canal on water temperature should be considered in paddy-field districts. The heat influx, \( Q_{in} \), is described by the following equations:

\[
Q_{in} = D_{in} (T - T_L) / A_d h \\
D_{in} = V_E \quad \text{(Cyclic Irrigation)}
\]

(2a)

\[
D_{in} = V_{pump} - V_E \quad \text{(Lake Water Irrigation)}
\]

(2b)

where \( D_{in} \) is the volume of water flowing into the main drainage canal (m³/s); \( T_L \) is the water temperature in Lake Biwa (°C); \( A_d \) is the surface area of the main drainage canal (m²); \( h \) is the water level of the main drainage canal (m); \( V_E \) is the rate of water loss as a result of evapotranspiration (m³/s); and \( V_{pump} \) is the volume of water intake by the pump (m³/s). In cyclic irrigation, \( D_{in} \) is from the inflow outside via the southern floodgate, and in lake water irrigation, \( D_{in} \) is the inflow of the surplus water irrigation (Fig. 2). In our model, it is assumed that water is lost mainly by evapotranspiration under irrigation on fine days.

In this model, the surface boundary condition is given by the surface energy exchange as follows:

\[
Rn = I + L_{atm} - L_w - LE - H
\]

(4)

where \( Rn \) is the net heat input at the water surface (W/m²); \( L_{atm} \) is the atmospheric long-wave radiation (W/m²); \( L_w \) is the back radiation at the water surface (W/m²); \( LE \) is the latent heat (W/m²); and \( H \) is the sensible heat (W/m²). The short-wave radiation is calculated as follows:

\[
I_{(z \geq 0)} = (1 - \alpha) \beta I \\
I_{(z < 0)} = (1 - \alpha)(1 - \beta) I
\]

(5a)

(5b)
where $\alpha$ is albedo at the water surface and $\beta$ is the surface absorption factor. The attenuation of solar radiation with depth follows Beer’s law:

$$I(n) = I(n-1) \exp(-\mu \Delta z)$$

where $I(n-1)$ is the short-wave radiation at the top of a horizontal layer of water (W/m$^2$); $I(n)$ is the short-wave radiation at the bottom of a layer (W/m$^2$); $\Delta z$ is the thickness of a layer (m); and $\mu$ is the extinction coefficient (m$^{-1}$). The extinction coefficient, $\mu$, is given as follows (Stefan et al., 1983):

$$\mu = \mu_w + \mu_{ss} \times SS$$

where $\mu_w$ is the extinction coefficient of lake water (m$^{-1}$); $\mu_{ss}$ is the specific extinction coefficient attributed to suspended solids (L/m/mg); and SS is the suspended solid concentration (mg/L). It is considered that SS composition does not change because the study district does not receive water from the outside except lake water and rain, i.e., SS in the drainage water was mainly supplied by runoff of paddy soil from the paddy fields. In equation (5), $L_{atm}$ is calculated using the estimation method of Nimiya et al. (1996):

$$L_{atm} = \sigma T_{air}^4 \left[ 1 - \left( 1 - \frac{L_{atmf}}{\sigma T_{air}^4} \right) C \right]$$

where $\sigma$ is the Stefan-Boltzmann constant (W/m$^2$/K$^4$); $T_{air}$ is the air temperature ($^\circ$C); $L_{atmf}$ is the atmospheric long-wave radiation in the fine sky; and $C$ is the cloud factor calculated by day length. The back radiation at the water surface, $L_w$, is calculated using Stefan-Boltzmann law:

$$L_w = \varepsilon \sigma (T + 273)^4$$

where $\varepsilon$ is the emissivity of the water body. Latent heat and sensible heat are calculated using aerodynamic bulk formulae:

$$LE = f(U_w)(e_s - e_{air})$$

$$H = cf(U_w)(T - T_{air})$$

where $e_s$ is the saturated vapor pressure (mmHg); $e_{air}$ is the vapor pressure (mmHg); $c$ is the Bowen’s coefficient (mmHg/$^\circ$C); $U_w$ is the wind speed (m/s); and $f(U_w)$ is the wind function (W/m$^2$/mmHg) (Brady et al., 1969).

In this study, equation (1) was solved numerically by the implicit finite difference method. The number of water layers was $n = 15$, and the thickness of a layer was calculated by dividing the measured water depth in the main drainage canal by 15. Therefore, the thickness of a layer changes temporally. The energy associated with the volume change, $E_v$, (J), is described as:
where $A$ is the surface area of water body (= 1.0 m$^2$) and subscripts $t$ and $t+1$ are the mean time step of the simulation. We assumed that the volume change was due to the inflow of water to the main drainage canal from the lateral drainage canals. In addition, we used a 1-dimensional equation for the water temperature model by assuming that water temperature did not change horizontally in the drainage canal. Under those assumptions, the energy associated with the volume change equals to the inflow of energy to the main drainage canal ($E_v$). Therefore, it is considered that the energy balance is conserved though the thickness of a layer changes. The parameters in this simulation, which should be determined from measured data, are $\mu_w$, $\mu_{SS}$, $\beta$, and $K$. These parameters were calibrated so that the measured water temperature at 0.25 m depth fits with simulated water temperature using one-year data measured in 2007. The value of $\mu_w$ and $\beta$ were set to 0.65 (m$^{-1}$) and 0.5 following literature (Hondzo and Stefan, 1993; Jacobs et al., 2008; Carrivick et al., 2012), and the others were determined by trial and error.

RESULTS AND DISCUSSION

Measurement of Water Temperature

Figure 3 shows the temporal variation in water temperature and SS in the main drainage canal and rainfall at the study site from 2006 to 2008.

Water temperature in the main drainage canal was about 2°C higher than that in Lake Biwa from April to June each year. This is because the drainage water continued to circulate in the field under cyclic irrigation. On the other hand, water temperature in the surface layer of the main drainage canal was nearly equal to that in Lake Biwa during the lake irrigation period (from July to August). Diurnal temperature variation in the main drainage canal was higher than that in Lake Biwa. Moreover, summer water temperature in Lake Biwa was lower than that in the main drainage canal, and winter water temperature in Lake Biwa was higher than that in the main drainage canal.

![Fig. 3 - Temporal variation in SS in the main drainage canal and water temperature at 0.25 m depth in the main drainage canal and in Lake Biwa.](image-url)
water temperature in the main drainage canal, where the water level was less than 2 m, was considered to be influenced by seasonal changes and climatic variations.

Suspended solids varied from about 5 to 300 mg/L over the entire period, and was higher during the cyclic irrigation period when drainage water was being reused as irrigation water (Hama et al., 2010). However, a clear relationship between SS and water temperature was not confirmed, indicating that SS has little effect on water temperature in the main drainage canal.

**Simulation of Water Temperature**

Figures 4(a), 5(a), and 5(b) show the results of simulation of water temperature at 0.25-m depth in the main drainage canal from 2006 to 2008. Although the model was calibrated using water temperature data for 0.25-m depth measured in 2007, the trend of simulated water temperature agreed well with the measured water temperature each year.

Figure 4(a) shows the results of the simulation of variation in water temperature in 2007, and Figure 4(b) shows the results of the same simulation but with $Q_{in} = 0$. In Fig. 4(b), simulated water temperature always exceeds the measured water temperature during the irrigation period (from mid-April to late August). In Fig. 4(a), simulated water temperature agrees well with the measured water temperature. Therefore, it is indicated that surplus irrigation water has a great influence on water temperature in the main drainage canal.

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**Fig. 4 - Simulation of water temperature in (a) 2007 and (b) 2007 with $Q_{in} = 0$.**

**Fig. 5 - Simulation of water temperature in (a) 2006 and (b) 2008.**
drainage canal during this period.

For the non-irrigation period, especially from late November to early February, the accuracy of the simulation was lower than that in other periods: the model underestimated water temperature during the non-irrigation period. The drainage canal water level tended to be low during the non-irrigation period because the pumps were not in operation and inflow of water did not occur on fine days. Therefore, there are two possible factors causing the underestimation of water temperature: the inflow of rainwater and heat flux from the sediment in the main drainage canal. Jacobs et al. (2008) reported that rainfall does not influence water temperature, even if the water body is small, and in fact, any influence of the rainfall on water temperature were not confirmed. Therefore, it is suggested that the heat flux from the sediment to the overlying water is an important factor affecting water temperature in the drainage canal during the non-irrigation period.

Figure 6 shows the results of simulation of water temperature at depths of 1.0 m and 1.25 m in 2007. Simulation results for 0.75-m depth agree well with the measured water temperature. However, simulation results for 1.25-m depth do not agree with the measured water temperature. In the simulation of water temperature for a depth of 1.25 m, the model overestimated water temperature in summer, and underestimated it in winter. This is because the model did not account for the heat exchange between the sediment and the overlying water in the main drainage canal, though sediments have been reported to act as heat sinks in summer and heat sources in winter (Hannah et al., 2008; Evans et al., 1998).

Figure 7 shows the results of the simulation of the vertical profile of water temperature on representative fine days in 2007. The measured water temperature shows thermal stratification for each day. The simulated water temperature agreed well with the measured water temperature at 0.25-m depth, and the model could simulate the decreases in water temperature in the depth direction. However, the model tended to overestimate the water temperature at 1.25-m depth in summer (Fig. 7(b)). This is because the model did not consider the sediment heat flux, as mentioned above.

![Fig. 6 - Simulation of water temperature in 2007 at (a) 0.75-m depth, and (b) 1.25-m depth.](image-url)
Sensitivity Analysis

Figure 8 shows the sensitivity of simulated water temperature to parameters ($K$: vertical diffusion coefficient and $\mu_{SS}$: specific extinction coefficient attributed to SS). We considered the water temperature in the upper layer on representative successive fine days in 2007 for the sensitivity analysis. The results of the sensitivity analysis show that $K$ has greater influence than $\mu_{SS}$ on the simulated water temperature. The results also indicate that SS does not influence water temperature to a great extent, and this observation agrees with the results of the measurements.

Fig. 7 - Simulation of the vertical profile of water temperature in (a) May 11, 2007, at 14:00, (b) July 18, 2007, at 14:00, and (c) October 6, 2007, at 14:00.

Fig. 8 - Sensitivity analysis: Influence of (a) vertical diffusion coefficient and (b) specific extinction coefficient attributed to SS on water temperature. Black solid lines show the values used in the simulation ($K$: $1\times10^{-4}$ (m$^2$/min), $\mu_{SS}$: 0.3 (L/m/mg)).
CONCLUSIONS
The main findings of our study are summarized as follows:

(1) During the cyclic irrigation period, water temperature in the main drainage canal was about 2°C higher than that in Lake Biwa because irrigation water was circulated in the paddy-field district and was warmed.

(2) No clear relationship could be confirmed between SS and water temperature, even though cyclic irrigation caused higher SS in drainage water.

(3) Water temperature simulated by the model agreed well with the measured water temperature, and the simulation results indicated that the inflow of irrigation water greatly affected the temperature of drainage water in the paddy-field district during the irrigation period.

(4) The model underestimated the water temperature during the non-irrigation period. The heat flux from the sediment to the overlying water is an important factor that affects water temperature when the water level of the drainage canal is low.

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