Thermal Structure of the Artificial Reservoir

TADASHI ARAI
Department of Geography, Risshyo University, Tokyo, Japan

Artificial reservoirs change the hydrologic, physical, and chemical properties of the original river water. The hydrologic change is caused mainly by the operation of reservoir control. The most fundamental physical and chemical change is the change in water temperature. Temperature changes the habitats of river animals and plants and also affects the water supply in the river basin, e.g., the irrigation, waterworks, and industrial water. In addition, since the reservoir itself is a huge mass of inland water, its limnological and hydrologic properties must be researched. For these and many other reasons, studies of the water temperature in the reservoir, the mechanism that governs the vertical distribution of water temperature, and the estimation of the temperature of water flowing from the reservoir and its control are needed.

Investigations of the thermal and hydrologic structures of reservoir water are needed for this study. The heat budget at the water surface and the distribution of physical quantities in the reservoir are regarded as two main aspects of the system that transfers energy from the air to the reservoir water. Heat budget considerations may distinguish the main factors that contribute to the distribution of water temperature. Investigations of the distribution of physical quantities in the reservoir may explain the heat redistribution mechanism of the lake.

The characteristics of the water temperature of a reservoir are completely different from those of natural lakes. The most important feature in the water balance relations of the reservoir is the complex movement of the water mass. A change in water level is more complicated in a reservoir than in a natural lake. Thus it may be assumed that advective heat transfer and vertical movement of the water mass can play important roles in the distribution of water temperature in an artificial reservoir. Advective heat transfer exceeds the heat supply from the water surface in many reservoirs. Thus water and heat budgets in an artificial reservoir show considerably different characteristics from those in natural lakes.

Thermal characteristics of the artificial reservoir are divided into two types according to the hydrologic condition. The water of the first type has a long travel time, so that a remarkable thermal stratification is created in the summer season. The water of the second type has a short travel time, and the thermal stratification is weak in comparison with that of the first type. Differences in heat balance are produced by the above-mentioned hydrologic conditions because advective heat is greatly affected by the amount of discharge and the water travel time in the reservoir.

In general, advective heat from an inflowing and outflowing water mass occupies a large part in the heat balance process of an artificial reservoir. The heat redistribution process in the water column differs with hydrologic condition as well as surface heat balance.

Heat and water balances for two representative reservoirs were calculated. The first is Tagokura Reservoir, which has a long water travel time, and the second is Sakuma Reservoir, which has a short water travel time in comparison to its volume. Heat balance and heat redistribution in the reservoirs were analyzed. In both reservoirs, advection occupies a large part in the heat balance process. Evaporation reaches its maximum in late autumn, and the temperature of the outflowing water reaches its maximum in November. Since Sakuma Reservoir discharges >300 m^3/sec of water in about 10 days of travel time, its advective heat is extremely great. The thermal stratification is very weak in this reservoir, and the isothermal layer extends from the surface to 80 meters below the surface.

The important hydrologic characteristic of the reservoir is the complex movement of the water mass, which causes the increment of vertical and advective heat transfer. Because advection occupies a large part in the heat budget of the reservoir, the movement and exchange of the water mass govern its vertical temperature profile. The magnitude of the exchange is illustrated by the turbulent diffusivity.

To carry out the general comparison of the diffusivity coefficient in the reservoir, the equation of heat balance in water that is assumed to be completely free from direct effects of surface heating is represented by

$$c\rho \int u \frac{\partial \theta}{\partial X} dZ = c\rho K\left(\frac{\partial \theta}{\partial Z}\bigg|_{z_1} - \frac{\partial \theta}{\partial Z}\bigg|_{z_2}\right)$$

The results of the calculation for several reservoirs are shown in Figure 1 in comparison with the results derived from the mixing length theory and from the heat storage calculation. As these coefficients are assumed to vary in relation to the stability of the flow, the order of magnitude of Richardson's number is also shown in this figure. The numerical value of the coefficient lies between the order of 10^0 and 10^1 and therefore surely exceeds the value for a natural lake.

In natural lakes, several results on eddy diffusivity were obtained on the basis of the analysis of heat balance or change in water temperature. According to these results the coefficient does not exceed the order of magnitude of 10^{-1} in lakes in Japan. Vertical heat transfer in a natural lake is governed mainly by the vertical eddy diffusion and the water mixing associated with the internal wave. The process of heat transfer is more complicated in the artificial reservoir than in the natural lake because many other heat transfer mechanisms exist in the reservoir.

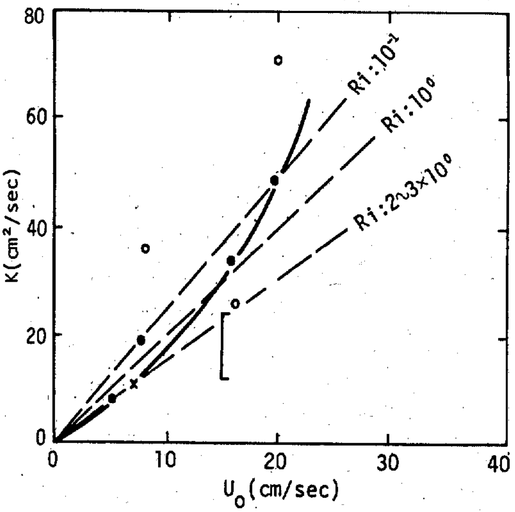

Fig. 1. Relation between diffusivity coefficient K and maximum velocity in the reservoir. The solid dots represent Tagokura Reservoir, the open dots represent the coefficient for Tagokura Reservoir obtained by the mixing length method, the cross represents the coefficient at Miwa Reservoir obtained by the heat storage method, and the bracket represents Sakuma Reservoir.

Because advective heat transfer and vertical water mixing exert important influences on the distribution of water temperature in the reservoir, the temperature in the summer season in the deep layer of the reservoir becomes higher than that of a natural lake at the same depth.

Water temperature in the deep layer of a deep lake in the temperate climatic zone is about 4°C, whereas that in the deep layer of an artificial reservoir is >4°C at the same level under the same climatic and morphologic conditions. Table 1 shows the comparison between water temperatures in deep layers in several lakes and those in reservoirs. Water temperatures approach 10°C at the 70- or 80-meter layer in midsummer in some reservoirs. This warmwater mass may be created in early summer when the heat is allowed to move to the deep layer because the advective heat flux shows a strong positive value and the thermal stratification remains relatively weak. When the discharge of the reservoir is large enough in comparison to its capacity, the water temperature of the reservoir is largely controlled by the inflowing water mass.

The distribution of water temperature in a reservoir is governed by its hydrologic properties, which are divided into two types. The criterion for the classification is the ratio, amount of advective heat transfer to net change of heat storage. Advective flux increases in proportion to the increase in discharge, as is explained in the analysis of the Sakuma Reservoir. Another example is the analysis of the Tagokura Reservoir in which a comparatively large net change of heat storage was obtained. It is difficult to obtain an accurate criterion for the classification of reservoirs, but the following approximate value may be applicable.

In the middle and high latitudes, where temperate lakes prevail, reservoirs can be divided thermally into two types by using two parameters. These parameters are calculated by using the volume V, surface area S, and discharge

TABLE 1. Comparisons of Water Temperature in Natural Lakes and Artificial Reservoirs

	Temperature, °C		
	Depth, 15 meters	Depth, 30 meters	Depth, 70 to 80 meters
Natural lakes			
Lake Towada	10	6	4
Lake Tōya	10	6	4
Lake Chūzenji	10	6	4
Lake Tazawa	12	7	4
Artificial reservoirs			
Tagokura (1960)	14	13	10
Tagokura (1961)	15	12	8
Tagokura (1962)	11	9	6
Tagokura (1963)	11	9	6
Okutadami (1962)	13	12	6
Okutadami (1963)	11	8	5
Sakuma (1958)	25	10	10

q of the reservoir and take the forms S/q and V/q. For a summer climate in Japan the following values of the parameters may be regarded as the boundary for the classification between large capacity (i.e., strong thermal stratification with a long water travel time) and small capacity (i.e., isothermal profile with a short water travel time) reservoirs: $S/q \simeq 0.1 \times 10^6$ sec/m and $V/q \simeq 3$ or 4×10^6 sec. Note that this method gives only a rough aid to the classification of reservoirs.

Several results of observations show that thermal stratification vanishes for a summer climate when the flow velocity in the reservoir exceeds about 20 cm/sec because heat is distributed to all water layers by strong mixing at that water velocity.

The construction of the drainage mouth greatly affects the distribution of water temperature in all reservoirs. The vertical distance between the water surface and the drainage mouth varies according to the change in water level in reservoirs that are not equipped with a surface drainage mouth. The analysis of water temperature must be made with regard to the reservoir control.

The analyses and discussions in this report have been made mainly by considering a summer climate in the middle latitude. In a tropical climate, there is only weak thermal stratification in the lakes. In addition, in the tropical zone the temperature of the river water approximates the temperature of the surface water of the lakes, and so the thermal stratification in a reservoir may be very weak.