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A Study of Impact of Riparian Vegetation on In-Stream Thermal Environment

Guangwei HUANG

Member of JSCE, Dr. of Eng., Associate Professor, Dept. of Civil Engineering, Kanazawa University
(Kodatsuno 2 chome, Kanazawa, Ishikawa 920-8667, Japan)

In this study, a modeling framework is presented for simulating water temperature in shaded stream. The attention is given to the function of riparian vegetation in regulating water temperature. The model solves the unsteady heat advection-dispersion equation with source terms accounting for various energy exchange processes. The performance of the model is examined in River Oppegawa, and then used to highlight a number of aspects of riparian vegetation shading, and the response of water temperature to change in riparian vegetation shading. It is shown that the water temperature can be significantly affected by bank-side vegetation shading. Particularly, the daily maximum water temperature is more sensitive to the shading than mean and minimum water temperature. In addition, the impact of stream temperature regime on aquatic life is briefly discussed.

Key Words : *water temperature, riparian vegetation, shading factor*

1. INTRODUCTION

In-stream thermal conditions have a complex array of effects on aquatic ecosystem, because most aquatic organisms are unable to internally regulate their core body temperature. Fish, insects, zooplankton, phytoplankton, and other aquatic species all have preferred temperature ranges. Water temperatures that exceed a species' tolerance level can cause increased metabolic activity, abnormal growth, and can lead to stress and decreased resistance to disease. Increased temperatures may also make juvenile fish more subject to predation by species that favor warmer waters. For Chinook acclimatized to 24°C, 2°C rise in water temperature may result in 50% death of the fish (Balz, 1987). Temperature is also important because of its influence on water chemistry. The rate of chemical reactions generally increases at higher temperature, which in turn affects biological activity. An important example of the effects of temperature on water chemistry is its impact on oxygen. Warm water holds less oxygen than cool water, so it may be saturated with oxygen but still not contain enough for survival of aquatic life. Biological Oxygen Demand (BOD) and other water quality parameters are also function of water temperature. Some compounds are more toxic to aquatic life at higher temperatures. Therefore, the water temperature may be viewed as one of the most important parameters in assessing stream ecological condition.

Many streams or rivers have been subjected to thermal stresses. Some common sources of water temperature alteration are channelization, impoundment, riparian vegetation removal and industrial discharge. However, in the field of river engineering of Japan, little attention has been given to the water temperature conditions over the past several decades. Water temperature study in Japan has mainly been conducted in the filed of agriculture for the purpose of irrigation. The effects of watershed development and river works on water temperature and associated aquatic life have been very much neglected. With the amendment of the river law of Japan in 1997, which added the preservation and enhancement of riverine environment into the management objectives, the demand for ecologic consideration in river improvement works is becoming stronger. Under the new law, in-stream habitat protection and enhancement is becoming a key component in nature-oriented river improvement works; it is time for systematic research on impact of man's activities on in-stream thermal environment, and to work out solutions accordingly.

A focal point for protecting and enhancing aquatic habitats is riparian buffers. A riparian buffer is a zone of trees and vegetation between water and an upland area. Riparian vegetation zones are important to the health of a stream. They shade the water; help control water temperature. They stabilize banks and intercept surface runoff. They also purify runoff by trapping sediment, fertilizers and pollution. They even provide food in the form of leaf litter for aquatic insects. The insects in turn are food for forage fish and trout. Ultimately, we can improve fish populations if we protect and enhance riparian buffers.

In this study, a model capable of predicting the function of riparian vegetation zones in regulating water temperature is developed, and used to improve our understanding of riparian vegetation shading, and to demonstrate the response of stream temperature to change in riparian vegetation. The purpose of this paper is to provide land managers and planers with some latest information with respect to the impact of riparian vegetation shading on in-stream thermal conditions and its modeling approach.

2. WATER TEMPERATURE MODELING

The thermal regimes in river system can be distinguished as being natural or human-altered regimes. The natural water temperature regime depends upon several factors such as stream geometry, flow patterns, meteorological conditions. Assuming well-mixed conditions in stream, the temperature prediction can be treated as a one-dimensional problem.

Over the past several decades, a number of models have been developed to describe and predict stream water temperature. These models can be classified into two categories: regression and physical-process-oriented models. Regression models are attractive due to their simplicity and understandability. However, they do not attempt to explain heat transfer process, but rather describe the relationship between meteorological variables, flow discharge and water temperature. They are quite limited in determining the incremental impact on water temperature due to changes in the water system. In addition, any empirical model is only representative of the single geographic location for which it was built, translations are generally invalid. By contrast, physical-process-oriented models are based on the energy budget approach. That is, they attempt to explain the changes in water temperature by calculating the gains and losses in thermal energy from individually described phenomena such as radiation, convection, conduction and evaporation. They are better suited to exploration of system changes and capable of assessing the efficiency of alternative water management solutions. The physical-process-oriented models may be further divided into two forms: analytical and numerical models. Assuming that the energy exchange process at water surface can be linearized and the stream flow is uniform, a closed-form solution of 1-D equation for water temperature can be derived as reported by Yotsukura and others (1973). Although closed-form solutions are easy to use, they are valid only for fairly constant flow and meteorological conditions. In practice, flow and meteorological conditions are subject to fluctuations, therefore, it is necessary to resort to the numerical simulation of the problem.

Brown (1969) has developed a numerical model to predict the hourly temperature of small streams. His work has probably been the basis for further refinement in the art of temperature modeling. The model, however, did not consider the advection and dispersion, therefore its use should be limited to short reaches. Raphael proposed a model for rivers and reservoirs analogous to Brown's model with the addition of accounting for tributary inflows. Morse (1972) developed a model for predicting hourly water temperature, which has the same features as Brown's model, but included a convective term. Johnson and Keefer (1979) presented an example of modeling the thermal regime of the Chattahoochee River near Atlanta, Georgia, in highly transient flow situation. Sinokrot and Stefan (1993) formulated a numerical model for stream temperature that is based on the solution of the unsteady heat advection-dispersion equation.

Probably, the riparian vegetation-related water temperature problem was first studied by Brown (1969), and followed by Pluhowski (1972), Lee (1978), Feller (1981) and others. However, in Brown's paper, he simply compared the water temperatures in shaded and unshaded streams, and did not pursue for shading computation. In the model of Sinokrot and Stefan, the sun shading by bank-side vegetation was treated as a constant adjusted through model calibration. In the present study, a dynamic shading computation procedure is incorporated into surface heat exchange module in order to deal with bank-side vegetation effects.

The model framework employed by the present study is described as following:

The governing equation takes the form below

$$\frac{\partial T}{\partial t}+\frac{\partial (AuT)}{A\partial x}=\frac{1}{A}\frac{\partial}{\partial x}(AD\frac{\partial T}{\partial x})+\frac{W(H_n+H_{sb})}{A\rho C_p} \qquad (1)$$

where T = stream water temperature; A = stream cross-sectional area; u = mean stream velocity; x = distance downstream; D = a longitudinal dispersion coefficient; W = surface width; and ρ is the density of water, C_p is the specific heat of water. The source or sink term (S) expresses the heat exchange rate with the surrounding environment.

$$S = H_n + H_{sb} \quad (2)$$

where H_n = net heat flux across the air-water interface; H_{sb} = net heat exchange between stream bed and stream water.

The surface heat exchange is composed of three different processes; radiation exchange, evaporation and conduction.

$$H_n = H_s + H_l - (H_b + H_c + H_e) \quad (3)$$

where H_s = net short-wave radiation flux, H_l = atmospheric long-wave radiation flux, H_b = back scattering radiation flux, H_c = conductive heat flux, H_e = evaporative heat flux.

The net short-wave radiation may be represented on an hourly basis by:

$$H_s = H_0 A_t (1 - A_w)(1 - 0.65 C_l^2)(1 - SF) \quad (4)$$

where H_0 = amount of solar radiation reaching the earth's surface; A_t = atmospheric transmission term; A_w = water surface albedo; C_l = cloudiness; SF = the fraction of solar radiation that is blocked by topography and stream bank vegetation.

The atmospheric transmission term A_t is calculated according to water vapor pressure, optical air mass and dust attenuation as described in Chow (1964). In the present study, the value of dust attenuation is taken to be zero. The extraterrestrial radiation H_0 can be computed according to the formulation given by Water Resources Engineering, Inc. 1967. The surface albedo can be estimated as a function of the solar altitude, α, by use of Andeson formula

$$A_w = 1.18\alpha^{-0.77} \quad (5)$$

However, since Anderson formula was developed for unshaded condition, the use of eq. (5) would lead to overestimation. Based on trial-and-error method, the present modeling framework adopts a modification as

$$A_w = \begin{cases} 1.18\alpha^{-0.77} & \alpha > \text{shade angle} \\ 0.2\alpha^{-0.57} & \alpha < \text{shade angle} \end{cases} \quad (6)$$

For atmospheric long-wave radiation, the Swinbank's formulation (1963) is used. The sensible heat flux and evaporative heat flux are parameterized by the bulk transfer formula with dependencies on wind speed as formulated by Sinokrot (1993). To account for wind sheltering by riparian vegetation, the following wind function calibrated by Gulliver (1986) is adopted in calculating sensible and evaporative fluxes

$$W_f = 17.5 + 2.4 W_9 \quad (7)$$

where W_9 = the wind speed at 9m above the water surface.

When wind and channel orientation do not coincide, vegetation and levee produce a sheltering effect on wind. Figure 1 shows the measured wind speeds on the flood plain at the sampling station 1, as depicted in Fig. 3, and at a near-by un-shaded position as well. This comparison indicates that the use of on-site wind data should be recommended. If on-site wind recording is not available, a wind sheltering coefficient may be introduced into the model for the purpose of model calibration.

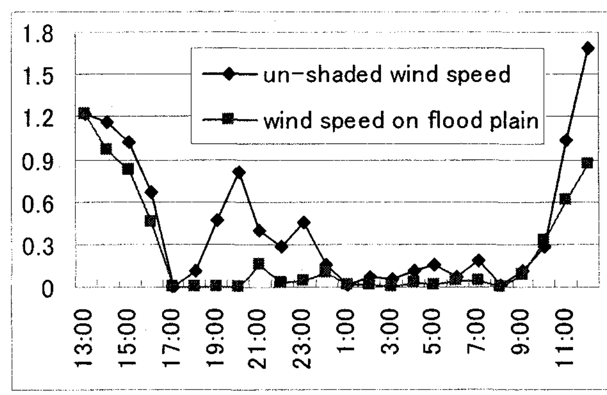

Fig.1 wind data at St.1, July 11-12, 1997

For deep rivers, the bed heat transfer is small enough to be neglected. However, the bed heat transfer is significant for shallow streams as reported by Brown and Kobatake. The penetration of short-wave radiation through the water column may be computed using eq. (8)

$$I_b = (1 - A_b) H_s e^{-\beta h} \quad (8)$$

where I_b=short-wave radiation at the bed; β=attenuation coefficient. A_b=bed reflectivity.

The equation for streambed temperature is

$$\frac{\partial T_b}{\partial t} = \lambda \frac{\partial^2 T_b}{\partial z^2} \quad (9)$$

where T_b=streambed temperature; λ=thermal diffusivity of the streambed material. Since solar radiation may penetrate the entire water column in shallow rivers, the direct warming by solar radiation is incorporated in calculating the heat flux at streambed as following

$$-k \left. \frac{\partial T_b}{\partial z} \right|_{z=0} + H_{w-s} = I_b \quad (10)$$

where H_{w-s} = flux due to temperature difference between water and river bed. At the deep boundary in the sediment, zero-flux condition is applied.

As illustrated in Fig.2, the bank-side vegetation and bank topography may intercept solar radiation from water surface. Because solar radiation can account for over 95% of the heat input in the midday period during midsummer, stream temperature may greatly be affected by shading produced by riparian vegetation and stream bank topography. In this study, the bank topographic shade is taken into consideration through adjusting the local sunrise and sunset time according to the east and west side topography. When solar altitude is greater than the topographic shade angle, a portion of solar radiation is intercepted by the riparian vegetation (if exists). The amount of intercepted solar radiation can be estimated based on parameters such as average height of bank-side vegetation (H), average maximum crown diameter (TC), vegetation offset (BD), vegetation density, and stream orientation (azimuth). The procedure can be summarized as following:

- Identify the sunward bank side according the solar and stream azimuth.
- Compute the solar shade width (SW) that is measured perpendicularly to the stream.
- Multiply the solar shade width with vegetation density to obtain the effective shade width.
- Then, the solar shade factor is approximated by the ration of the effective shade width to the width of stream surface.

More details are to be presented in a separate paper due to space limitation.

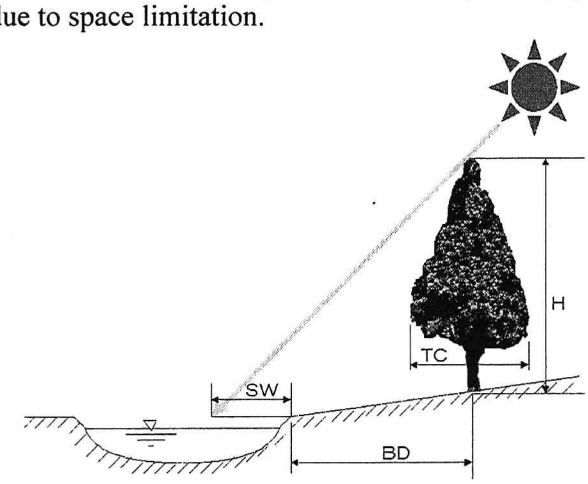

Fig.2 Topographic and vegetation shading

3. MODEL TEST

A reach of the Oppe River was selected to test the model described above. The reach under consideration is located at $139^0 23'$ N, $35^0 58'$ E, and sketched in Fig.3. The streambank inclination is approximately 65^0. The width of that reach is about 15m. The photo showing the riparian vegetation along the reach is given in Fig.4. To obtain necessary data to run the model, field measurement was conducted for two days in July 1997. At the three sites shown in Fig.3, water temperature, flow velocity and water depth were measured at an interval of one meter across the river every two hours. Meteorological conditions including air temperature, wind speed and direction, solar radiation, and relative humidity were recorded continuously at the sampling St.1 and St.2. Besides, measurements of water depth, flow velocity and water temperature were also conducted at a number of different location with less frequency. According to the location of the reach, bank topography and the observed vegetation data, the overall shading factor around St.1 and St.2 are estimated to be 7% and 12%, respectively, by the procedure described in the previous section. The governing equation is solved by the implicit four-point finite difference scheme in a coupled mode with river flow simulation.

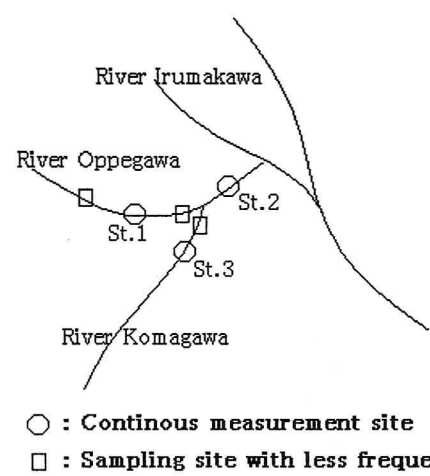

Fig.3 Selected study reach

Fig. 4 Bank-side vegetation along the study reach

4. SIMULATION RESULTS

Figure 5 presents simulated stream temperatures (^{0}C) with and without shading, and measured data at the St.2 for comparison. The simulation is initiated with linear interpolation of measured temperatures at computational boundaries. As can be seen, the temperature model with shading module performed fairly well; the maximum error is 1.21^{0}C, mean absolute error is 0.38^{0}C, and the root-mean-square error (RSME) is approximately 0.67.

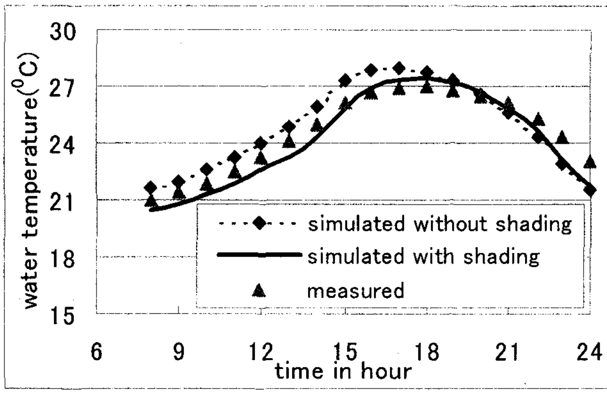

Fig.5 *Comparison of prediction with measurement at St.2*

Figure 6 shows how the solar shading factor would vary with the stream orientation when the riparian vegetation conditions are given. It indicates that streams that run in N-S direction is most susceptible to riparian shading and the shading factor is sensitive to change in stream orientation when the stream azimuth is between 20 and 60 degree because the curve is steep within this range. Such factors should be taken into consideration when planning river improvement works in which the direction of stream is often altered.

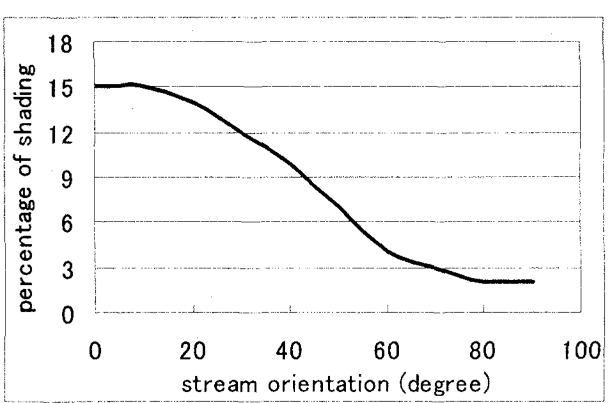

Fig.6 Relationship between shading and stream orientation

For streams running in N-S direction, Fig.7 indicates that the shading factor could be expressed by a second-order polynomial function of vegetation height non-dimensionalized by the distance from vegetation trunk to the center of stream (BD+W/2)

$$SF = Ax^2 + Bx + C; \; x = H/(BD + 0.5W) \quad (11)$$

However, the coefficients A, B and C are dependent on vegetation density (ρ_{veg}). To correlate the coefficients with vegetation density, a series of computations for the vegetation shading under different vegetation density are performed. Based on those results, regressive relations are derived for the coefficients as below:

$$\begin{aligned} A &= -0.115\rho_{veg} + 0.587 \quad (R^2 = 0.96) \\ B &= 0.525\rho_{veg} - 1.3 \quad (R^2 = 0.98) \\ C &= 0.194\rho_{veg} + 0.509 \quad (R^2 = 0.94) \end{aligned} \quad (12)$$

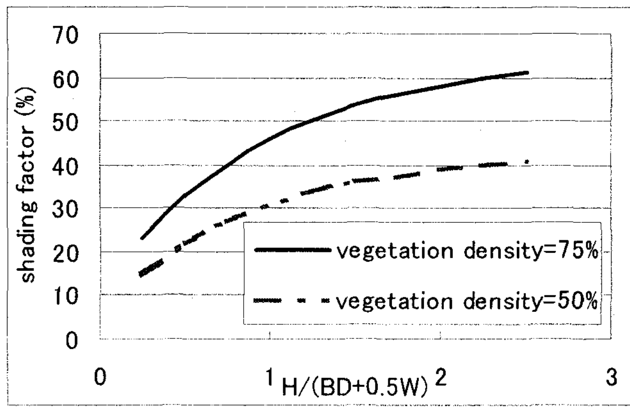

Fig.7 Relation between shading and vegetation for N-S streams

Figure 8 shows the dependence of daily maximum, mean and minimum water temperature on the shading percentage. As can be seen clearly, the daily maximum temperature is more sensitive to sun shading than the daily minimum. The difference between the maximum and minimum, in other words, the daily temperature amplitude tends to become smaller with increasing vegetation shading.

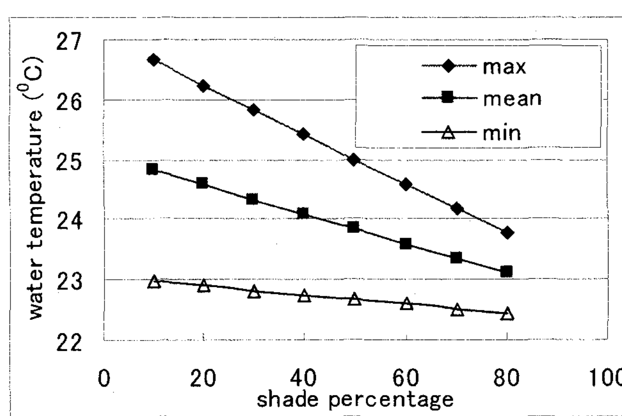

Fig.8 Dependence of water temperature on shading percentage

5. DISCUSSION

Stream thermal regime and its impact on aquatic life have received less attention than what should be in the field of Civil Engineering of Japan. A common misperception is that a few degrees change in water temperature might have some impact, but not fatal. This misunderstanding is probably caused by insufficient documentation on material evidence with respect to thermal effect. It is further complicated by the fact that the maximum temperature that fish can tolerate varies with the species, life-stage, oxygen availability and other conditions.

The study by Barton[3] found that trout populations in southern Ontario streams were dependent on weekly maximum water temperature. Streams with weekly maxima less than 22^0C had trout; warmer streams had, at best only marginal population. Vigg and Burley[16] found that maximum daily consumption rate of northern squawfish from the Columbia River increased exponentially as a function of water temperature. Connor and Burge[5] suggested that summer flow augmentation, which decreases water temperature, could benefit Snake River subyearling Chinook salmon.

On the other hand, Murphy indicated that increased light reaching the stream surface with the removal of riparian vegetation could stimulate aquatic primary and secondary production. The author of this paper feels that the elevated water temperature may allow the invasion of warm water species into formerly cool reach, which might result in the eliminate of the native species due to increased competition from intruders. Besides, as the water temperature rises, juveniles most likely move upstream to cooler water, where the carrying capacity of the habitat area may limit the number surviving.

River engineers need to develop a better understanding of the relationship between riparian vegetation zone and in-stream processes in order to restore in-stream habitats. Water temperature model may be used as one of the primary steps in assessing management alternatives under different conditions. For instance, it can help determine integrated riparian vegetation management strategy such as deciding the allowable length of stream to be totally exposed to sunlight for the purpose of creating a diverse aquatic ecosystem.

6. CONCLUSION

The present paper serves the purpose of highlighting the importance of studying the connection between riparian vegetation and in-stream environment, and presenting a model framework capable of predicting the impact of riparian vegetation on stream temperature regime. The model allows one to systematically study the formation of water temperature under varying conditions such as different level of bank-side vegetation cover, different channel orientation. And it can be used to assess river restoration alternatives.

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