Stream Temperature Modeling and its Application to Oppegawa

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1. INTRODUCTION

The evaluation of stream thermal conditions has gained considerable interests recently because of ecological concerns. The temperature of a stream directly affects the entire aquatic ecosystem including fish survival, growth, and reproduction. According to NAS/NAE, for chinook acclimatized to 24°C, 2°C rise in water temperature may result in 50% death of the fish. Therefore, the water temperature may be viewed as the single most important parameter in assessing stream ecological condition, and water temperature modeling can also be used in the design stage for nature-oriented river improvement work such as fish habitat construction.

The thermal regime of natural streams depends upon several factors such as stream geometry, flow patterns, meteorological parameters and the amount of heat added by tributary inflows or power plants. For an unregulated stream, the water temperature distribution is mainly controlled by atmospheric conditions.

Assuming well-mixed conditions in stream, the temperature prediction can be treated as a one-dimensional problem. A 1-D heat transport model that predicts the water temperatures in different streams to within 1°C standard error has been developed by Stefan in 1980, and modified by Sinokrot and Stefan in 1993. In this paper, the model of Sinokrot and Stefan is further extended to better account for bank-side vegetation effects on stream water temperature. The objective is to shed some more light on the sun shading and the wind sheltering effect by bank vegetation, and to discuss possible measure for improving stream environment. The stream temperature model is applied to a single reach of river Oppegawa which is located in Saitama prefecture, and it is a second-order tributary of Arakawa river. The insight gained from this study will serve to broaden the understanding in the formation of stream water temperature.

2. MODEL FOR STREAM WATER TEMPERATURE PREDICTION

The model considered in the present study is basically the MNSTREM model developed by Stefan, which is an implicit finite-difference model used for the simulation of water temperatures in the experimental channels of the USEP/Monticello Ecological Research Station. A summary of the model is given as follows:

The water temperature is predicted with the thermal-energy-transport equation which takes the following form:

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

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.

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

H_n = net heat flux across the air-water interface.

H_{sb} = net heat exchange between stream bed and stream water.

One of the central issues in stream temperature modeling is to accurately calculate the net heat exchange across the water surface which is determined by the summation 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 = short-wave radiation flux, H_l = long-wave radiation flux, H_b = back scattering radiation flux

H_c = conductive heat flux, H_e = evaporative heat flux

Key words : stream water temperature, bank-side vegetation, vegetation shading

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

$$H_s = H_0 At(1-Ab)(1-0.65C_l^2)(1-SF) \tag{4}$$

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

The atmospheric transmission term At is calculated according to water vapor pressure, optical air mass and dust attenuation as described in reference 2. 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.(see 2).

The net long-wave radition can be computed as

$$H_l = 2.89\times 10^{-6}\sigma(T_a + 273)^4 \times (1.0 + 0.17C_l^2)(1-R_l) \tag{5}$$

σ: Stefan-Boltzman constant;

R_l: reflectivity of atmospheric radiation.

Another source of radiation transfer through the air-water interface is the long-wave back radiation from the water surface, which can be expressed by the Stefan-Boltzman Fourth Power Radiation law for a blackbody as

$$H_b = 0.97\sigma(T + 273)^4 \tag{6}$$

For convective heat transfer:

$$H_c = 0.61 * \frac{P_a}{1000}\rho L W_f (T - T_a) \tag{7}$$

W_f: wind speed function;

T_a: atmospheric temperature (^{0}C);

Pa: atmospheric pressure.

The evaporative heat transfer may be estimated by the following relation:

$$H_e = \rho L W_f (e_s - e_a) \tag{8}$$

W_f: the same wind speed function as that used for the estimation of convective heat transfer.

e_s: saturation vapor pressure;

e_a: water vapor pressure.

The stream bed heat transfer H_{sb} is calculated as the product of the thermal conductivity and the measured temperature gradient of the bottom material.

3. MODEL REFINEMENT

As illustrated by the schematic in Fig.1 , 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 affected by shading produced by riparian vegetation and stream topography. In this study, the 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 measured perpendicularly to the stream.
- Multiple 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.

In the present study, modifications are also introduced to account for wind sheltering by bank vegetation and topography in the following way:

(1) If a portion of the water surface is protected from the wind by bank vegetation, that portion of water surface would have no forced convection heat loss, therefore, the expression for convective heat transfer should be modified as:

$$H_c = 0.61 * \frac{P_a}{1000}\rho L W_f (T - T_a) \times (1 - VC) \tag{9}$$

where VC is the wind sheltering factor.

(2) By the same token, the evaporative heat transfer may be modified as

$$H_e = \rho L W_f (e_s - e_a) \times (1 - VC) \tag{10}$$

(3) In stream water temperature modeling, the so-called "wind functions" (W_f) are often used to describe the wind sheltering effects on air-water heat transfer when the rate of transfer is controlled by resistance on the air side. However, wind functions used so far in water temperature simulations have been often based on studies for large water surface area, so that relationships developed may not apply well to sheltered streams. In the present study, a calibrated wind function for sheltered stream is adopted which is given below:

$$W_f = 17.5/(1-VC) + 2.4W_9 \tag{11}$$

where W_9 the measured wind speed at 9m above the water surface.
In this study, the wind sheltering factor is assumed to be equal to the solar shading factor (VC=SF).

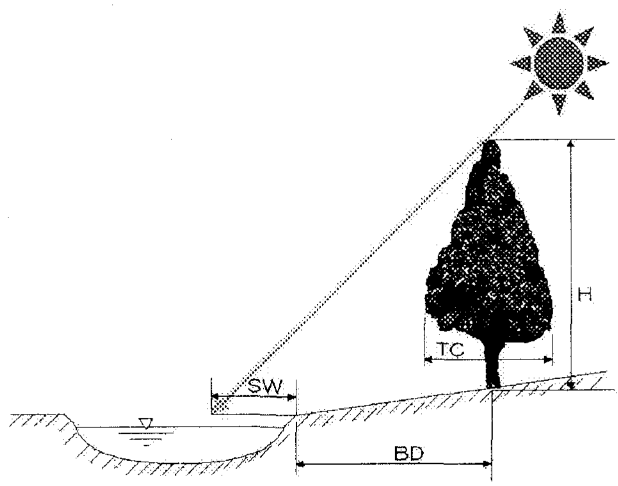

Fig. 1 Schematic of topographic and riparian vegetation shading

4. STUDY SITE AND RESULTS

The modified stream temperature model is applied to a portion of the Opegawa stream(Fig. 2). The reach under consideration is located at 139°23' N, 35°58' E, and nearly W-E oriented. The streambank inclination is approximately 65°. The width of that reach is about 15m. The photo showing the riparian vegetation along the reach is given in Fig. 3 To obtain necessary data to run the model, field measurement was conducted in July, 1997, for two days. Water temperature and hydraulic data were collected every two hours at three sites as shown in Fig. 1. In addition, Water temperatures are also measured at several different places with longer time interval. The streamflow (m^3/s) variation at the upstream site(東和田樋管) is plotted in Fig. 4.

According to the location of the reach, bank topography and the observed vegetation data, the shading factor along the reach is estimated to be 7% by the procedure described in the previous section.

Meteorological data such as wind speed, air temperature, sunshine hours were obtained from Hatoyama AMeDAS station. Since the Hatoyama AMeDAS station is not very close to the study site, this may be considered as a drawback in the current study. Fig. 5 shows the daily variation of the net short wave radiation(W/m^2). The cloudness is calculated with AMeDAS data as following:

$$C_l = \begin{cases} 0.826A^3 - 1.234A^2 + 1.135A + 0.298 & 0 < A \le 1 \\ = 0.2235 & A = 0 \end{cases} \tag{12}$$

where A is the hourly sunshine level based on AMeDAS data. By substitution of eq.(12) into eq.(4), the net short wave radiation can then be computed.

Figure 6 presents both simulated stream temperature (°C) and measured data at the St.1 site for comparison. In this run, the model parameters are selected in the way that the blocking or shading effect of bank stream vegetation is 5% reduction. The simulation is initiated with linear interpolation of measured temperatures at computational boundaries. As can be seen, the simulated peak value of the water temperature appears to be acceptable, the effect of solar shading is appreciable in the afternoon at the study site. The difference in the morning between predicted and measured value may be attributed to the lack of meteorological data at the study site. Now, if assume different percentage of surface coverage by bank vegetation, Fig. 7 indicates that the water temperature daily pattern tends to become flatter with increasing coverage. In other words, the difference between the maximum and minimum water temperature decreases with increasing vegetation shading.

Figure 8 shows the computed long wave radiation, evaporative heat transfer and conductive heat transfer across the stream water surface. The contribution of long wave radiation to water temperature is much larger than that of evaporation and heat conduction. The sensitivity of stream water temperature to the cloudness is given in Fig.9. The maximum water temperature is greatly reduced as the cloudness goes up.

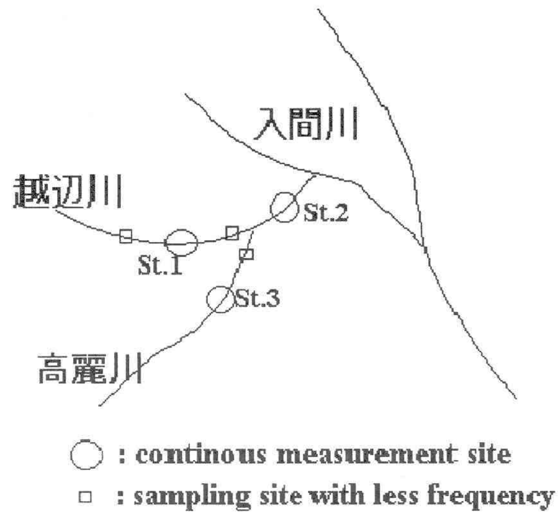

Fig. 2 Schematic of study site

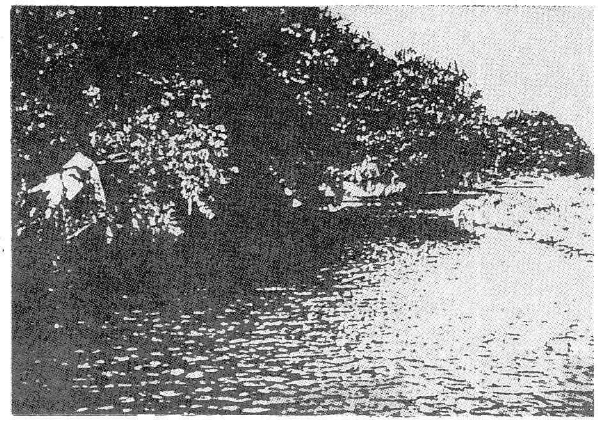

Fig. 3 Bank-side vegetation in Oppegawa

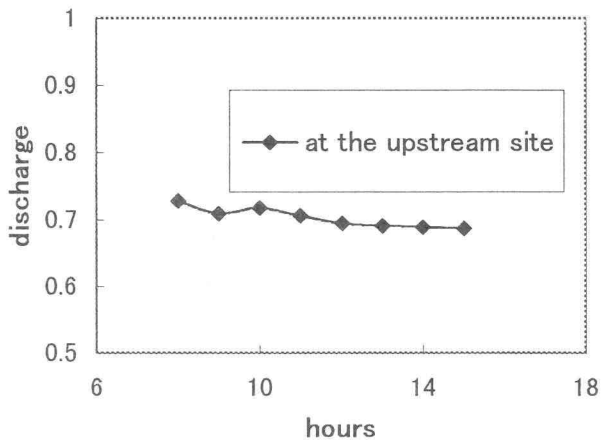

Fig. 4 Streamflow variation with time

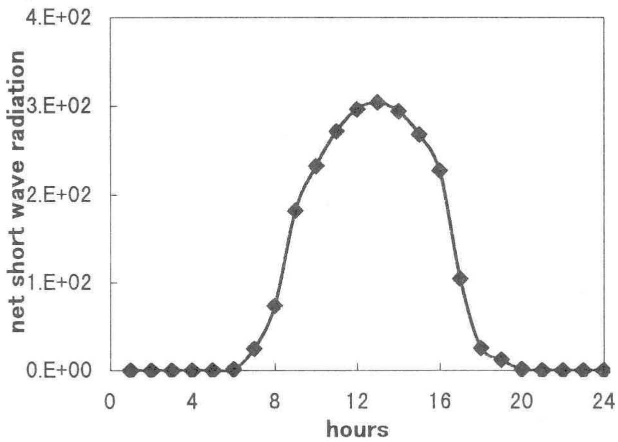

Fig. 5 Net short wave radiation pattern

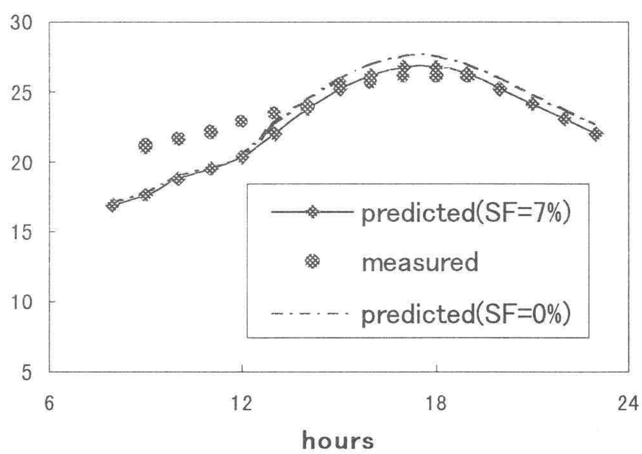

Fig. 6 Comparison between simulated and measured stream temperature at St.1

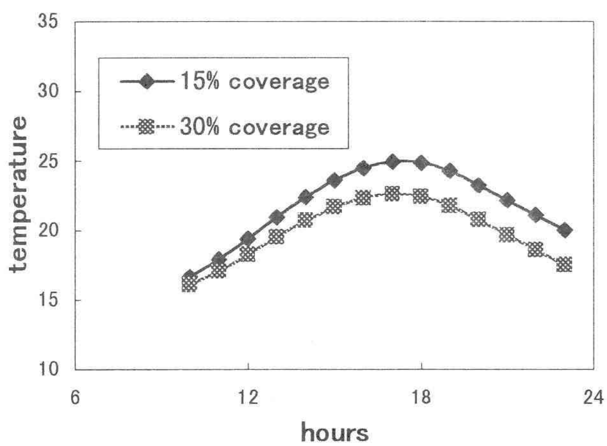

Fig. 7 Stream temperature dependence on bank vegetation

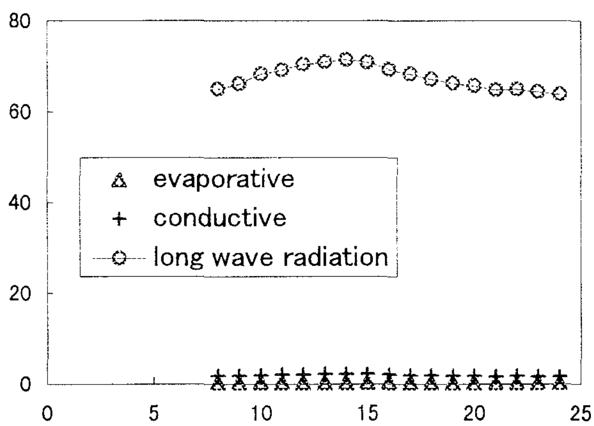

Fig. 8 Relative importance of difference sources

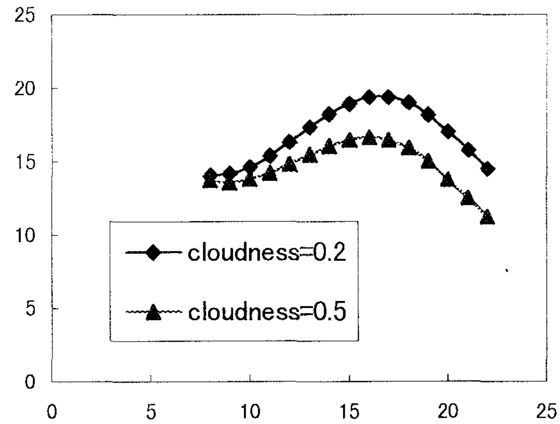

Fig. 9 Sensitivity of water temperature to cloudness

With the riparian vegetation conditions kept constant, Fig. 10 shows how the solar shading factor would vary with the stream orientation. It can be realized from the figure that the shading factor is sensitive to stream orientation when the stream azimuth is between 20 and 60 degree. This finding might be useful in river improving work.

Figure 11 indicates that the solar shading factor decreases in an approximately linear way with the distance between vegetation trunk and the water surface edge.

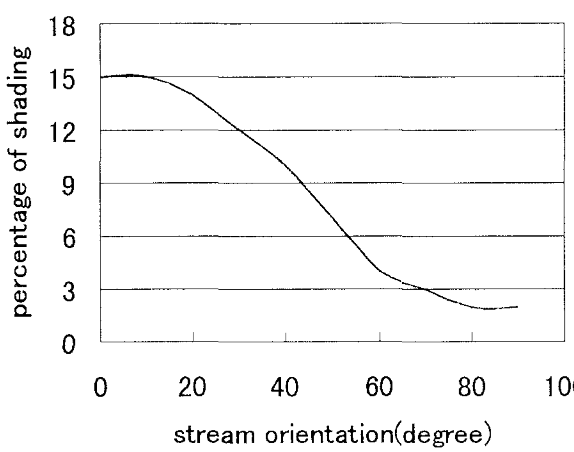

Figure 10

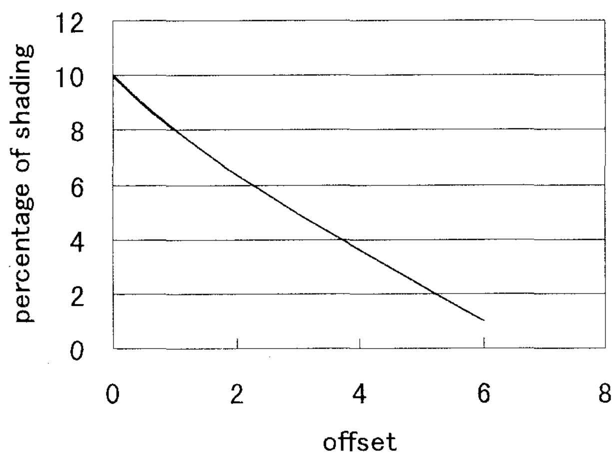

Figure 11

5. DISCUSSION

The governing equation for stream water temperature, given by eq.1, is a nonlinear parabolic partial differential equation. In general, it is not possible to obtain analytic solution of eq.1. However, if assuming that the heat exchange terms (the source terms in eq.1) can be expressed by first or second order approximation, and the stream flow is uniform, a closed-form solution of eq.1 can be derived. The authors are also working on the refinement of those analytic solutions. Nevertheless, this kind of solutions is valid only for stable meteorological conditions. In practice, meteorological conditions and riparian vegetation shading are subject to fluctuations. For predicting stream water temperature under such conditions, it is necessary to resort to the numerical simulation of the problem.

In the present study, a modified version of MNSTREM model is proposed, and applied to a single reach of Oppegawa. The model is able to deal with the solar shading and the wind sheltering caused by local topography and bank-side vegetation. The preliminary results show that the technique to account for bank-side vegetation shading effect outlined earlier is a promising tool for predicting water temperature in small, shallow streams. However, it should be emphasized that it is just the first step toward the development of a comprehensive water temperature model, further refining work must be done. As illustrated by the results of sensitivity analysis, the stream water temperature is very sensitive to meteorological conditions. Therefore, in order to refine the model of stream water temperature, accurate on-site meteorological measurements are indispensable. The numerical results suggest that evaporation and convection seem to play a minor role in the formation of water temperature. Besides, the model output indicates that stream thermal condition can be improved through the manipulation of bank-side vegetation.

During the field measurement, it was observed that there is a difference in habitat use by juvenile and by adult fish. Small, young fish seems to prefer somehow warmer place than grown-up fish. And the avoidance of direct exposure to sunlight seems to be the first choice in habitat selection for grown-up fish. Therefore, it might be postulated that there would be a diurnal change in habitat selection by fish.

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