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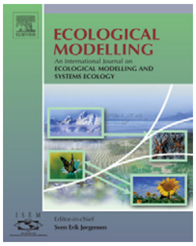

Modification of a stream temperature model with Beer's law and application to GaoShan Creek in Taiwan

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ABSTRACT

A physics-based stream temperature model [Tung, C.P., Lee, T.Y., Yang, Y.C., 2006. Modelling climate-change impacts on stream temperature of Formosan Landlocked Salmon habitat. Hydrol. Process. 20, 1629–1649] was improved by incorporating shading effects caused by both cliff terrain and riverbank dense vegetation to simulate hourly stream temperature variations in 1 day. Daily maximal stream temperature is a critical factor to the habit distribution of the Formosan Landlocked Salmon, an important and endangered species. Currently, it only can be found in ChiChiaWan Creek and GaoShan Creek in Taiwan. The former stream temperature model only considers the shading effects of cliff terrain and works well for ChiChiaWan Creek, but overestimates stream temperatures of GaoShan Creek having dense riverbank vegetative covers. The model was modified with the Beer's law and a parameterization scheme to describe the diminishing of the incident solar radiation to take vegetative shading effects into account. Simulation results of GaoShan Creek show the success of this improvement. The shading effects induced by both terrain and vegetation can significantly affect stream temperature distributions. Simulation experiments were conducted to indicate shading effects are varied in different watersheds and seasons.

1. Introduction

The Formosan Landlocked Salmon is a land-locked species currently only exists in the upstream tributaries of TaChia River in Taiwan (Fig. 1). It is the salmon that can be found at the lowest latitude today, but becomes endangered due to the development of hydraulic structures and the deforestation for agriculture (Tung et al., 2006). The stream temperature is a very important environmental factor affecting the distribution of the Formosan Landlocked Salmon. The favorable water temperature is between 9 and 17 °C (Tzeng, 1999), and 12 °C is the threshold for the spawning period. According to a recent field study (Yang, 1997), the 12 °C isotherm has moved toward upstream for a distance of 1.56 km since 1985. In order to evaluate the impact of natural and anthropogenic changes on this unique species, a stream temperature model is needed to simulate stream temperature distribution.

There have been many studies working on simulating stream temperatures. Brown (1969, 1970a,b) estimated hourly stream temperature based on the energy balance of stream reaches, and concluded that the incident solar radiation is a major component changing stream temperatures and the shading by trees along riverbank has significantly influence on the receipt of radiative heat flux. Crittenden (1978) also concluded wind speed, the thermal properties of the streambed, stream depth, and the amount of shading are the most important variables. Leblance et al. (1997) proposed a physical model to evaluate the effects of land use changes on stream temperature. His study identified three key factors, including the transmissivity and the shadow area of tree cover along river-

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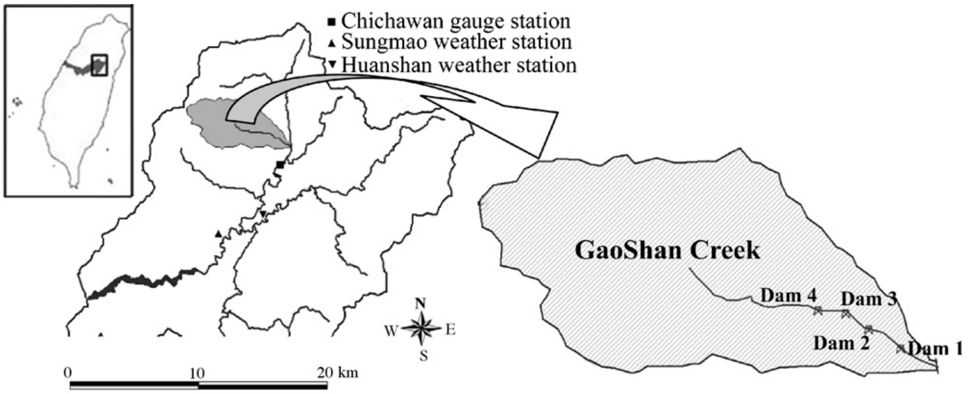

Fig. 1 – The upstream basin of TaChia River and the study area: GaoShan Creek.

bank, groundwater exchange, and the width of river surface area. Air temperature is often applied as an index to describe stream temperature since the heat exchange between air and water is an important process. Stefan and Preud'homme (1993) found hourly and daily stream temperatures are highly related to the variations of air temperature. Krajewski et al. (1982) proposed a graphical technique to predict average stream temperature. Mohseni et al. (1999) also developed a model to describe the relationship between air and stream temperatures. These former studies usually concerned only simple vegetative shading effect or only provide average stream temperature. In this study, we will revise a model to consider both terrain and vegetative shading effect simultaneously. The local study (Yang, 1997) indicates that Formosan Landlocked Salmon is very sensitive to daily maximal stream temperature. Thus, the revised model is developed to simulate diurnal stream temperature for habitat assessment.

A physics-based stream temperature model was developed by Tung et al. (2006) and applied to ChiChiaWan Creek, the primary habit of the Formosan Landlocked Salmon. Only the terrain shading rather than the vegetative shading was considered in their work, because the main reach of ChiChiaWan Creek has wide river surface and cliffy terrain where the influence of vegetative shading is negligible. However the vegetative shading effect might become important to other streams having narrow river valley and dense vegetation, such as GaoShan Creek, the secondary habitat of the Formosan Landlocked Salmon. Thus, the purpose of this study is to integrate the vegetative shading into the former model developed by Tung et al. (2006) for simulating the stream temperature of GaoShan Creek. Besides, the modified physics-based model can simulate both cliff terrain and vegetative shading effects, which makes the model more applicable for other watersheds.

2. Stream temperature model

The stream temperature model developed by Tung et al. (2006) is treated as a foundation in this study. The model was designed to modeling hourly stream temperature under a clear sky condition on a day and the clear sky condition is treated as "the worse scenario" for Formosan Landlocked Salmon. The governing equation of stream temperature distribution is given as (Tung et al., 2006; Kim and Chapra, 1997):

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} = \frac{\partial}{\partial x}\left(D\frac{\partial T}{\partial x}\right) + \frac{q}{A}(T_L - T) + \frac{H_T w}{c_w \rho_w A} + \frac{H_B p}{c_w \rho_w A} \qquad (1)$$

where T is the cross-sectional average stream temperature (°C), u the mean velocity of stream flow (m/s), D the longitudinal dispersion coefficient (m^2/s), T_L the groundwater temperature (°C), q the groundwater discharge (m^2/s), H_T the surface flux of thermal energy (J/m^{2}s), w the surface width of the channel (m), p the wetted perimeter (m), A the cross sectional area (m^2), H_B the stream bed flux of thermal energy or bed conduction, c_w the specific heat of water (J/kg °C), and ρ_w is the density of water (kg/m^3). Eq. (1) can be written as

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} = \frac{\partial}{\partial x}\left(D\frac{\partial T}{\partial x}\right) + \frac{q}{A}(T_L - T) + \frac{H_T + H_B}{c_w \rho_w h} \qquad (2)$$

The digital elevation model (DEM) is used to generate the river network resolving as spatial grids. The surface flux of thermal energy of each grid was adjusted with the terrain shading effect. Terrain shading effect is considered as a dichotomous variable, as shown in Fig. 2. Direct solar radiation is assumed to be zero when incident solar radiation is blocked by mountain. In Fig. 2, the angle θ_T is maximal angle to have terrain shading effect and the angle β is the Zenith angle of the sun. Therefore, the incident solar radiation will be zero until $\beta > \theta_T$. That is the terrain shading effect

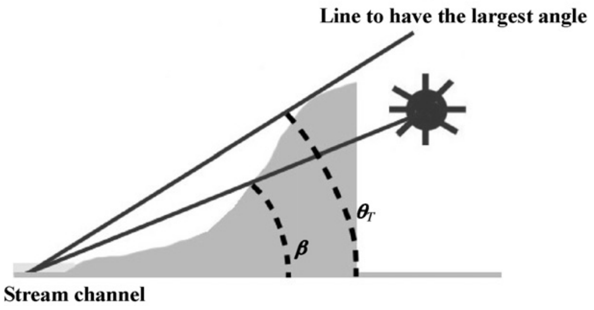

Fig. 2 – Determination of terrain shading effect.

considered in the stream temperature model. The DEM can be used to determine θ_T.

The energy balance in the stream temperature model includes short-wave radiation, long-wave radiation, latent heat, sensible heat, etc. The Crank–Nicolson method was applied to solve Eq. (2), because the method has a property of second-order accuracy in both space and time and is unconditionally stable (Yogesh and Torrance, 1986). It is a popular method applied to parabolic type equations (Kim and Chapra, 1997; Sinokrot and Stefan, 1993). With this approach stream temperature of each grid in every time step can be obtained. The detailed description of model and the equation of radiation balance were given in Tung et al. (2006).

3. The modification of stream temperature model

3.1. *The result of previous model*

The previously described stream temperature model with considering terrain shading effects can provide reasonable predictions for ChiChiaWan Creek which has insignificant vegetative shading effects. However, when the model is directly applied to GaoShan Creek, having narrow river valley with dense riparian vegetation, the model overestimates stream temperatures.

The observed stream temperature data on 3 January 1996 and 7 July 1996 (Yang, 1997) at Dam No.1 of GaoShan Creek were used to represent the diurnal stream temperature for winter and summer seasons, respectively. The meteorological data, including air temperature, relative humidity, atmospheric pressure and wind speed was obtained from the Sungmao and the Huanshan weather stations as listed in Table 1. The hydraulic data were obtained from Yeh et al. (1998–2002). The relationships between flows and the channel width and water depth were developed based on flow records and field measurements of channel geometry in this study as follows:

$$W = aQ^b \tag{3}$$

$$D = cQ^d \tag{4}$$

where a, b, c and d are constants but different for different river segments (listed in Table 2).

Table 1 – The weather and streamflow data for model calibration and validation

Date	3 January 1996	7 July 1996
Maximum air temperature (°C)	18	29.2
Minimum air temperature (°C)	−2	15.6
Relative humidity (%)	77	62
Atmospheric pressure (mb)	643	640
Wind speed (m/s)	1	0.8
Streamflow (cm/s)	1.17	2.3

Table 2 – The hydraulic parameters of GaoShan Creek

Section	*a*	*b*	*c*	*d*
Upstream of Dam No.4	4.46	0.27	0.26	0.50
Dam Nos. 4–3	5.71	0.14	0.20	0.70
Dam Nos. 3–2	4.82	0.26	0.26	0.35
Dam Nos. 2–1	4.22	0.32	0.23	0.54
Downstream of Dam No.1	4.50	0.31	0.24	0.55

The stream temperature model was applied to GaoShan Creek without considering vegetative shading effects. Due to the lack of the observed stream temperatures of the headwater and all grids, the initial and boundary conditions are assumed to be equal to monthly average temperature, because streamflow during low flow period is mainly discharging from groundwater and groundwater temperature is related to air temperature (Todd, 1980). Besides, there is only one gauge station in the study area. Groundwater discharges from each stream segment is assumed proportional to its sub-basin's area since land cover is very uniform in the study area. Sub-basin's area for each segment can be determined based on DEM. The results are given in Fig. 3, which indicates overestimates of stream temperature in two cases, especially in the period from 7:00 am to 5:00 p.m. It is believed that the original model overestimated the solar radiation into the stream surface of GaoShan Creek. The reason of overestimate is that GaoShan Creek and ChiChiaWan Creek have different geographic and vegetative characteristics. The main stream of ChiChiaWan Creek has a wider river valley and close to the

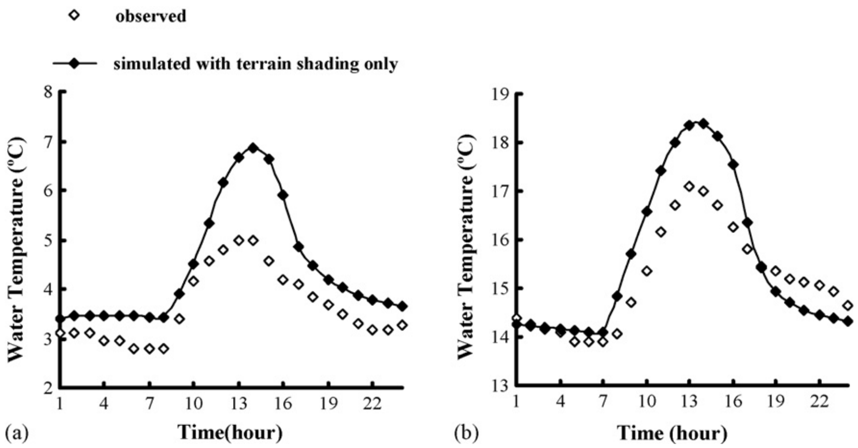

Fig. 3 – The observed stream temperature vs. the simulated stream temperature with only considering terrain shading effect at GaoShan Creek Dam No.1 on (a) 3 January 1996, and (b) 7 July 1996.

cliff. Under this situation, even though there are some plants on the toe of cliff and along riverbank, the vegetative shading effect is insignificant. However, GaoShan Creek has a narrow river valley and dense riverbank vegetation. Thus, when the vegetative shading effect is ignored, stream temperature might be overestimated as shown in Fig. 3.

Theurer et al. (1984) constructed a stream temperature model, SNTEMP, with both topographic and riparian vegetation shadings. However, their works did not model the attenuation of the radiation during a day. Furthermore, SNTEMP model simulates daily average stream temperature. Although it also provides maximum/minimum daily stream temperature, these values are estimated based on an empirical approach. In order to simulate the stream temperature more precisely in each segment of the river during a day, the Beer's law with a parameterization scheme is proposed to estimate the vegetative shading effect and integrated to the previous stream temperature model by Tung et al. (2006).

3.2. *The Beer's law*

When a light passes through a matter, after interception, a quantum may suffer one of two fates: it may be absorbed; or it may be scattered. The beam is said to be "attenuated" by absorption or scattering (Monteith and Unsworth, 1990). The Beer's law is used to describe the attenuation where radiation is absorbed but not scattered when it passes through a homogeneous medium (Monteith and Unsworth, 1990). Suppose that the flux density of radiation at distance x into the medium is $\phi(x)$, the change of radiation intensity at this distance x can be written as

$$\frac{d\phi}{dx} = -k\phi(x) \tag{6}$$

where the constant of proportionality k, described as an "attenuation coefficient", is the probability of a ray being intercepted within the small distance dx. Integrate Eq. (6) gives

$$\phi(x) = \phi(0)\ \exp(-kx) \tag{7}$$

where $\phi(0)$ is the flux density at $x = 0$.

The Beer's law is the most popular equation applied to estimate the solar radiation passing through the atmosphere or the canopy. When the changes of kx are small, Eq. (7) can still give a good approximation of attenuation of broadband radiation with distance (Campbell and Norman, 1998).

3.3. *Estimate of the radiation passing through the canopy*

Monsi and Saeki introduced the application of the Beer's law to describe the light extinction through plant canopies (Larsen and Kershaw, 1996). Since their work, many scientists applied variations of the Beer's law to model the light environment in plant canopies. According to Eq. (7), the Beer's law can be rewritten as

$$R_v = R_0\ \exp(-k\,\mathrm{LAI}) \tag{8}$$

where R_0 is the radiation density on the top of the canopy, R_v the radiation passing through the canopy, k attenuation coefficient and LAI is leaf area index (Campbell and Norman, 1998).

The effect of different canopy structure and scattering was ignored in this study. In Eq. (8), there are three parameters that need to be estimated before applying the Beer's law to describe the attenuation of radiation: including R_0, k and LAI. R_0 can be calculated by Eq. (9) (Tung et al., 2006):

$$R_0 = (1-\alpha_P)I_0\ \sin\beta(1-T_S) \tag{9}$$

where α_P is planet albedo, I_0 a solar constant and β is the elevation of sun in degrees and is equal to $90^\circ - \theta_Z$ (the Zenith angle), T_S is an index for terrain shading. The value of k and LAI were determined based on field measurements, which is described in more detail in the following section.

3.4. *Paramization of vegetative shading effect*

The vegetative shading effect is considered to happen after the terrain shading effect in this study. The relationships between the Zenith angle, the terrain shading effect and the vegetative shading effect are illustrated in Fig. 4. Fig. 4(a) gives an example to show that stream is under the terrain shading when Zenith angle β is smaller than θ_T. Fig. 4(b) shows Zenith angle is larger than θ_T but smaller than the maximal angle to have vegetative shading effect (θ_v, defined in Fig. 5(a), which $\theta_v = \tan^{-1}(H/L)$: L is the distance between the tree and river center, and H is the height of the tree), and thus riverbank vegetation takes over shading effects during this period. The Zenith angle β in Fig. 4(c) is larger than θ_v, and thus the shortwave radiation can reach river surface directly without any shading.

Therefore, attenuation coefficient k, leaf area index LAI, and maximal angle having vegetative shading effect θ_v are three kinds of additional parameters required for the revised stream temperature model. Field measurements are required for determining parameters. It is not realistic to measure these parameters along the river in great detail. Thus, this study suggests dividing a river into several sections, and then estimates these parameters for each section. Then, three kinds of parameters of grids within the same section are assumed the same

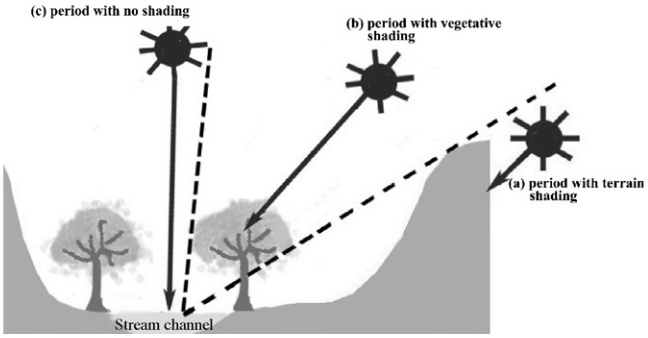

Fig. 4 – The relative position of sun, terrain and vegetation: (a) the period that direct solar radiation is blocked by terrain; (b) the period that solar radiation is blocked by riverbank vegetative; (c) the period that solar radiation directly reaches stream surface.

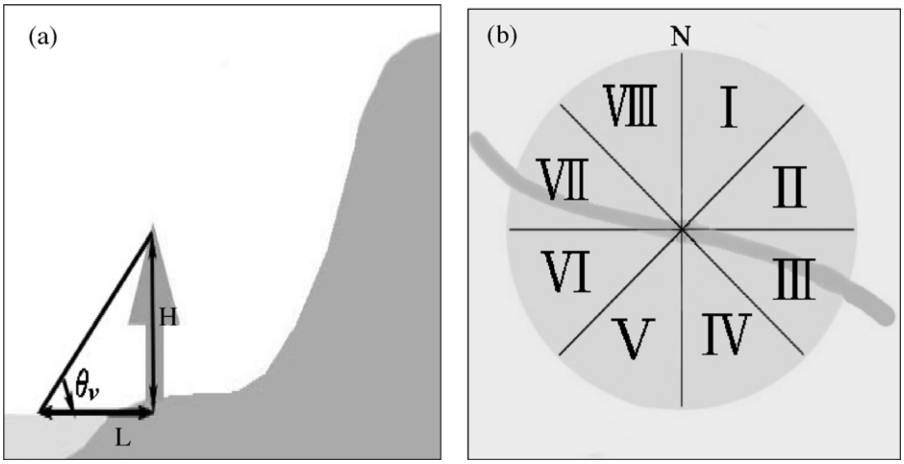

Fig. 5 – The maximal angle to having shading effects (*H* is the vegetation height, *L* is the distance between vegetation and the river center, I–VIII represent different angles for the measurements of θ_v).

in the simulation model. Besides, because Zenith angle is different on a day and in different seasons, an area is divided into eight sub-areas (I–VIII) as given in Fig. 5(b). Then, the θ_v is measured for each sub-area.

In this study, LAI is measured from the field investigation by the equipment of LAI-2000 Plant Canopy Analyzer, produced by the LI-COR Company. This equipment measures the radiation above and below the canopy with a “fish-eye” optical sensor (148° field-of-view). The detail description of the equipment is given in Welles and Norman (1991). The angles of θ_v for eight areas are also measured directly in this study. In each river section, these measurements were done in several points and then averaged. In the stream temperature model, the position and direction of the sun is known during estimating short-wave radiation. Therefore, the position of sun in which direction is known, and it determines which sub-area’s θ_v should be considered. Then, the Zenith angle and θ_v are compared to determine if the radiation is affected by vegetation. In GaoShan Creek, the position of sun is usually in areas III and IV in the morning and areas V and VI in the afternoon.

The dividing points of river section in this study are four dams in GaoShan Creek, which canopy is similar within the same section. The locations of these four dams are given in Fig. 1. The measurements of R_v, θ_v, and LAI have been made at several sample points in each river section and the average values were used for the same section. The flowchart of the revised stream temperature model is given in Fig. 6.

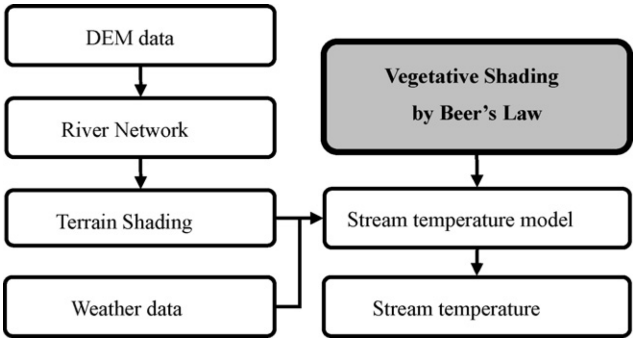

Fig. 6 – The conceptual flowchart of revised stream temperature model.

4. Results of the revised model

The field investigation of GaoShan Creek has been done on 21–23 January 2004. Because riverbank vegetation is not significantly different between winter and summer seasons in the study area, investigation for summer is not further done. The items that have been measured were LAI, R_v and θ_v in eight directions for each section. The average LAI and θ_v in eight directions are given in Table 3. The angle of 90° for θ_v in some directions indicates vegetation totally cover stream surface.

The measurements of radiation above and below canopy can be used to determine the attenuation coefficient, *k*. The

Table 3 – The LAI and maximal angle to have vegetative shading effect in eight directions of GaoShan Creek

Section	LAI	θ_I	θ_II	θ_III	θ_IV	θ_V	θ_VI	θ_VII	θ_VIII
Upstream of Dam No. 4	3.00	83	84	90	90	90	90	70	90
Dam Nos. 4–3	2.42	74.8	86	84	76.5	77.8	66.7	78.5	84.2
Dam Nos. 3–2	2.40	74.4	60.6	74.6	60.9	54.4	73.3	75.1	84.1
Dam Nos. 2–1	2.03	79.8	73.6	63.2	56.2	54.4	59.4	74.4	76.6
Downstream of Dam No.1	2.12	74.1	78.3	58.4	54.9	59.4	51.9	67.7	72.4

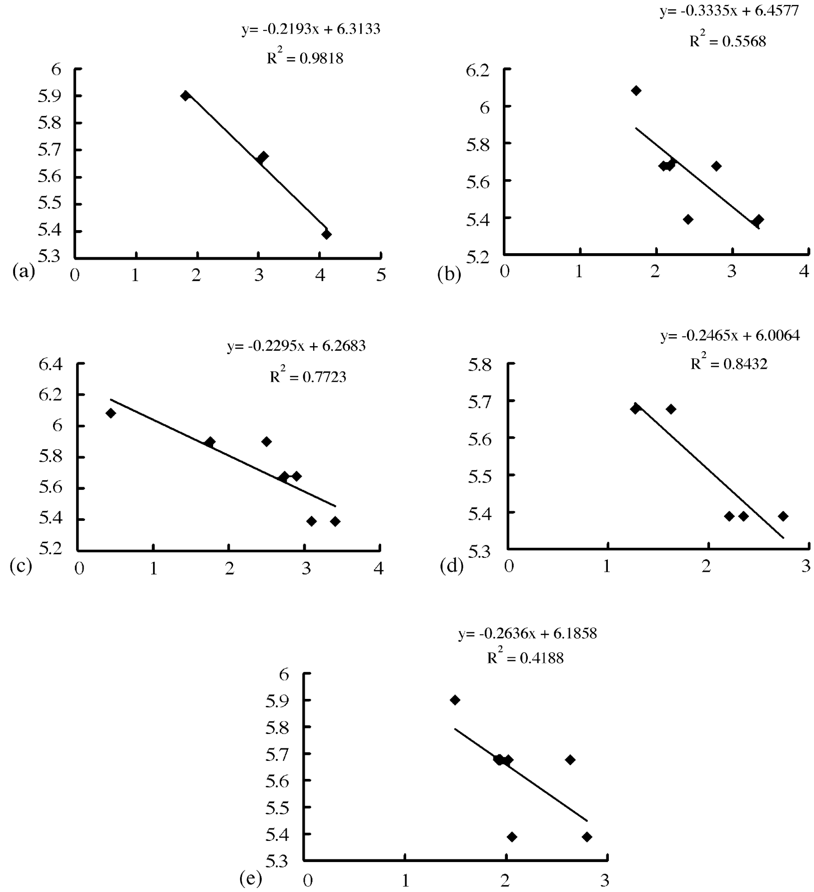

Fig. 7 – The regressive result of LAI and $\ln R_v$ in (a) upstream of Dam No. 4; (b) Dam No.4–3; (c) Dam No. 3–2; (d) Dam No. 2–1; (e) downstream of Dam No.1. The *X*-coordinate represents LAI and the *Y*-coordinate represents $\ln R_v$.

radiation was measured by "NR LITE", the equipment produced by Kipp & Zonen Company. A statistical approach was used to obtain *k* by taking the natural logarithm of both sides of Eq. (8) and finding coefficients of Eq. (10) by regression analysis

$$\ln R_v = \ln R_0 - k\,\mathrm{LAI} \tag{10}$$

The result of regression is given in Fig. 7(a)–(e), which the X-coordinate is LAI and the Y-coordinate is $\ln R_{v.}$ According to Fig. 7, the attenuation coefficients *k* of the five river reaches are 0.2193, 0.3335, 0.2295, 0.2465 and 0.2636, respectively. Since the field investigation was made in winter, the simulation of 3 January 1996 was used for calibration and the summer simulation of 7 July 1996 for validation. The simula-

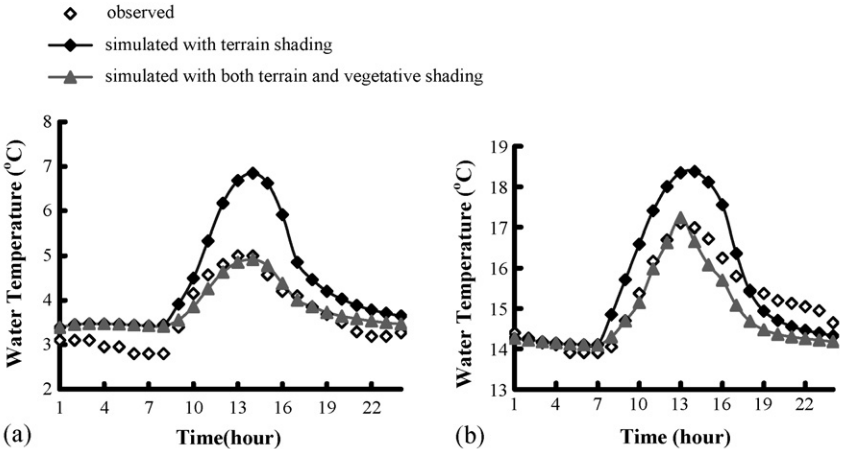

Fig. 8 – The observed stream temperature vs. the simulated stream temperature considered terrain and vegetation cover effect at GaoShan Creek Dam No.1 (a) calibration on 3 January 1996, (b) validation on 7 July 1996.

Table 4 – The differences between simulated and observed stream temperatures in calibration and validation studies

	3 January 1996 (calibration)		7 July 1996 (validation)	
	Terrain shading only (°C)	Both shading (°C)	Terrain shading only (°C)	Both shading (°C)
RMSE	0.93	0.33	0.80	0.49
$\Delta T_{\max}$	1.84	0.80	1.27	0.12

RMSE: root mean square error; $\Delta T_{\max}$: the absolute difference between simulated and observed maximal stream temperature.

tion result of stream temperature model is given in Fig. 8(a) and (b).

According to Fig. 8, when the vegetative shading effect was considered in the stream temperature model, the simulated stream temperature during daytime can be significantly improved to reproduce the observed data. The vegetation can attenuate the incident solar radiation and thus cause lower stream temperature. Meanwhile, because the field investigation was done in the winter, the simulated result 3 January 1996 is little better than 7 July 1996. The RMSE of winter and summer simulation are 0.34 and 0.49 °C, respectively (as shown in Table 4). Because the vegetative shading effect only influences the short-wave radiation, the stream temperature before sunrise has no difference between with and without the vegetative shading effect.

5. Discussions

According to the results, both terrain and vegetative shading effects are the most important factors to influence the incoming solar radiation into the upstream rivers in Taiwan. However, a quantitative analysis on the impact of different shading effect should be able to help us understand more about the stream temperature change on a day.

In this section, comparisons were made between four different simulation scenarios: (1) without any shading effect (WAS), treated as a basis scenario; (2) terrain shading only (TSO); (3) vegetative shading only (VSO); (4) both shading effects (BSE). Fig. 9(a) and (b) are the simulation results of Dam No.1 at GaoShan Creek on 3 January 1996 (winter case) and on 7 July 1996 (summer case), respectively. According to Fig. 9(a) and (b) and taking the result of the WAS scenario as a comparison basis, the BSE scenario causes the most reduction of stream temperature in both seasons. Although Tung et al. (2006) indicated that the vegetative shading effect is not significant in the nearby upstream watershed, ChiChiaWan Creek. According to Fig. 9, the vegetative shading plays a more important role than the terrain shading in GaoShan Creek. However, both shading effects considered can provide the best simulation results.

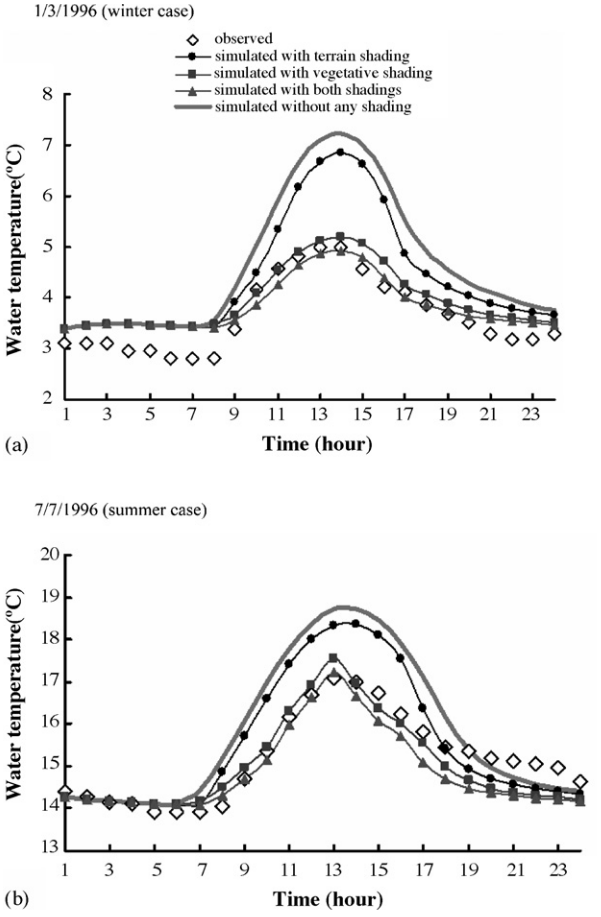

Fig. 9 – The comparisons between four stream temperature simulations at GaoShan Creek Dam No.1: (a) 3 January 1996, (b) 7 July 1996.

Furthermore, the shading effects cause different impacts on the time when stream temperature begins arising (TSA) and the time to reach maximal stream temperature (TSM). According to Fig. 9, the observed TSA is during 8:00–9:00 a.m. and 7:00–8:00 a.m. in winter and summer, respectively. The WAS and TSO scenarios results in the simulated TSA during 7:00–8:00 a.m. in winter and 6:00–7:00 a.m. in summer, respectively, 1 h earlier than observed in both seasons. The two other scenarios with vegetative shading effects predict the same TSA as the observed in both seasons. The shading effects have the same predictability of TSA in the both seasons, but different predictability of TSM. Different shading effects still have the same simulated TSM in winter, but the vegetative shading results in better TSM forecasts in summer. Although the vegetative shading effect is insignificant in the nearby ChiChiaWan Creek, it plays an important role in GaoShan Creek. The terrain and vegetative shading effects may have different influence in different watersheds and different seasons.

6. Conclusions

A physics-based stream temperature model developed by Tung et al. (2006) was further revised to integrate both terrain and vegetative shading effects, and then applied to simulate the stream temperature for GaoShan Creek. Without considering the vegetative shading effect causes the overestimate of stream temperature in GaoShan Creek. The Beer's law and a scheme of parameterizing the vegetative shading effect were incorporated into the model, and the overestimate of stream temperature is improved apparently. A simulation experiment was further conducted to assess the shading effects in GaoShan Creek. The results indicate that both the vegetative and terrain shading effects should be considered for the purpose of best predictability.

Ten parameters for each river section are required for the revised model, including k, LAI, and eight θ_{v} for eight directions. Although the parameters can be calibrated by inverse analysis, it is not recommended. If there are four sections, there will be 40 parameters, which may result in high parameter uncertainty and poor predictions. If parameters are calibrated by inverse analysis, the analysis of parameter uncertainty is strongly recommended. These parameters are suggested to be determined based on field measurements. Before field measurements, prior analysis can be done to reduce the number of parameters. For example, because of the latitude of this study site, the position of sun is usually in areas III–VI. Thus, only θ_{v} in these four areas need to be measured.

The modified model has been verified to provide reasonable diurnal stream temperature simulation for upstream rivers which have both cliff terrain and dense riparian vegetation. Both studies of Sekine et al. (1997) and Wildhaber and Lamberson (2004) indicate that stream temperature is an important index of aquatic environmental condition influencing the distribution of fish population. Thus, well-modelled stream temperature is essential for predicting the distribution of fish population. The modified model in this study can serve as a useful tool for future research, such as evaluating the impact of climate change on stream temperature and further on the distribution of fish population. Besides, the model is a physics-based model, and thus it is expected to work well for other watersheds with their own local parameter estimation.

REFERENCES

Brown, G.W., 1969. Predicting temperatures of small streams. Water Resour. Res. 5 (1), 68–75.

Brown, G.W., 1970a. Predicting the effect of clear cutting on stream temperature. J. Soil Water Conserv. 25 (1), 11–13.

Brown, G.W., 1970b. Effects of clear-cutting on stream temperature. Water Resour. Res. 6 (4), 1133–1139.

Campbell, G.S., Norman, J.M., 1998. An Introduction to Environmental Biophysics. Springer-Verlag New York Inc., New York.

Crittenden, R.N., 1978. Sensitivity analysis of a theoretical energy balance model for water temperatures is small streams. Ecol. Model. 5, 207–224.

Kim, K.S., Chapra, S.C., 1997. Temperature model for highly transient shallow streams. J. Hydraul. Eng. 123 (1), 30–40.

Krajewski, W.F., Kraszewski, A.K., Grenney, W.J., 1982. A graphical technique for river water temperature predictions. Ecol. Model. 17, 209–224.

Larsen, D.R., Kershaw Jr., J.A., 1996. Influence of canopy structure assumptions on predictions from Beer's law a comparison of deterministic and stochastic simulations. Agric. For. Meteorol. 81, 61–77.

Leblance, R.T., Brown, R.D., FitzGibbon, J.E., 1997. Modeling the effects of land use change on the water temperature in unregulated urban streams. J. Environ. Manage. 49, 445–469.

Mohseni, O., Erickson, T.R., Stefan, H.G., 1999. Sensitivity of stream temperatures in the United States to air temperatures projected under a global warming Scenario. Water Resour. Res. 35 (12), 3723–3733.

Monteith, J.L., Unsworth, M.H., 1990. Principles of Environmental Physics. Edward Arnold, London.

Sekine, M., Imai, T., Ukita, M., 1997. A model of fish distribution in rivers according to their preference for environmental factors. Ecol. Model. 104, 215–230.

Sinokrot, B.A., Stefan, H.G., 1993. Stream temperature dynamics: measurement and modeling. Water Resour. Res. 29 (7), 2299–2312.

Stefan, H.G., Preud'homme, E.B., 1993. Stream temperature estimation from air temperature. Water Resour. Bull. 29 (1), 27–44.

Theurer, F.D., Voos, K.A., Miller, W.J., 1984. Instream water temperature model. Instream Flow Information Paper 16. U.S. Fish and Wildlife Service, FWS/OBS-84/15. V.P., Washington, DC.

Todd, D.K., 1980. Groundwater Hydrology. Wiley, New York.

Tung, C.P., Lee, T.Y., Yang, Y.C., 2006. Modelling climate-change impacts on stream temperature of Formosan Landlocked Salmon habitat. Hydrol. Process. 20, 1629–1649.

Tzeng, C.S., 1999. Studies on population ecology of the Formosan landlocked salmon *Oncorhynchus masou formosanus* (II). Construction and Planning Agency, Ministry of Interior, SHEI-PA National Park Management Office, Taiwan (In Chinese).

Welles, J.M., Norman, J.M., 1991. Instrument for indirect measurement of canopy architecture. Agron. J. 83, 818–825.

Wildhaber, M.L., Lamberson, P.J., 2004. Importance of the habitat choice behavior assumed when modeling the effects of food and temperature on fish populations. Ecol. Model. 175, 395–409.

Yang, C.H., 1997. The Effect of the Water Temperature on Taiwan Landlocked Salmon (*Oncorhynchus masou formosanus*) in ChiChiaWan Stream Basin. MS Thesis. NTHU, Taiwan (in Chinese).

Yeh, Z.S., Duan, J.H., Lian, H.B., 1998–2002. An Experimental Study of Channel Habitat Improvement for ChiChiaWan Creek (1)–(5). Construction and Planning Agency, Ministry of Interior, SHEI-PA National Park Management Office, Taiwan (in Chinese).

Yogesh, J., Torrance, K.E., 1986. Computational Heat Transfer. Hemisphere Publishing Corporation, Washington, DC.