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環境變遷對櫻花鉤吻鮭棲地水溫之影響評估〔2/2〕

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計畫主持人：童慶斌

計畫參與人員：潘信宏、李宗祐

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行政院國家科學委員會專題研究計畫成果報告

環境變遷對櫻花鉤吻鮭棲地水溫之影響
The Impacts of Environmental Changes on the Stream Temperature of the Taiwan Salmon Habitat

計畫編號：NSC-91-2313-B-002-318
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主 持 人：童慶斌 副教授 台灣大學生物環境系統工程學系
研究人員：潘信宏、李宗佑 研究生

Abstract: Stream temperature is a very important ecological index. The change of stream temperature might influence growth rate and survival of fish and other aquatic organisms, so many researchers have put emphasis on the study of stream temperature. This research provides a physical model for predicting the impact of climate change on stream temperature, by calculating energy balance. Because upstream watershed in Taiwan is surrounded with high and steep mountains, the influence of mountain shading on solar radiation and long wave radiation is taken into account in this study. The changes of temperature and streamflow were derived from the predictions of four General Circulation Models (GCMs). The result indicates stream temperature decreases 2%~9% in August and increases 4%~14% in November when the concentration of atmospheric carbon dioxide is doubled.

Keywords: Global warming; Taiwan salmon; Water resources; Ecology; Simulation

1. INTRODUCTION

Taiwan Salmon is very important species not only in Taiwan but also for the world, because it is the salmon found in the lowest latitude. Central Mountain divides Taiwan Island into two parts. The rivers in the west flow into Taiwan Straight, while those in the east flow into Pacific Ocean. Scientists believe that Taiwan Salmon swam up river systems from the Pacific Ocean in its spawning long long time ago, which imply that they should be easily found in the eastern river systems, but it is not the case today. Taiwan Salmon is a land-locked specie and currently can only be found in the upstream of TaChia creek, located in the west of Taiwan Island. Thus, the existence of Taiwan Salmon may also represent a story of serious geographical changes in Taiwan.

Taiwan Salmon is very sensitive to water temperature. The suitable stream temperature is between 9~17 ^{o}C [Tseng, 1999], and 12 ^{o}C is the threshold for Taiwan Salmon in spawning period. According to recent survey (during 1985~1997), the isotherm of 12 ^{o}C has moved upstream 1.56 km [Tseng, 1997]. On the other hand, stream temperature more than 17 ^{o}C has been observed in some locations of the habitat in summer.

Global warming due to increasing greenhouse gases has drawn much attention. [IPCC 1995] suggested that air temperature could increase 1.5~4.5 ^{o}C due to global warming. Stream temperature is strongly related to air temperature. Thus, global warming may also danger Taiwan Salmon's habitat.

There has been much research working on the study of stream temperature. Brown [1969；1970a；1970b] estimated hourly stream temperature based on energy balance, and concluded that solar radiation is a major component and that trees cover along riversides may significantly influence receipt of radiation. Leblance et al. [1997] proposed a physical model to evaluate the effects of land use on stream temperature. His study identified three key factors, including transmissivity and shadow area of tree cover along riversides, groundwater, and width of river surface area. Stefen and Preud'homme [1993] developed a relationship between air temperature and stream temperature, which concluded that hourly or daily water temperatures will response to the change of air temperature with some time delay. Mohseni et al. [1999] also developed a model to describe the relationships between air and stream temperatures.

The purpose of this study is to develop a physical model to evaluate the impacts of climate change on stream temperature of Taiwan Salmon's habitat. Steep mountains are along upstream of most rivers in Taiwan. The shading of mountains may be more important than that of tree cover. The model was designed to consider the effects of mountain shading. The model was applied to the ChiChiaWan creek which is an important habitat of Taiwan Salmon.

2. MODEL DEVELOPMENT

The proposed simulation model for stream temperature takes into account not only solar radiation, air temperature, wind speed, etc., but also the effect of shading of surrounding mountains. To evaluate the effect of mountain shading, DTM data were used.

2.1 Stream Network From DTM

Digital Terrain Model (DTM) data can be applied to determine the stream network. The DTM data for Taiwan area can be obtained from Council of Agriculture. There are three steps to determine stream network: (1) Leveling DTM data; (2) Determining flow direction for each grid; (3) Identifying stream network.

2.1.1 Leveling DTM Data

The DTM data may result in unreasonable sinks and peaks, and often cause troubles in determining stream network. Thus, the first step here is to level data. If the height of a grid is lower than or higher than the heights of all grids surround it, the height of the central grid is reassigned as the same as the closest height.

2.1.2 Determining Flow Direction

According to the heights of grids, flow directions for all grids can be determined. The flow of a grid could run to the eight grids surrounding it (Figure 1). By comparing heights of the central grid and surrounding grids, flow direction can be determined and a number is assigned to represent flow directions in computer program. The numbers for eight directions are given as Figure 1. Flowing to more than two directions are allowed.

32	64	128
16		1
8	4	2

Figure 1. Numbering of Flow direction.

2.1.3 Establishment of Stream Network

A unit of uniform overland flow was applied, and then accumulated flow of each grid was estimated to determine stream network. Flow of a grid runs to the lowest height among grids surround it. If there are n grids having the lowest height, the n grids equally receive 1/n flow. A grid was marked as stream channel, if its accumulated flow is more than a given threshold.

2.1.4 Verification

The above procedure to determined stream network was applied to the ChiChiaWan creek. The DTM used is in the resolution of 40m×40m and grids of 300×300. The result of stream network is given in Figure 2. Comparing with map and other digitized stream network by other independent studies, the determined major stream networks are alike. However, quantification analysis was not done, which may bring uncertainty for stream temperature simulation and needs further study.

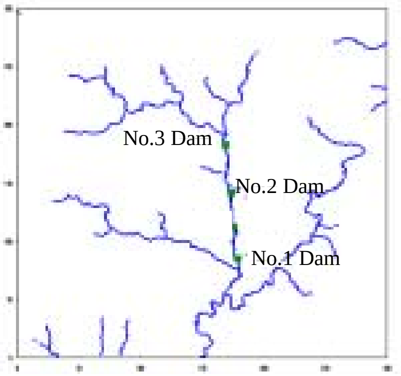

Figure 2. Simulated stream network.

2.2 Energy Balance of Stream Channel

The energy balance was calculated to determine stream temperature. The model was applied to evaluate the impacts of climate change. The statistical relationship between stream temperature and other environmental factors may not still hold in climate change conditions. Thus, the model was developed as a physical model instead of a statistic model. The variation of stream temperature due to the change of received energy can be described as follows.

$$\Delta T = \frac{\Delta H \cdot A}{Q \cdot C_W \cdot \rho_W} \qquad (1)$$

where ΔT is the change of stream temperature (^{o}C); ΔH is the change of receiving energy (W/m^2); A is stream surface area (m^2); Q is stream flow (cms); C_W is heat capacity of water (J/kg ^{o}C); and ρ_W is water density (kg/m^3).

The components of energy balance in stream include net radiation (H_{NR}), conductive heat (H_C), latent heat (H_E), sensible heat (H_H), advection heat (H_A), etc.

$$\Delta H = H_{NR} + H_C + H_E + H_H + H_A \qquad (2)$$

2.2.1 Net Radiation (H_{NR})

Net radiation, one of the most important factors, can be determined from short-wave radiation (R_S) and long-wave radiation (R_L), which can be written as $H_{NR} = R_S + R_L$ in the unit of W/m^2.

2.2.2 Short-Wave Radiation (R_S)

Solar radiation is major energy source for ecological system. The received short wave radiation was described as

$$R_S = (1-\alpha_P)(1-\alpha_W)S_0 \cdot \sin\beta \cdot (1-M_S) \quad (3)$$

where α_P is planet albedo, α_W is water albedo, S_0 is a solar constant (1362 W/m^2), M_S is an index for mountain shading, and β is the elevation of sun in degrees. The value of β is equal to 90^o - θ_Z that θ_Z is zenith angle. The value of α_W depends on β, and can be estimated as in Anderson [1954].

The position of sun, described by zenith angle (θ_Z) and azimuth angle (θ_A), depends on time in a day, date in a year, and latitude. The θ_Z and θ_A can be determined as Jansen [1985].

The method to consider mountain shading is shown in Figure 3. Direct short wave radiation is assumed to be zero when incoming solar radiation is blocked by mountain. In this case, the value of M_s in equation (3) is assumed to be 1. Otherwise M_s=0. The value of M_s depends on the elevation of sun (β) and the maximum angle (θ_S) determined by stream channel and mountain in the direction to sun.

$$M_S = \begin{cases} 1 & if\ \theta_S \geq \beta \\ 0 & otherwise \end{cases} \quad (4)$$

2.2.3 Long Wave Radiation (R_L)

Long wave radiation includes downward (L_D) and upward radiation (L_U). The upward long wave radiation is emitted by the water body, while downward long wave radiation is emitted by atmosphere (L_A) and surrounding trees and mountains (L_T).

Radiation emission can be described by Stefan's Law. Water is a gray radiation body and its emitting radiation is given as

$$L_U = -\varepsilon \cdot \sigma T_W{}^4 \quad (5)$$

where negative sign on the right side is to represent outgoing energy, ε is effective emissivity and the value of 0.98 [Leblance et al., 1997] was used in this study, T_W is water temperature (K), and σ is Stefan-Botzman Constant ($5.67\times10^{-8} W/m^2\ K^4$).

The received atmospheric long wave radiation is modified by sky visible fraction (SVF). By considering SVF, L_A can be determined as equation (6). The value of SVF can be determined from DTM data.

$$L_A = SVF \cdot \sigma T_A^4 \quad (6)$$

Surrounding mountains are considered as a gray body, its emitting radiation (L_T) is given as

$$L_T = F \cdot \varepsilon\sigma T_A{}^4 \quad (7)$$

where F is a shape factor and can be determined as equation (8).

$$F = \int \cos\theta_W \cdot \cos\theta_T \frac{1}{\pi \cdot r^2} dA_T \quad (8)$$

where dA_T is surrounding area, θ_W, θ_T, and r is shown in Figure 4.

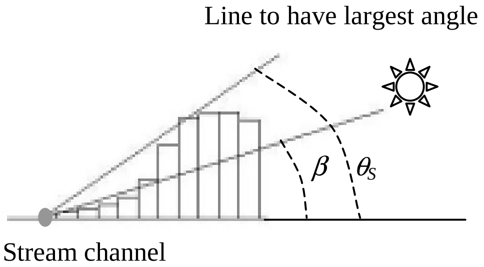

Figure 3. Mountain shading.

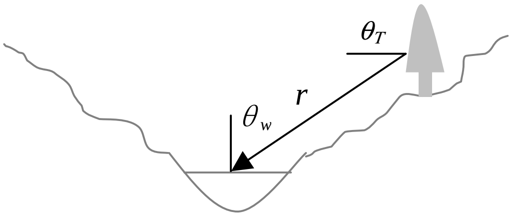

Figure 4. The relationships between θ_W, θ_T, and r.

2.2.4 Conductive Heat (H_C)

Conductive heat is to describe the energy exchange between the water and the streambed. This item is omitted in this study, which may bias the simulation results and needs further study in future.

2.2.5 Latent Heat (H_E)

Latent heat is used to vaporize water from liquid phase to gas phase, and can be estimated from the equation of evaporation(Edinger et al. [1974]). However, suitable equations for the local area may need further testing.

$$H_E = \left(25.3 + 1.27 \cdot U_W{}^2\right) \cdot \left(e_s - e_a\right) \quad (9)$$

where e_s is saturated vapor pressure, e_a is air vapor pressure, U_W is wind speed.

2.2.6 Sensible Heat（H_H）

Sensible heat can be determined by latent heat and Bowen Ratio (B), i.e. $H_H = B \times H_E$. The value of B can be estimate as

$$B = 0.61 \cdot \frac{P}{1000} \cdot \left(\frac{T_W - T_A}{e_s - e_a}\right) \tag{10}$$

where P is air pressure (mb), T_W is water temperature and T_A is air temperature.

2.2.7 Advection Heat (H_A)

Advection heat includes energy brought by rainfall, overland flow, upstream flow, and groundwater discharge. The purpose of this study is to estimate critical condition of stream temperature, which normally happens in a no-rainfall period. Thus, the advection heat brought by rainfall and overland flow can be omitted. To estimate advection heat due to channel flow, a stream is divided into several sections. The energy received in previous section and previous time step is brought to downstream sections in later time steps.

3. VERIFICATION

The proposed model was applied to the ChiChiaWan creek for verification. The research area and adopted environmental and meteorological data were addressed as follows.

3.1 Study Area

The ChiChiaWan Creek, located on latitude between 24°20' and 24°25'north and longitude between 121°10' and 121°20' east. The length and area are 15.3 km and 56 km^2, respectively. The average annual streamflow, 5.4 cms, is measured at ChiChiaWan station. Streamflow is significantly different in wet (May through October) and dry seasons (November through April).

The land uses of the ChiChiaWan watershed include natural forest, artificial forest, meadow, fallow, tea garden, orchard. Forest occupies 88.4% of this watershed, meadow and fallow 10%, and orchard and tea garden 1.5% [Tung and Lee, 2001]. Taiwan Salmon are present in the stream.

3.2 Required Data

The required data are weather data and streamflow, which were taken from SungMao, HuanShan weather station and ChiChiaWan gauge station, respectively.

The weather data were used to calculate energy balance, for which temperature, relative humidity, atmospheric pressure and wind speed were required. The former three are derived from historical weather data of SungMao station, and the last one is derived from HuanShan station. In order to know the variation of water temperature during extreme conditions, a no-rainfall period 8/3/1997~8/5/1997 was chosen. The weather data during the period is shown in Table 1.

Table 1. Weather data, 8/3/1997~8/5/1997.

	8/3	8/4	8/5
Highest temperature (^{o}C)	27.0	27.0	27.2
Lowest temperature (^{o}C)	15.8	15.1	17.8
Relative humidity (%)	81	78	78
Atmospheric pressure (mb)	639	640	639
Wind speed（m/s）	0.7	1.6	0.9

Water temperature was simulated for the stream channel between the dam of No.1 and No.3 in ChiChiaWan Creek (See Figure 2). There are different flow velocities, widths of river, and retention times because of the distribution of dams. The hydrological data for the stream channel is given in Table 2 [Yang, 1997].

Table 2. Hydrological parameters in different reach.

	Grids	Length (m)	Velocity (m/s)	Retention time (min)	Width (m)
Dam of No.3	21573				
		1740	45.6	38.2	3.0~3.5
Dam of No.2	24969				
		1859	36.7	51.7	4.5~5.2
QuanYuTai	28859				
		750	42.7	17.6	5.8~6.7
Dam of No.1	29852				

To estimate change of temperature for a stream section, one needs to know streamflow. However, there is no recorded streamflow for all the river section. Thus, streamflow of a section to flow recorded by a gauge station is proportional to the catchment of the river section to the catchment of the gauge station. The areas of the catchment of river section and gauge station can be derived from DTM data. The grids representing areas for different river section are given in Table 2. The recorded flows in the simulation period in SungMao gauge station are 2.65, 2.53, and 2.41 cms, respectively.

The recorded hourly stream temperature was provided by Dr. Tseng. The lowest water temperatures were used to represent groundwater temperature, and considered to be the same under climate change conditions.

3.3 Validation

This research emphasises the variation of stream temperature of the ChiChiaWan Creek. The reach between the dam of No.1 and No.3 was one of the main habitats of Taiwan Salmon. The ChiChiaWan Creek between the dam of No.1 and No.3 was separated to three reaches by the dam of No.2 and QuanYuTai. The simulated stream temperatures before dam No.2 and No.1 are plotted in Figure 5 and 6.

The simulation between the dam of No.3 and No.1 was started with the water temperature of the dam of No.3 (upstream) and calculated toward the dam of No.1 (downstream). The result revealed that during 8/3/1997~8/5/1997 the highest water temperature of the dam of No.2, QuanYuTai and the dam of No.1 were about 16.2~16.4 ^oC, 17.7~18.0 ^oC, 18.4~18.8 ^oC, respectively. With the comparison of the highest simulated and recorded stream temperatures, the differences at the dam of No.2 and No.1 are 0.6~1 ^oC and 0.1~0.5 ^oC, respectively. The simulated water temperatures of the reaches during night were underestimated. However, the trend of simulated and measured stream temperature over time are close. The correlation coefficients of simulated and measured water temperature of the dam of No.2 and No.1 are 0.98 and 0.95, respectively. It can be concluded that the proposed model can reasonably predict the change of the water temperature.

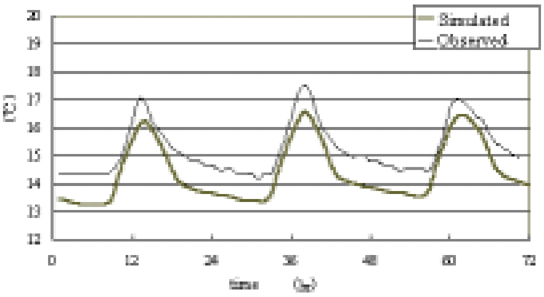

Figure 5. Simulated and observed stream temperature of the dam of No. 2.

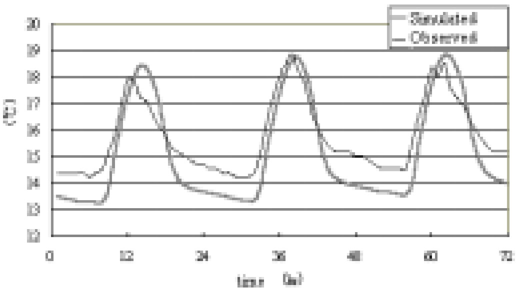

Figure 6. Simulated and observed stream temperature of the dam of No. 1.

4. CLIMATE CHANGE IMPACTS

The climate change impacts on stream temperature may be due to the changes of energy terms and streamflows. The higher air temperature implies more atmospheric energy and thus more energy input to water. On the other hand, the higher air temperature may cause more evaporation and tends to cool stream temperature. Besides, according to Tung and Lee [2001], climate change may cause higher flows in wet season and lower flow in dry season in the ChiChiaWan, which may further impact stream temperature.

4.1 Climate Change Scenarios

Four General Circulation Models' predictions, including CCCM, GFDL, GISS, and UKMO were adopted to setup climate change scenarios. These scenarios represent possible future climate when atmospheric CO_2 is doubled. The same scenarios were used by Tung and Lee (2001), and the changes of streamflow due to climate change was taken from their study directly.

Taiwan Salmon could only survive in the water under 17°C and require even lower temperatures during spawning time. Two critical periods were chosen as study periods. One was in August which may have the highest stream temperature, and the other was in November which is the period of spawning.

Stream temperature would be affected by air temperature and streamflow under different climate change scenarios. The predicted changes of mean air temperature and streamflow are given in Table 3. The changes of temperature were added to current recorded temperature, while the current recorded streamflows were multiplied by the change of streamflows.

Table 3. Changes of temperature and streamflow.

	Temperature (°C)		Streamflow (%)	
	August	November	August	November
CCCM	1.75	2.39	19	-21
GFDL	2.12	2.77	31	-5
GISS	4.18	3.72	24	-5
UKMO	2.74	2.25	15	-3

4.2 Results

Substituting the modified air temperature and the streamflow of different climate change scenarios into the simulation model, the results are shown in Table 4. The results indicate that the change of streamflow in August is different from in November. In August, the increase of air temperature and streamflow results in the decrease of water temperature about 2%~9%. In November, the increase of air temperature and the decrease of streamflow results in the increase of water temperature about 4%~14%. Because the climate change impacts on the temperature of groundwater discharge was not considered in this study, the change of stream temperature may be underestimated..

Table 4. The changes of stream temperature.

	August	November
CCCM	-5%	12%~14%
GFDL	-9%~-8%	6%
GISS	-4%~-3%	7%
UKMO	-3%~-2%	4%

5. CONCLUSIONS AND SUGGESTIONS

This research used the concept of energy balance to build a physical model to simulate stream temperature. The model uses DTM data to evaluate the effects of mountain shading. Through verification, the model was able to provide reasonable simulation, and thus may be used to assess the impact of climate change for four climate change scenarios. The results revealed that stream temperature might decrease 2~9% in August and increase 4~14% in November.

In August, the increase of streamflow reduces the increase of stream temperature due to increasing air temperature, but it would cause more sediment and would washout more small fishes downstream during flood periods. More sediment may deposit on the streambed and then reduce the suitable habitat for spawning. In November, the increase of stream temperature would cause serious damage to Taiwan Salmon's spawning. These issues need more attention.

This study identifies the importance of climate change impacts on the Taiwan Salmon's habitat. More research should be undertaken to refine the impact assessment and to identify adaptation strategies. The most import would be to develop a model to evaluate the impacts of climate change on groundwater. With the increase of air temperature, the increase of groundwater temperature could be expected, which may significant increase stream temperature. The climate change impact on groundwater temperature and further on stream temperature was not included in this paper, and needs further study in future.

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