AN ANALYSIS OF RIVER WATER TEMPERATURE VARIATIONS AT DIFFERENT TIME SCALES

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In this study, water temperature variations at the Nagaoka gauging station of the Shinano River are analyzed within different time framework. It is found that the daily maximum, daily mean and daily minimum air temperatures are good indicators of the daily maximum, daily mean and daily minimum water temperatures at yearly scale. But the relationships between air and water temperatures depart from linearity on monthly or shorter time scales. It is also shown that the 7-day moving averages of daily maximum water temperatures are linearly correlated with the 7-day moving averages of daily mean water depths over seasonal base. Besides, the issue of temperature sampling frequency is explored. It is revealed that one sampling per day in the morning may be able to capture the overall variation pattern of water temperature. Finally, the influence of upstream control upon downstream water temperature is discussed in light of diurnal change of water temperature.

Key Words : *Water temperature, diurnal variation, time scale(or base), correlation, Shinano River*

1. INTRODUCTION

The temperature of river water affects the integrity of a river ecosystem. A variety of human activities such as channelization, impoundments, forest cover removal, irrigation and industrial discharge can lead to significant changes in water temperature regimes and that the effects are often cumulative. Permanent shifts in temperature regimes can render formerly suitable habitat unusable for native species[1)]. For instance, elevated peak summer water temperatures may reduce or even eliminate salmonid feeding in some streams, increase harmful metabolic effects, and increase the feeding activity of fish that prey on juvenile. Therefore, it is not possible to protect or restore river ecosystems without maintaining appropriate temperature regimes.

Despite the important role played by water temperature, the effects of watershed development and river engineering works on water temperature have received much less attention than what it should be. 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 engineering works is becoming stronger. Thus, a full understanding of water temperature to various drivers is essential to proper river management.

The present study provides an analysis of water temperature variations on various time scales. Particular attention is given to how air-water temperature relationships vary with temporal framework. The objective is to better understand time scale effects upon water temperature responses to external drivers. It also attempts to address the issue of what effect does sampling frequency have on our ability to capture the essential features of water temperature dynamics. Besides, discussions are provided to shed new light on the impact of upstream control on downstream water temperature.

2. STUDY SITE

The Shinano River is the longest river in Japan, which runs through both Niigata and Nagano prefectures and flows into the Sea of Japan. The area of the Shinano basin is 11,900km^2. The present study investigates water temperature characteristics at the Nagaoka hydrological gauging station, which is about 70 km from the river mouth, N 37^{0}26'44" in latitude and E 138^{0}50'28" in longitude. The Shinano River Office manages the measurement of hourly water temperature data at the Nagaoka gauging station. Continuous recording of hourly water temperature data may be credited as a pioneering administrative step in the river management practice of Japan. For the purpose of confirmation, we measured the water temperature distributions in both transverse and vertical directions at the Nagaoka station in the summer of 2003, and no significant difference was detected. Therefore, one point measurement at the site is justifiable.

3. WATER-AIR TEMPERATURE CORRELATIONS

Figure 1 illustrates a normal pattern of diurnal variation of water temperature. It rises in the morning, reaches its peak in late afternoon, then cools down at night. Fig.2 shows the diurnal variation of water temperature at the Nagaoka station on May 1, 2003. It deviated from the normal pattern in a way that the water temperature did not decrease at night. This diurnal pattern repeated continuously for a week, and it totally appeared on 50% days approximately in May 2003.

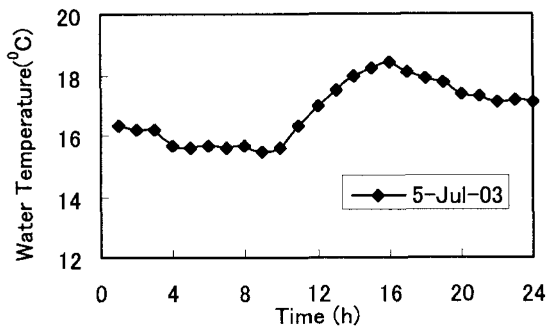

Fig.1 A normal water temperature pattern.

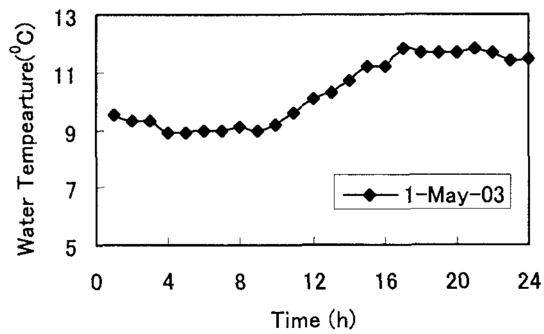

Fig.2 An anomaly water temperature variation.

Fig.3 shows the diurnal variations of both air and water temperatures at Nagaoka for the first week of May. The meteorological data for Nagaoka are obtained from the Nagaoka Local Meteorological Observatory, which is about 1.5 km away from the Nagaoka hydrological gauging station. As seen in the figure, the air temperatures varied in a normal way. The correlation coefficient between hourly air and water temperatures during that week is as low as 0.3. This indicates that air temperature is not a good indicator of water temperature at hourly base. It is because that the hourly variation of water temperature depends on a number of factors such as solar radiation, wind speed, and flow conditions.

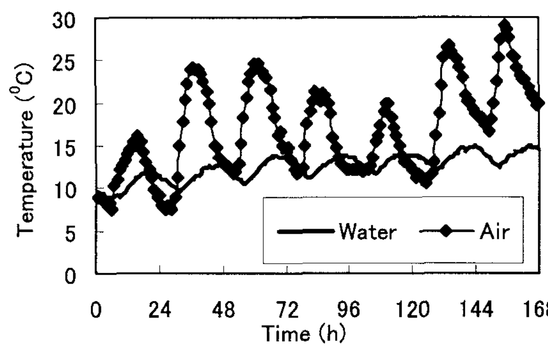

Fig.3 Variations of water and air temperatures.

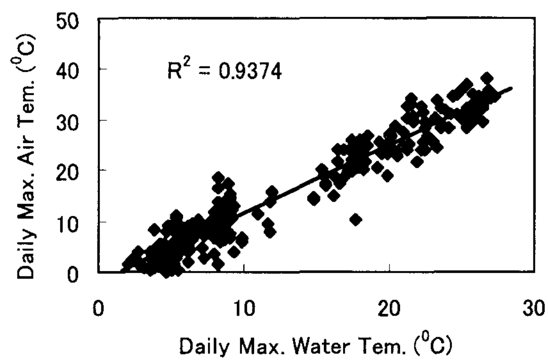

Fig.4 Daily maximum water-air temperature correlation at yearly base.

Although air temperature can not directly explain diurnal variation of water temperature, Fig.4 shows that the daily maximum water temperatures are well correlated with daily maximum air temperatures for the period from July 2002 to July 2003. However, if the data are plotted over the summer season of 2002 or at the monthly time base (July 2003), one can see from Fig.5 that daily maximum water temperatures become less correlated with daily maximum air temperatures. This implies that the daily maximum air temperatures may tell the general variation pattern of daily maximum water temperatures at a yearly base, but it does not work as a surrogate for daily maximum water temperature at shorter time span due to local and short-term disturbances. River water temperature variations are best determined through energy budget analysis[2]. However, in the absence of detailed energy balance data, air-water temperature correlations may be used to estimate water temperature from the more accessible air temperature. In light of the dependence of correlation strength on temporal scale, at least one-year air and water temperature data at a representative site should be collected in order to achieve accurate spatial interpolation.

If 7-day moving averages of daily maximum water and air temperatures are taken, Fig.6 indicates that the moving averaged daily maximum water and air temperatures are well correlated on seasonal scale.

Figures 7 and 8 show the correlations between the mean and minimum daily water and air temperatures, respectively, for the period from July 2002 to July 2003. Similar to daily maximum temperature, the minimum water-air temperature relationship is linear on annual scale, but significant departures from linearity are observed on monthly scale. Smith[3] showed that regression relationships between daily minimum water and air temperatures tend to be more scattered than those for mean or maximum values. However, the present study indicates that it is only true over short time span, the correlation coefficient could be as high as for mean or maximum values as temporal scale increases from monthly to annually.

Similar to air-water relationship, the water temperatures are also not correlated with water depths at hourly base. Fig.9 shows that the 7-day moving averages of daily maximum water temperature and daily mean water depths during the summer of 2002. The moving average values of daily maximum water temperature are inversely related to the average values of daily mean water depth. The correlation coefficient is –0.82. It can also be noticed that when the water temperature reaches to 25^{0}C, it becomes less sensitive to water depth. This may be attributed to the fact that high water temperature enhances back radiation from the water surface. This suggests that at high temperature range, maximum water temperatures might be more weather-dependent than flow-dependent.

If water temperature varies sinusoidally over a day, the relationship between the daily maximum, mean and minimum temperatures will be

$$T_{\max} = 2T_{mean} - T_{\min} \qquad (1)$$

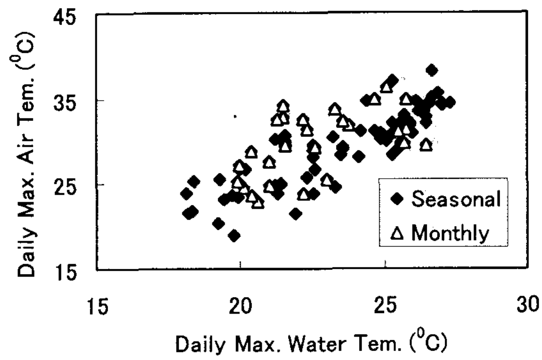

Fig.5 Water-air temperature relations over a season and over a month.

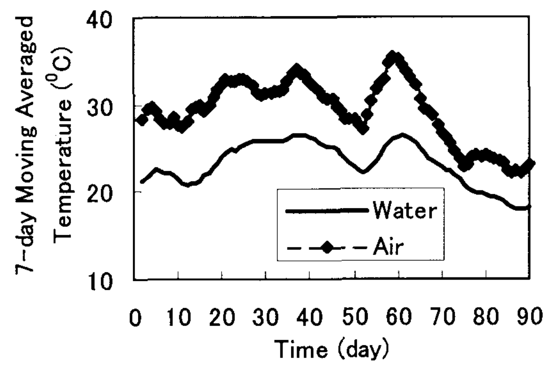

Fig.6 Correlation between 7-day moving averages.

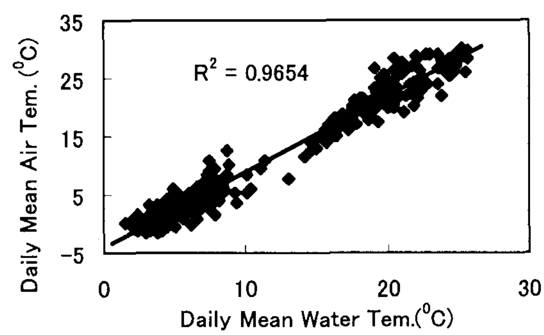

Fig.7 Daily mean water-air temperature correlation at yearly base.

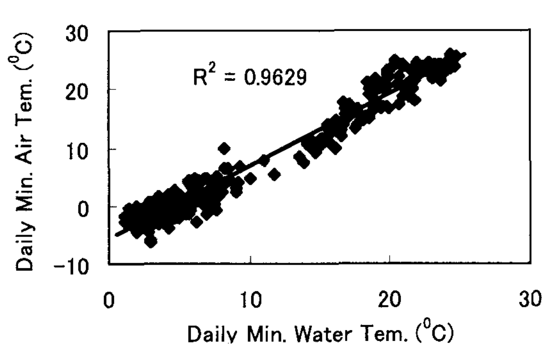

Fig.8 Daily minimum water-air temperature correlation at yearly base.

By performing multiple regression analysis with hourly data from June to July of 2003, the relationship at the Nagaoka station is found to be

$$T_{\max} = 2.5T_{mean} - 1.5T_{\min} \qquad (2)$$

The difference between Eq.(1) and (2) may be used to describe the degree of deviation of actual temperature variations from sinusoidal form.

Figure 10 indicates that the rate of change of daily mean water temperature may depend on the difference of daily mean air and water temperatures.

$$\frac{\partial T_w^m}{\partial t} \sim \ln(T_a^m - T_w^m) \qquad (3)$$

4. TEMPERATURE SAMPLING FREQUENCY

For the purpose of protecting natural water temperature regimes in streams or rivers, a well-designed, reliable monitoring system should be installed as a first step. However, the current water temperature sampling interval in most major rivers of Japan is once a month except a few stations where more frequent sampling has begun recently[4]. For example, at the Uonumabashi gauging station in the middle reach of the Shinano River, the monthly temperature measurements were often taken around 20th, and the sampling time was about 10:00AM. If this sampling protocol is applied to the Nagaoka station, and the spot measurements are compared with the monthly averages obtained from hourly records, some results are shown in Fig.11. It can be seen clearly that the monthly spot samplings provide no information on the actual monthly maximum and minimum water temperatures, although they might be close to the actual monthly mean values by chance.

Then, the usefulness of one sampling per day is examined. As shown in Fig.12, a sampling at 10:00AM per day allows one to capture the overall variation pattern of the daily mean water temperature on weekly, monthly and yearly scales. However, the absolute values should be used with caution because the difference could be ±2°C. The cause of the difference can be attributed to the deviation of diurnal variation from sinusoidal form. This finding may be used to design a cost-effective water temperature sampling protocol if the detection of temperature variation trend is the main focus.

5. INFLUENCE OF UPSTREAM CONDITION

An important issue in studying in-stream thermal environment is the determination of water temperatures downstream of a point heat source. A conventional model for waste heat discharge may be written as Eq.(4)

$$\frac{\partial \delta T}{\partial t} + U\frac{\partial \delta T}{\partial x} = -\frac{K}{\rho C_p H}\delta T \qquad (4)$$

where δT is temperature excess over the natural state; H is mean depth, ρ is water density and C_p is

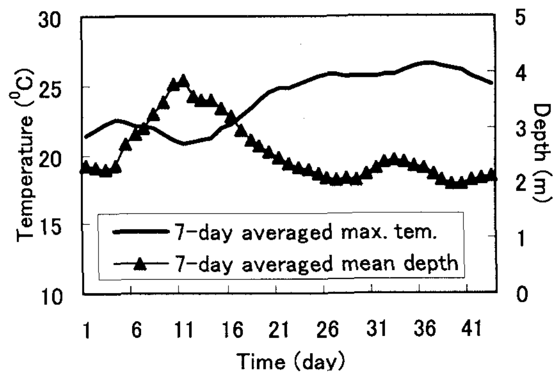

Fig.9 7-day moving averages of daily maximum water temperature and daily mean water depths.

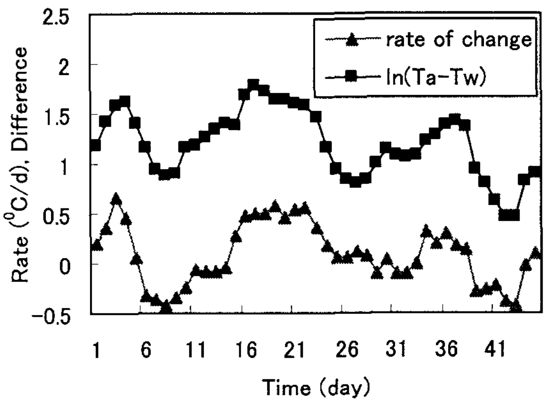

Fig.10 5-day moving averages of the rates of change of daily mean water temperature and the logarithms of air-water temperature differences, in the summer of 2002.

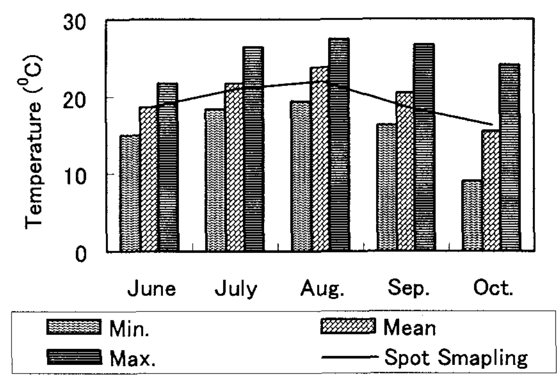

Fig.11 Comparison of monthly sampling with true monthly maximum, mean and minimum values.

specific heat of water. K is termed as the surface heat exchange coefficient, which characterizes the decay of heat load below the source; It can be easily derived that $\delta T = \delta T_0 \times \exp(-Kx/U\rho C_p H)$. Edinger[5] suggested a formula for the estimation of K

$$K = \frac{\rho C_p \pi H}{12\tan(\frac{2\pi\tau}{24})} \qquad (5)$$

where τ is the time lag between maximum water temperature and maximum solar radiation.

The typical summer value for K is 30 $Wm^{-2}\,{}^0C^{-1}$ as reported by Edinger[6]. In the Shinano River, however, the time lag may reach to 6 hours as illustrated in Fig.13. This can be attributed to the high heat capacity of large river. Therefore, the value of K in the Shinano River could be as low as 0.15 $Wm^{-2}\,{}^0C^{-1}$. Consequently, heat load might decay very slowly in such a situation although it follows an exponential law. The impact of time lag on the decay rate and its ecological implication deserve further in-depth study.

Dam may act as an upstream control to downstream water temperature through its water release. Depending on the depth where water is drawn from the reservoir, the downstream water temperature can vary in a wide range. The water temperature could be too warm for cold-water fish to reproduce if the water is drawn from the surface layer of a reservoir, while it could be too cold for warm-water fish to grow if the water is drawn from the bottom layer. Theoretically, dam might be operated to provide desirable water temperature by installing selective withdrawal device. However, the impact of dam operation may be far more complicated than what had been thought. A big question is what would be the temperature goal for downstream reach in determining the operation of selective withdrawal device. For protecting Sweat Fish (Ayu) from suffering from the so-called cold-water disease, and controlling river turbidity, selective withdrawal devices in many dams across Japan have been often operated to draw water from closer to the reservoir surface[7]. The consideration for Ayu is important, but the flourish of Ayu does not guarantee the well-being of the entire river ecosystem. Indeed, there are many other aquatic lives those prefer low temperature than Ayu in streams or rivers where dams are constructed. Therefore, the dam operation is a dilemma between concerns for different species at different life stages.

Figure 13 shows the water temperature variations with depth from May to September in 2002 within the reservoir of Y dam, which is located in the central region of Japan. So far, the dam has been operated to release water from the surface layer

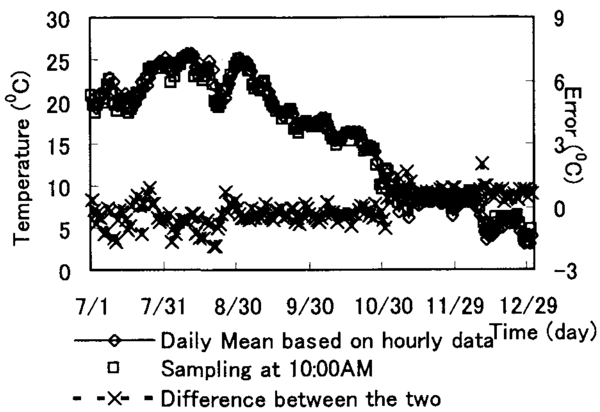

Fig.12 Reliability of one sampling per day.

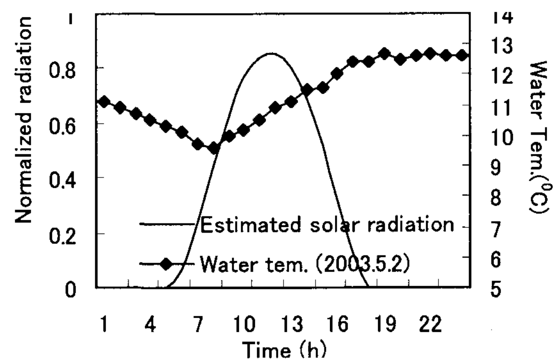

Fig.13 Large time tag of daily maximum temperature in the Shinano River.

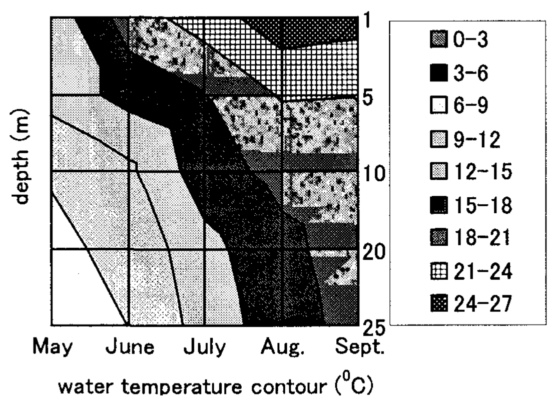

Fig.14 Water temperature variations in Y dam.

during this period of time. In addition to Ayu and Yoshinobori, Satsukimasu salmon (Oncorhynchus ishikawae) is also present in the river under consideration. Since the optimal growth temperature range for Satsukimasu salmon is from 12 to 14 ^0C according to Brett[8], and the temperature for migration is about 15~16^0C[9], the continuous release of surface water from the dam might harm this already endangered species if the temperature excess does not decay quickly.

According to the present study, if the time lag of maximum water temperature in the downstream reach is lager, the water release from the surface layer might be causing serious problems due to the very slow decay rate. Therefore, for the sake of environmentally sound dam operation, the diurnal variation of water temperature in downstream reach should be scrutinized in order to assess the decay rate of temperature excess correctly.

On the other hand, if water is released from middle or low levels of a reservoir, the temperature of release water could be quite constant on weekly or monthly scales, taking the Y dam for example. Then, considering two particles of water leaving the reservoir at sunrise and sunset, respectively. As sketched in Fig.15, the particle leaving at sunrise will be warmed up by solar radiation till sunset, while the one leaving at sunset will be subjected to nighttime cooling for 12 hours. As a result, at the location equivalent to half day's travel time, the diurnal variation could be amplified as long as the weather and flow conditions do not change dramatically in 24 hours. Locations of large diurnal variation may create potential thermal barriers to migrating fish as suggested by Berman and Quinn[10].

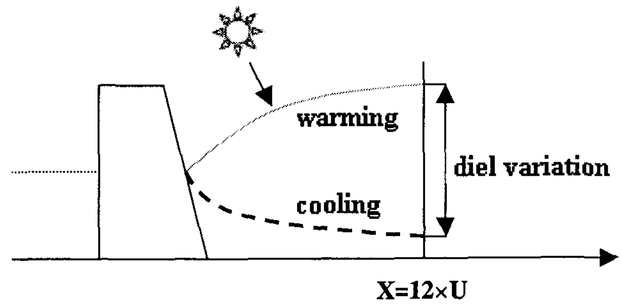

Fig.15 Schematic explanation of amplification of diurnal variation at certain location.

6. CONCLUSIONS

1. The daily water temperature variations are not in phase with daily air temperature variations.
2. Linear relationships between daily maximum, daily mean and daily minimum water and air temperatures are evident on yearly scale. However, they are weakened as time scale decreases from yearly to monthly.
3. Smith concluded that regression relationships between daily minimum water and air temperatures tend to be more scattered than those for mean or maximum values. However, the present analysis shows that Smith's conclusion may be only valid at monthly base as far as the Shinano River is concerned.
4. 7-day moving averages of daily maximum water and air temperatures are well correlated on seasonal scale.
5. Hourly water temperatures are not in phase with hourly water depths, but strong correlation is observed between 7-day moving averages of daily maximum water temperatures and daily mean water depths in summer season.
6. The time derivative of daily mean water temperature is well correlated with the logarithm of air-water temperature difference.
7. The current practice of one temperature sampling per month in most Japanese rivers needs to be re-evaluated.
8. One sampling per day around 10:00AM may able to capture the essential variation pattern of daily mean water temperature at weekly, monthly and yearly bases. But the absolute values should be used with caution.
9. In the Shinano River, there is a possibility for heat load to decay very slowly because of the large time lag of peak temperature.
10. For environmentally sound dam operation, diurnal variations of water temperature in downstream reach should be carefully assessed.

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(Received September 30,2003)