MAINTAINING NATURAL
WATER TEMPERATURE REGIME
FOR PROTECTING AQUATIC LIFE

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This paper is intended to address the need to pay more attention to water temperature conditions for environmentally-sound river management. It discusses the importance of maintaining proper water temperature regimes for the health of aquatic life, and provides some insight into the impact of upstream control on downstream water temperature regimes. It suggests that adverse impact might be alleviated if upstream control is properly managed. To characterize in-stream thermal environment, a thermal diversity index is proposed. In addition, the inadequacy is pointed out of the current water temperature monitoring systems along major rivers in Japan.

Key Words : water temperature, diurnal variation, upstream control, thermal diversity index, fish

1. INTRODUCTION

Water temperature is an aspect of water quality that affects the metabolic rates, physiology, and life-history traits of every aquatic organism. 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. Water temperature influences the behavior of fish more than any other nonliving variable[4], and permanent shifts in temperature regimes can render formerly suitable habitat unusable for native species[13]. For instance, adult fish holding in warm water experience bioenergetic stress and consume their stored energy more rapidly, which may result in reduced spawning success. Higher temperatures may also reduce fish's resistance to disease, and ability of predator avoidance. In addition, warm water can present thermal barriers to adult and juvenile migrations. Temperature-dependent life stages for fish such as salmonids, include spawning, egg incubation, emergence, rearing, smoltification, migration, and pre-spawn holding. Any of these life stages can be present (depending on species and location) during summer months when streams are warmest. Higher 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. Human activities can harm cold-water refuges by reducing variation in water temperature and flow, reducing channel complexity, and disrupting seasonal recharge of groundwater. To ensure the long-term survival of native fish populations, it is necessary to protect and restore cold-water refuges. Although water temperature improvement alone can not restore native fish populations, it is not possible to restore requisite freshwater habitat without

temperature improvements.

Water temperature study in Japan has traditionally been conducted in the field of agriculture for the purpose of irrigation. The effects of watershed development and river engineering works on water temperature and associated aquatic life 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. Under the new law, in-stream habitat protection and enhancement is becoming a key component for integrated river management. It is time for systematic research on impact of man's activities upon in-stream thermal environment, and to work out solutions accordingly. This paper attempts to address the importance of maintaining natural water temperature regimes for protecting river's ecosystem, and to discuss about how to establish water temperature criteria for achieving management objectives. As a result, it points out some potential impact of flow regulation on downstream temperature variations, and problems related to the current water temperature monitoring programs along major rivers in Japan. Besides, a thermal diversity index for characterizing in-stream thermal environment is proposed in this paper. It should be mentioned that the discussion given in this paper is not intended to be comprehensive, but representative.

2. WATER TEMPERATURE REGIME

Because water temperatures in streams are dynamic over space and time, it is difficult to talk about a stream's temperature as though it could be represented by a single value. Therefore, water temperature should be discussed in terms of a "regime". A regime includes the concepts of magnitude, frequency, duration, timing, and rate of change. Consequently, a temperature regime describes the distribution of the magnitude of water temperatures, the frequency with which a given temperature occurs, and the duration of time for which a waterway is above or below a given temperature. Processes that are external to the

stream as well as processes that occur within the stream and its associated riparian zone influence stream temperature regimes. The various gain, loss and transfer processes of energy involved may be analyzed in terms of a heat budget approach. Quantification of the heat budget has been central to numerical models for water temperature predictions. Components in the heat budget include climatic drivers such as solar radiation and wind speed, stream morphology, bed influence and riparian conditions. Fig.1 shows an example of computed heat budget for a reach in the Oppe River. In the simulation, the net short-wave radiation (H_s) is calculated on an hourly basis by:

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

where H_0 = amount of solar radiation reaching the earth's surface; A_t = atmospheric transmission term; A_w = water surface albedo; C_l = cloudiness; SF = the fraction of solar radiation that is blocked by topography and stream bank vegetation. For atmospheric long-wave radiation, the Swinbank's formulation[21] is used. The sensible heat flux and evaporative heat flux are parameterized by the bulk transfer formula with dependencies on wind speed as formulated by Sinorkrot[19]. To account for wind sheltering by riparian vegetation, the wind function of Gulliver[7] is adopted in calculating sensible and evaporative fluxes. The bed heat flux is computed with the streambed temperature profile, which is obtained by solving the heat conduction equation with proper boundary conditions. For more details, see Huang[14].
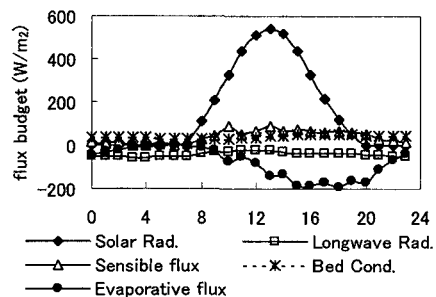

Fig.1 Example of simulated river heat budget

As illustrated in Fig.1, the solar radiation can be viewed as the singularly most important radiant

energy source for heating streams during daytime. For un-shaded streams, over ninety percent of the incoming energy would become available to that stream.

Over the past several decades, a significant change in the landscape of Japanese rivers is the disappearance of riparian forest to a grievous extent. The vegetation removal in upstream reach is mainly due to the construction of dam and forest pathways, while the deforestation along the middle reach mainly resulted from land-use development and river engineering works. Fig.2 shows the water temperature records at the Tatsumiguchi monitoring station in the Tedori River. The uprising trend is clear.
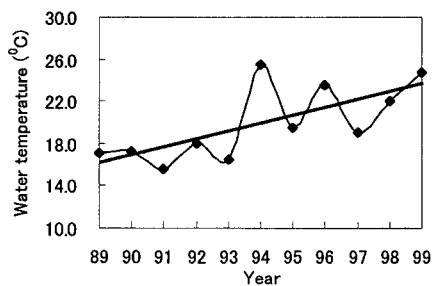

Fig.2 Water temperature at the Tatsumiguchi

Riparian vegetation has a variety of functions, but one of them is to prevent sunlight from reaching the water surface. Brown and Krygier[7] reported an average monthly maximum temperature increase of about 8^0C after clearcutting a small watershed. Amaranthus[1] described maximum water temperature increases ranging from 3.3^0C to 19^0C in a watershed burned to varying degrees. Feller[10] recorded maximum temperature changes of 3.6^0C to 5.7^0C in two coastal watersheds. Hewlet and Forston[12] reported maximum stream temperature increase of 11^0C in a clearcut stream in the southeast United States. In an irrigation channel located in the city of Furano, a field survey indicated water temperature at a monitoring station increased 4^0C with the removal of riparian vegetation, and the longitudinal water temperature gradient increased four times. In short, the literature from a variety of geographic locations and theoretic analysis suggest that increases to maximum temperatures of $2-10^0C$ due to removal of stream shading have been
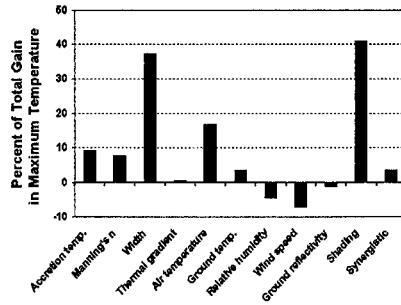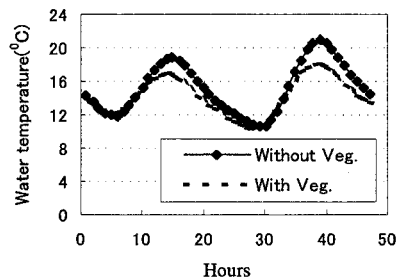

Fig.3 Sensitivities to various factors

Fig.4 Impact of riparian vegetation in a hypothetic channel

common. In addition, riparian vegetation removal can also destabilize stream-banks, therefore widening the channel, and ultimately affecting the water temperature regimes of the stream.

Barthalow[3] conducted the sensitivity analysis and concluded, as shown in Fig.3, that when predicting maximum daily water temperature, riparian shading is the most sensitive input variable.

Huang[14] showed that shading factor is sensitive to change in stream orientation when the stream azimuth is between 20 and 60 degree. This implies that even slight change in river course due to river engineering work might result in un-negligible change in surface heat exchange. Fig.4 illustrates that the removal of riparian vegetation not only increases the maximum daily temperature, but also enlarges the diurnal variation. Most studies of thermal influence on fisheries concentrate on the response of particular species to step changes in temperature over a long period of time, rather than species response to changes in the diurnal temperature regime. However, Berman and Quinn[5] reported that fish searched for and remained in the thermal refugia during the warmest hours of the day. Locations of large diurnal variation may create

potential thermal barriers to migrating fish. Ecological implication of diurnal variation patterns deserves further in-depth study.

If the presence of riparian vegetation is recognized as one of the key factors in protecting water temperature, a question arises naturally. That is how long it will take for the temperature of a cleared stream to return to normal as re-vegetation is implemented. This may be referred to as "thermal recovery". No comprehensive studies were found of temperature recovery by manipulating riparian vegetation in Japan.

Another important aspect of water temperature regime is the spatial variation, which can occur within a few meters, such as with pools and riffles, or at a larger habitat scale including stream reaches, individual streams, and stream networks. Over the past decade, the water temperature has been perceived as a macro parameter under the framework of IFIM[18]. However, growing evidences indicate that the water temperature should also be considered as a micro index for fish habitat evaluation[2]. At fine spatial scales, water temperature can vary substantially according to the localized configuration of the stream such as pool/riffle sequences. Significant lateral variations were also reported as a consequence of different heating between shallow and deeper zones and floating vegetation shading as well[8]. These small-scale variations in water temperature are important component of stream habitat because fish may use this variability to avoid elevated water temperature or to maximize metabolic efficiency. Thus, thermal diversity within a steam reach allows individual fish to select optimal water temperature for growth, foraging or other activities on a daily or hourly basis. As river channel complexity has been markedly reduced in many Japanese rivers over the past several decades, the thermal diversity in these rivers could have been significantly degraded. Although there is an obvious lack of long-term data to characterize historical water temperature regimes, numerical simulations may be able to describe natural temperature conditions to certain extent. This type of work should be pursued for the purpose of river restoration.

In summary, the concept of temperature regimes can be used to describe in-stream thermal dynamics across space and over time at various scales. To provide a framework for further discussion, a preliminary hierarchical classification is presented in Fig.5. At the top level is the basin regime, which provides a "baseline" to the other regimes. This implies that catchment-scale disturbances or climatic variations could exert influences down to fine scales. At the bottom is the micro thermal regime, which describes the temperature characteristics at fine scales of a few centimeters to a few meters such as cross-sectional variations. The reach regime may be related to morphological units such as pool/riffle structures. Segments are made up of stream reaches so that the segment regime may be used to quantify variation in mean water temperature between reaches. The driving forces of each regime and the interdependency between regimes shall be important subjects to study.
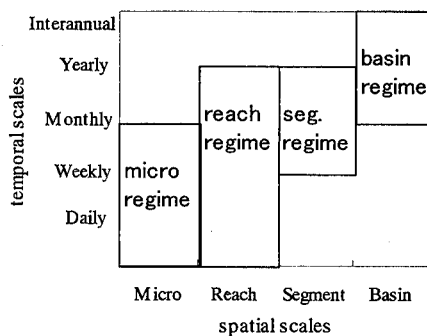

Fig.5 A hierarchical classification of regimes

3. IMPACT OF UPSTREAM CONTROL ON WATER TEMPERATURE REGIME

Over time, humans have substantially altered the physical context of streams in various ways. One of them is the construction of dam. Dam affects downstream water temperature through at least two mechanisms. One of the two is the water release. Depending on the depth where water is drawn from the reservoir, the downstream water temperature may 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 in determining the operation of selective withdrawal device. Selective withdrawal devices have been installed in many dams across Japan. However, the operation has been mainly concerned with the requirement of irrigation use and the protection of Sweat Fish (Ayu) owing to its high economic value. Since Ayu could suffer the so-called cold-water disease, selective withdrawal devices in many dams are often operated to draw water from closer to the reservoir surface. According to a survey by Yoshida[24], among 21 dams equipped with selective withdrawal device, 16 dams release water from the surface layer, and only one dam discharges from the hypolimnetic layer. The remaining are operated according to season. 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. On the other hand, hypolimnetic release would not only endanger Ayu, but also reduce downstream faunal richness in both fishes and invertebrates. Even for cold-water fish such as salmon, hypolimnetic release might cause a problem. Saltveit[20] found that cooler summer hypolimnetic releases from a mountain reservoir led to higher mortality and lower production of adult salmon because smoltification was delayed by a year. Therefore, the dam operation is a dilemma between concerns for different species at different life stages.

The another mechanism, by which the dam affects downstream temperature, is the flow reduction. To generate hydropower during periods of peak electrical demand, dams are often operated such that summertime flows below dams are severely restricted, sometimes to the point of river stagnation. When flow is largely reduced, stream capacity for heat assimilation is greatly lost.

In recent years, the so-called Flexible Dam Operation (FDO) was initiated by the Ministry of Land, Infrastructure and Transportation, and has been adopted on a trial basis in about 15 dam sites across Japan[23], and the number is expected to increase. The FDO utilizes the flood control storage capacity of a reservoir to store extra water, which is then released according to downstream conditions prior to flood events. The aim of FDO is to restore downstream river environment through releasing maintenance water or environmental flow. It can be operated at different time scales for different purposes. For maintenance water supply, it runs continuously on weekly or monthly basis such as the cases in Kanayama dam and Sanguri dam, while it run on hourly basis for flush discharge such as the cases in Miyagase dam and Taisetsu dam. The FDO is obviously effective in turning a dried river reach back to a natural-looking state. It is also effective in cleaning up riverbed[22] and improving the riparian landscape. Nevertheless, the response of water temperature regime to the FDO has not been explicitly taken into consideration in the FDO planning so far. In what follows, we try to highlight the necessity of performing water temperature assessment in relation to the FDO.

The one-dimensional model of water temperature can be described as:

$$\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial x} = D\frac{\partial^2 T}{\partial x^2} + \frac{H}{\rho C_p d} \qquad (2)$$

where H = net heat exchange at an air-water interface; U = velocity of the river; D = dispersion coefficient; C_p = heat capacity of water; d = average depth. When studying waste heat discharge it is customary to simplify the model by linearising the source term with a base temperature. According to Edinger[9]

$$H = K(T_e - T) \qquad (3)$$

where T_e = equilibrium temperature; K = surface heat exchange coefficient. Jobson[15] argues that the natural water temperature is a better base temperature than the equilibrium temperature. The natural temperature T_n is the temperature, which would have been measured in the absence of any human influence. The present study adopts this line of reasoning, and further assumes that the natural

Table 1 Values of model parameters

G	λ	$m(day)$	$m(night)$	ω	$\omega\,\delta$
2×10^{-3}	10^{-4}	0.2	0	$\pi/12$	$-2\pi/3$

temperature takes a sinusoidal form:

$$T_n = T_a + m \sin \omega(t - \delta) \qquad (4)$$

in which T_a is a reference temperature; m, ω, δ are parameters characterizing the time variation of T_n.

Replacing T_e with T_n, and substituting eq.(3) into eq.(2), the governing equation can be rewritten as:

$$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} = G - \lambda T + m \sin \omega(t - \delta) \qquad (5)$$

The initial and boundary conditions are:

$$T(x,0) = T_i; \ T(0,t) = T_0; \ T'(\infty,t) = 0 \qquad (6)$$

$G - \lambda T$ in eq.(5) may be interpreted as the linearization of the incoming long-wave radiation, back-radiation from the water surface, evaporation, and convective contributions.

To confirm that such a simple approach may give reasonable prediction of water temperature, a fieldwork was conducted in the summer of 2002, on a relatively uniform reach of the Tedori River near the Gotsu bridge. The site is about 23 km from the river mouth, $36^0 23'04$ in latitude and $136^0 36'51$ in longitude. A water temperature logger with manufacturer-specified accuracy of 0.2^0C was deployed at the center of the segment, recording water temperature at 5-min intervals for 6 hours. Another logger of the same accuracy was used to measure water temperature every 60 minutes at the upstream end of the segment, which is about 100 m away. It is found that the water temperatures at the two sites were virtually the same during the measurement. The flow rate and water depth were also measured, and found no temporal variation. The values of model parameters are determined via model tuning and listed in Table 1.

Figure 6 shows the simulated water temperatures for the measurement site. It can be seen that the numerical model is able to predict water temperature variation to an accuracy of 0.25^0C (RSME). In particular, the maximum water temperature was well simulated. It must be reiterated here that the emphasis of the present study is not placed on developing a general numerical model, but on shedding some light on water temperature problem with numerical approach. Although the above model is simple, and the model parameters are site-specific, it can help to identify potential
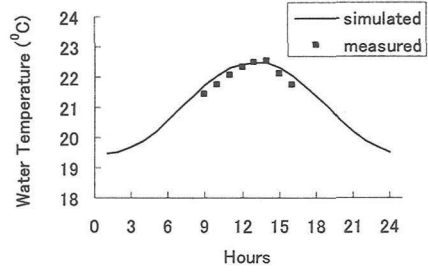
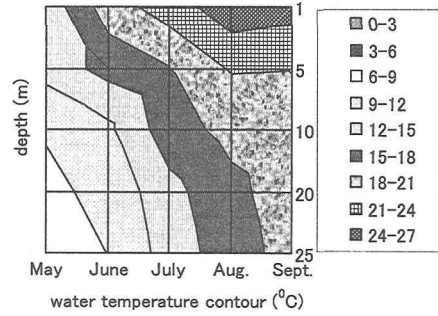**Fig.6** Comparison of model simulations with measured water temperatures

water temperature contour (^{0}C)
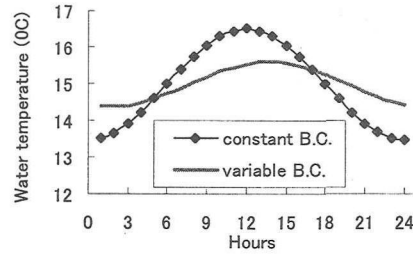
Fig.7 Water temperature variations in Y dam

Fig.8 The diurnal variations of water temperature under different upstream condition at x=12×U
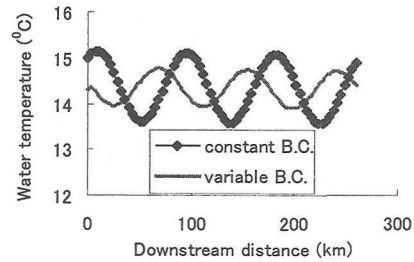
Fig.9 The spatial distributions of water temperature under different upstream condition after three-day continuous release

- 164 -

problems and deepen our understanding. Therefore, the use of such an idealized approach is justifiable.

Figure 7 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 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 temperature range for Satsukimasu salmon is between 12 to 14 ^{0}C according to Brett, and the temperature for migration is about 15~16^{0}C[26], the continuous release of surface water from the dam may harm this already endangered species. However, if hypolimnetic water is discharged, it could cause problem to Ayu and Yoshinobori. Thus, mid-level withdrawal seems to be a promising solution. The following numerical results, however, indicates that it is not such a simple matter.

In the middle or low levels of a reservoir, water temperature regimes are characterized by its slow variation with time. For weekly simulation, the release temperature from the middle level may be taken as constant. To investigate the impact of constant upstream temperature on downstream water temperature regimes, the afore-mentioned model is used. The model parameters are assigned the same values as in Table 1 except that δ is taken to be zero for simplicity.

Assuming a uniform channel with a constant flow velocity of 1.0m/s, numerical simulations are carried out with different upstream boundary conditions. First, a constant water temperature of T_0 = 15^{0}C is prescribed at the upstream end, and the model is run to obtain spatial and temporal distributions of water temperature downstream. Then, the upstream boundary condition is changed to T_0 = 15+sin(π(t-1)/12). For such a hypothetical stream, Fig.8 shows the diurnal variations of water temperature predicted by the model at the location corresponding to 12 hours of travel downstream (x=12×U). The water temperature variation over a diurnal cycle is larger with the constant boundary condition than with the variable boundary condition. The same is true at further downstream locations of x=N×12×U (N=3,5,7...). Such locations of
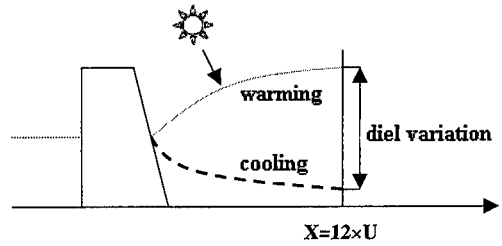

Fig.10 Schematic explanation of amplification of diurnal variation at certain location

amplified diurnal cycle have been observed in Klamath River below Iron Gate Dam. As reported by Lowney[16], Iron Gate release temperature is approximately the same or just slightly less than daily average river temperatures, and without the diurnal signal. Similar behavior is also found in Sacramento River. Fig.9 shows the spatial distributions of water temperature under different upstream control. It indicates that a constant upstream control might enhance spatial variation of water temperature, and lead to higher maximum temperature and lower minimum temperature in comparison with the case under variable upstream condition. This phenomenon may be explained by considering two particles of water leaving the reservoir at sunrise and sunset, respectively. As sketched in Fig.10, 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 12 hours.

It should be emphasized here that the above analysis is not intended for systematic assessment of water temperature problems, but to highlight the need of having an environment-friendly upstream condition in order to maintain proper in-stream thermal regimes downstream of a dam.

For the purpose of protecting natural water temperature regime in streams or rivers, a well-designed, reliable monitoring system should be installed as a first step. However, the current water quality monitoring systems installed in most major rivers of Japan do not take into consideration of

diurnal variation. It records water temperature once a day at scarcely spaced sampling sites. It also lacks consistency in sampling time. As an example, Fig.11 shows that the water temperature sampling time varied from 9:40 to 12:20 at the Aimotobashi station, the Kurobe River. One might argue that the sampling time is changed in light of seasonal variation of water temperature. Nevertheless, without long-term measurements of diurnal variation, such an argument is groundless. Besides, it is also found that the sampling time differs from station to station along a river course. As suggested by the present analysis, negative impacts of some external factors may manifest only at certain locations, the current monitoring systems appear to lack systematic consideration on this aspect in deciding the monitoring locations

Such a water temperature monitoring protocol has little chance to detect alteration of the diurnal cycle or spatial distribution. In conclusion, temperature data are of limited use if the sampling objectives, sampling design, and data quality procedures are not examined carefully.

4. TEMPERATURE STANDARDS

Developing temperature standards to protect aquatic life is challenging in part because scientific understanding of stream temperature dynamics, fish biology/ecology, and their interactions is imperfect. Therefore, the framework for developing criteria must be flexible in order to accommodate new scientific findings and uncertainties. The conventional approach to developing water quality standards is to identify a threshold value based on the purpose of water use. For water temperature, however, there are several reasons why a single threshold approach could not be applied. River water temperature increases naturally from headwater to river mouth, it also varies significantly with time. If a single threshold value is applied uniformly across the whole river, it might allow human-caused thermal degradation in upstream while giving false alarming in downstream where water temperature is naturally warmer. Therefore, in setting water temperature standards, the natural variation with space and time must be thoroughly examined. A good standard will protect high quality
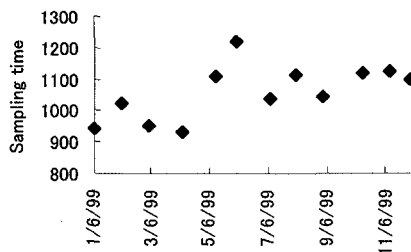

Fig.11 Inconsistency in sampling time at the Aimotobashi station, the Kurobe River.
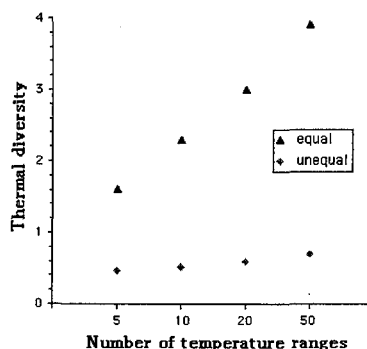

Fig.12 The dependency of thermal diversity index on the richness of temperature variation

habitat and guide restoration of degraded habitat, while recognizing that some naturally warm reaches are also part of the aquatic landscape. A straightforward alternative is to develop multiple thresholds for different reach and different season. However, since thermal requirement of fish is species-dependent, the multiple thresholds might be under-protective for some fish and overly stringent for others.

In view of the difficulties in setting temperature criteria, we propose to develop thermal diversity index to characterize in-stream thermal environment, and to use such an index to guide river planning. A plausible way to do so is to adapt the Shannon index to describing in-stream thermal diversity. The Shannon index was originally used as a species diversity index in ecology[27].

Dividing a stream segment into M meshes, and assuming that the range of temperature variation within the segment is DT, and further dividing DT

into a number of sub-ranges as dt_1, $dt_2...dt_n$. Indicating the number of meshes in which the water temperature is within the range of dt_i as k_i, the thermal diversity index takes the following form

$$TDI = -\sum_i \frac{k_i}{M} \ln(\frac{k_i}{M}) \qquad (7)$$

To explain how this index may work, an example is given below.

For a reach consisting of 100 meshes, the number of temperature sub-ranges is assumed to be 5, 10, 20 and 50, respectively. For each scenario, TDI is calculated for the condition in which the occurrence of each sub-range in the segment makes up an equal proportion of total number of meshes, and for the case in which one sub-range occupies 90% of the meshes, and the remaining sub-ranges are distributed evenly. The triangles in Fig.12 represent TDI for the first equal proportions, and the diamonds represent values for TDI for the unequal proportions. The value of TDI increases dramatically with the number of available temperature sub-ranges for the equal case. This indicates that TDI could provide information about the richness of in-stream thermal habitat and its distribution. Therefore, it has the potential to be used as a criterion to evaluate the impacts of human activities and to guide river restoration.

5. CONCLUSIONS

The present paper highlights the importance of maintaining natural water temperature regimes and discusses the ways to establish water temperature criteria. It is mainly focused on the impact of dam operation upon downstream water temperature regimes. By using a simple numerical approach, it is shown that the dam water release with constant temperature might lead to larger diurnal variation at certain locations downstream. It suggests that the dam water release operation with a selective withdrawal device should be optimized in a way that the temperature of release water mimic the natural variations as close as possible. Most importantly, the water temperature consideration should be given to a wide range of aquatic life, not just certain species in order to maintain biological balance in river's ecosystem.

In view of various factors affecting water temperature regimes and fish's selection of thermal habitat, it seems to the authors of this paper that fixed or single value criteria of water temperature is inappropriate because it can not accommodate natural temperature variations and environmental preference differences between species. What is needed is a dynamic temperature control protocol, which can account for natural temporal and spatial variations, and can ensure protection of in-stream thermal diversity, especially, cool or cold-water pockets that fish can use to avoid elevated water temperatures. A thermal diversity index is then proposed following this line of thinking.

Besides, problems related to the current water temperature sampling protocols implemented in major rivers in Japan are pointed out.

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水生生物保全のための水温自然変動の重要性について

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　　水温は河川生態環境に関わる一つの重要指標である．本論文では，適正な水中熱環境を維持することの重要性を提唱している．上流側の制御が下流域の水温の変動に与える影響を議論し，水温の自然変動を考慮した操作が行われれば，ダム放流による水温変動の影響が軽減できることを示した．また，河川水中熱環境を評価するために，水温多様性指標を提案した．さらに，全国一級河川における現在の水温観測システムの問題点等を指摘した．