SIGNATURE OF HUMAN-CAUSED ALTERATIONS OF IN-STREAM THERMAL ENVIRONMENT

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This study investigates characteristics of water temperature variations in the middle reaches of the Shinano River. Attention is given to the impact of a hydropower plant on downstream water temperature daily regime. Peculiar diurnal variation of water temperature appears immediately downstream of the power plant. At a different site, 17 km downstream of the power plant, thermal anomaly manifests in a different form that is designated herein as in-stream tropic night.

Key Words: water temperature, hydropower plant, Shinano River, thermal anomaly

1. INTRODUCTION

Water temperature is an important parameter among water quality characteristics; it influences the distribution and well-being of aquatic communities. Permanent shifts in temperature regimes can render formerly suitable habitat unusable for native species. 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 juveniles. Therefore, it is impossible to protect or restore river ecosystems without maintaining appropriate water temperature regimes. Despite the important role played by water temperature, effects of watershed development and river-engineering activities on water temperature regimes have received much less attention than they should in the field of civil engineering in Japan. The study of river water temperature has mainly centered upon irrigation in Japan. Consequently, little information is available in the literature concerning thermal degradation in Japanese rivers.

The present note provides an analysis of water temperature variations in the middle reaches of the Shinano River. Particular attention is given to alterations of daily water temperature regimes caused by human activities.

The Shinano River is the longest river in Japan. It runs through both Niigata and Nagano prefectures and flows into the Sea of Japan. The Shinano basin area is 11,900 km². Because of the broad basin area and peculiar climate, its annual runoff is the most affluent in Japan. More than 50 kinds of fish, such as salmon and sweet fish, inhabit the river. It is even said that almost all species of fish that live in Honshu are found in the Shinano River. More details about the Shinano River may be found at the website of the Shinano River Office or from a handbook.

The river area selected for the present study is between the Ojinya and Nagaoka sites, which are about 34.5 and 17.5 km from the river mouth, respectively. Field measurements have shed new light on the influence of hydropower plants upon downstream thermal characteristics.

A hydropower plant run by East Japan Railway Company exists at the Ojiya site (Fig.1). It takes water through a tunnel from the Miyanaka Dam, which is located about 40 km upstream of the power plant. The power plant releases water twice a day, during the early morning and late afternoon. Figure 2 shows daily variations of the water level at the Ojinya gauging station and at Nagaoka as well. The Ojinya gauging station is about 500 m downstream of the hydropower plant. The generated electricity is transmitted to the Tokyo Railway Network to meet peak demand during daily rush hours. The Myoken weir was constructed in 1990 to reduce the downstream water level variations resulting from power plant operations. However, as Fig.2 shows, the im-
pact of the water level variation at the Ojiya has not been eliminated at the Nagaoka station.

A weeklong continuous measurement of water temperature was conducted at the Ojiya site in October 2003 for the purpose of investigating water temperature characteristics downstream from the Ojiya hydroelectric plant. An additional measurement was conducted at the same location in August 2004. These data were examined from the perspective of diurnal variation. Comparison was also done with the water temperature at the Nagaoka gauging station, which is about 17 km downstream from the power plant. Results showed that the water temperature at the Ojiya site was peculiar. Water temperature data at the Nagaoka, which was monitored by the Shinano River Office, was used to illustrate another thermal anomaly observed in summer that was also likely to result from the operation of the Ojiya hydropower plant. The autumn water temperature at the Nagaoka site was also examined, but the anomaly observed in summer was less appreciable in autumn. An explanation is given in discussion concerning seasonal differences.

2. WATER TEMPERATURE VARIATIONS AT OJIYA

As typified in Fig. 3, a common feature was that the daily maximum water temperature appeared earlier than the daily maximum air temperature under fine weather; a smaller second peak was observed in the afternoon. This pattern of variation appeared in correspondence with the water release operations. The fact that the daily maximum water temperature appeared earlier than the daily maximum air temperature implies that the water temperature dynamics at the Ojiya site was not driven by meteorological conditions.

Figure 4 shows a comparison of the water temperature at Ojiya with that at Nagaoka. Under pristine conditions, downstream reaches are normally warmer than upstream reaches. However, Fig. 4 indicates that the water temperature at Ojiya was higher than the downstream water temperature in the morning, which I believe is attributable to the water release from the power plant. Figure 5 shows that the relation between water temperatures at Ojiya and Nagaoka seems normal when only daily mean values are examined. Besides, since the difference in altitude between the two sites is around 20 m, the difference in daily mean water temperature between the two sites could not simply be explained by the difference in elevation. Further study is needed.

A supplemental weeklong observation was made at the Ojiya site in August 2004 to determine whether
or not the water temperature changed similarly in summer and in autumn. As represented in Fig.6, the two-peak variation pattern was also present in summer. Timing for the two peaks in summer was almost identical to that in autumn.

3. WATER TEMPERATURE ANOMALY AT NAGAOKA IN SUMMER

Figure 7 shows a diurnal variation pattern of water temperature observed at the Nagaoka station. It deviated from a normal pattern: the water temperature remained high at night. This pattern repeatedly appeared from May through August. For instance, it accounted for about 50% days in May 2003. Under natural conditions, water temperature decreases at night through radiative cooling. In urban areas, the so-called heat island phenomenon may make it difficult for air temperature to decrease at night; this phenomenon is often called tropic night in urban thermal environment studies. Therefore, the unusual water temperature variation pattern at the Nagaoka site shares some common feature with the tropic night induced by urban heat island. By this analogy, the phenomenon by which water temperature is elevated at night is hereafter referred to as in-stream tropic night.

Ratios showing daily maximum water temperatures appearing at different time zones were classified for each month of 2003 to elucidate this thermal anomaly. Figures 8–10 show ratios for June, July and August, respectively. The ratio that the daily maximum water temperature appearing around midnight was 6.7% in June, but it reacted to 29% in August.

Cross-correlation analysis of hourly water temperature time-series of both Nagaoka and Ojinya revealed that water temperature variations at Nagaoka lagged the temperature fluctuations at Ojinya by approximately 5 h. As shown in Fig.11, incorporation of this lag effect into regression analysis revealed a statistically significant relationship between the water temperature at Ojinya and that at Nagaoka. The correlation coefficient was as high as 0.95. The curve also shows that the relationship departs from a linear relationship at both high and low ends of the recorded data. Factors such as enhanced back radiation and an increase in moisture-holding capacity of the atmosphere may explain the departure in general. However, more work is needed to clarify specific causes for the case under consideration.

It is noteworthy that the in-stream tropic night phenomenon was recorded only once in October 2003. An explanation was given in the discussion about the seasonal difference.
4. DISCUSSION

Effects of temperature on fish physiology have been well studied in the laboratory. Temperature regimes in laboratory experiments have been mainly approximated as having constant temperature, a sequence of constant temperatures, or a sinusoidal-patterned variation with a mid-afternoon high and an early-morning low. To the author's knowledge, the response of fish to a two-peak diurnal thermal regime has never been studied either in the laboratory or in the field. Considering the fact that migrating salmonids have adapted to taking refuge during warm afternoons and taking advantage of cool nights and early morning hours, the two-peak daily variation of water temperature might create a thermal barrier to migrating fish.

The long-term average flow rate at the Ojiya station for summer time is approximately 400 m³/s, suggesting that the mean flow velocity is higher than 1 m/s. Our flow measurements around the Ojiya site in the summer and autumn of 2003 confirmed that the velocity was slightly greater than 1 m/s (or 3.6 km/h). Therefore, water released from the power plant may flow to the Nagaoka site in 5-6 h. This inference is consistent with the results of cross-correlation analysis described in the previous section. The water released from the power plant in late afternoon might reach the Nagaoka site at night. Thereby, the nighttime water temperature at the Nagaoka site might be elevated if the additional heat load is not dissipated sufficiently in the course of advection. This phenomenon of a water temperature hike at night and its ecological implications deserve further detailed study.

Another question is why the phenomenon of in-stream tropic night did not appear in autumn. The air temperature around the Nagaoka site and its water level were examined to reveal some clues. Air temperature data were obtained from the Nagaoka Local Meteorological Observatory, which is about 1.5 km away from the Nagaoka hydrological gauging station. Figure 12 shows ratios of magnitude of daily air temperature variation to the daily means for August and October 2003. Diurnal variations were appreciably larger in October than August. Figure 13 shows magnitudes of daily air temperature variations (ΔT) divided by the monthly average (ΔT_month) in days when in-stream tropic nights occurred in August 2003. As the figure shows, 90% were below the monthly average. Figure 14 indicates that water levels were lower overall in October than in August. These factors foster the interpretation that in-stream tropic nights might occur when meteorological conditions are less variable and the water level is relatively low.

\[ y = 0.894x + 2.6147 \]
\[ R^2 = 0.5544 \]

Fig. 11 Relationship between water temperatures at Ojiya and Nagaoka, the dashed line indicating linear fitting.

Fig. 12 Comparison of the magnitude of diurnal air temperature variation between August and October.
In light of the above discussions, one can conclude that maintaining proper in-stream thermal regimes requires close monitoring of water temperature and hydrological and meteorological conditions. Nevertheless, water and air temperatures are currently recorded only once a month at most gauging stations along the major rivers of Japan. Such discrete samplings may be useful for long-term trend analysis, but they provide only limited information regarding water temperature regimes. For protecting natural water temperature regimes in streams or rivers, a well-designed monitoring system with sufficient temporal and spatial resolutions should be installed.

5. CONCLUSIONS

The main findings are summarized below:

1. The signature of in-stream thermal environment alteration appeared to be remarkable immediately downstream of the hydropower plant. Daily variation of water temperature at the Ojiiya site was characterized with two peaks: one in the morning ahead of highest air temperature, and the other in the afternoon. This pattern accords with the daily water level variation induced by operation of the Ojiiya hydropower plant.

2. Water temperature at the Ojiiya site in the morning exceeded that at the Nagaoka site, which is about 17 km downstream. However, such a phenomenon is undetectable with daily mean water-temperature data.

3. At the Nagaoka site, 17 km downstream of the power plant, another thermal anomaly, designated in this study as in-stream tropic night, was detected by classifying the timing for daily maximum water temperature. Results demonstrated that the number of days with in-stream tropic night were significant in summer 2003. The water release from the power plant in the afternoon was considered to cause this anomaly.

4. Days that were favorable for the occurrence of in-stream tropic night were inferred to be those with small daily variation in meteorological conditions and relatively low water levels.

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