Journal of Japan Society of Civil Engineers, Ser.
B1 (Hydraulic Engineering), Vol. 68, No. 4, I_283-I_288, 2012.

WATER AND ENERGY BUDGET ANALYSIS OF AN URBAN RIVER UNDER STRONG ANTHROPOGENIC INFLUENCE

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To reveal the anthropogenic influences on thermal environment in urban rivers, stream temperatures from 1990 to 2010 of the Tama River were investigated. Both the long-term and longitudinal changes of stream temperature, as well as flow rate, effluent temperature and volume, and water and energy budget were revealed. Stream temperature in winter season increased significantly at points where the temperature and discharge volume of effluents from wastewater treatment plants increased over the past 20 years. The different longitudinal variations in upstream temperature between winter and summer seasons were found primarily due to the flow rate decrease. Water and energy budget analysis suggested that the anthropogenic heat inputs from the wastewater were the dominant warming factor both in winter and summer seasons in downstream segments, while other factors such as groundwater recharges, and air-water and water-sediment interactions were contributing to suppress the stream water warming.

Key Words **:** *human impact, stream temperature, wastewater effluents, water and energy budget*

1. INTRODUCTION

Stream temperature is an important measure of water quality and ecosystem health affecting physical, chemical and biological river processes. It determines the ecosystem productivity and affects the geographic distribution of aquatic life[1]. Thus, it is essential to reveal the thermal behavior of river systems under different environmental conditions and human impacts.

Stream temperature depends on various physical processes of heat energy added or lost to/from the watershed, both natural and anthropogenic. Natural processes mainly include tributary and groundwater flows, and exchanges across the water surface and streambed[2]. Human activities can affect stream temperature through global climate change, riparian deforestation and warm effluents discharge[3]. Factors that influence stream temperature vary spatially and temporally, making comprehensive understanding and prediction of stream temperature variation a complex task.

Recent investigations in stream and river temperature give particular attention to the past and future trends, fundamental controls on thermal behavior and thermal heterogeneity at different spatial scales. Particularly, studies of how human activity may alter stream and river temperature behavior have continued to command attention[4].

This work has put forward a new discovery with respect to the stream temperature variations on both temporal and spatial scales of the Tama River in Japan, as a result of strong anthropogenic influence. The objectives of this study are: (1) to reveal the stream temperature changes in recent 20 years, (2) to identify major causes of past changes of stream temperature, (3) to analyze water and energy budget in several segments for identifying significant processes that determine temperature regime. By utilizing these conclusions, scientific information can contribute better to environmental management and conservation.

2. STUDY AREA AND DATA SOURCE

The Tama River is located in the east of Japan,

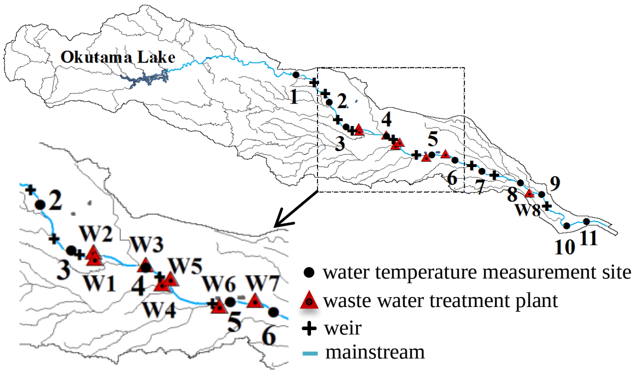

Fig.1 Study catchment showing the Tama River system, mainstream, and locations of stream temperature measurement, wastewater treatment plant and weir.

and has been a major river system running through the central Tokyo. The upstream region is basically covered by grass and forest whereas the downstream region has been highly urbanized. The Tama watershed consists of 60% forests, 31% urban area, 2% farmland, 1% paddy field and 6% others.

Stream temperature has been measured at 11 stream temperature measurement sites (S-1 through 11) as shown in **Fig. 1**. At these sites, data of stream temperature and flow rate from 1990 to 2010 were available from the Ministry of land, infrastructure and transport, Japan, with records of monthly measurement which were taken 2 or 3 times in a particular day in every month. The information related to wastewater treatment plants (WWTPs), such as monthly discharge volume from 1990 to 2009 and monthly effluent temperature from 1993 to 2009 was provided by the Tokyo Bureau of Sewerage. Meteorological conditions such as air temperature, global short-wave radiation and sunshine duration were obtained from Japan Meteorological Agency.

3. STREAM TEMPERATURE

By analyzing the available data, both the long-term and longitudinal stream temperature changes were identified.

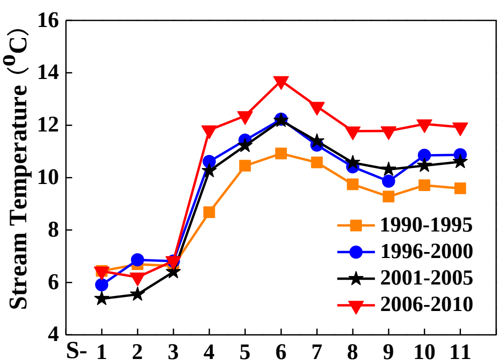

Fig.2 Stream temperature variations at S-1 through S-11 in winter months from 1990 to 2010.

The 5 or 6-year average of monthly measured temperatures at S-1 through S-11 for winter months (December through February) were compared among four periods from 1990 to 2010 (**Fig. 2**). We found that stream temperature in the most recent period was much higher than that of the preceding periods at S-4 to S-11, whereas at S-1 to S-3, no obvious temporal change was observed, probably due to unchanged land use conditions and cold water released by the upstream dam. Longitudinal temperature varied along the mainstream. An abrupt increase occurred between S-3 and S-4, the highest temperature appeared at S-6 and no obvious longitudinal temperature changes were observed in the further downstream region.

It is of great importance to identify the possible causes related to significant stream temperature changes in recent years in downstream region.

4. EFFLUENT FROM WWTPs

Large part of the Tama River runs through rapidly urbanized areas generating a great amount of heat effluents from WWTPs. There are 8 WWTPs (W_1-W_8) distributed along the mainstream **(Fig. 1)**. W_1-W_3 and W_4-W_7 are located between S-3 to S-4 and S-4 to S-6 respectively. In our analysis, the effect of W_8 was neglected due to the relatively minor discharge volume and close position to the river mouth.

Fig. 3 illustrates the average of discharge volume and effluent temperature from WWTPs in winter months among 4 periods, which shows the overall effluent temperature increase over the study period. The increase trends of discharge volume from W_1-W_3 and W_4-W_7 are also relevant, which were approximately twice amount in recent years than that of 20 years ago. The long-term stream temperature increase at S-4 and its downstream sites in winter months (**Fig. 2**) is likely due to the increase of both effluents temperature and discharge volume from WWTPs. More quantitative discussion will be given in the later part.

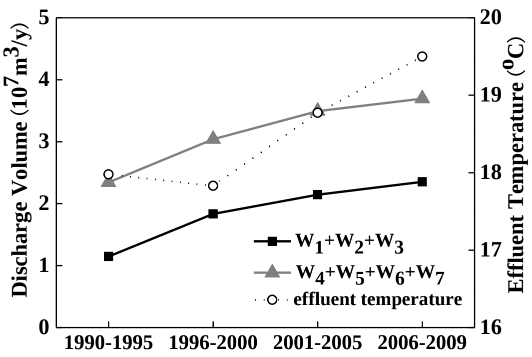

Fig.3 Effluent temperature and discharge volume from WWTPs in winter months from 1990 to 2009.

Longitudinal stream temperature variation (**Fig. 2**) is probably caused by the distribution of WWTPs. The clear discrepancy in stream temperature was found between S-3 and S-4, because of heat input from the WWTPs (W_1-W_3). The highest stream temperature occurred at S-6 could be attributed to wastewater released from the WWTPs (W_4-W_7), of which the discharge amount was approximately twice of that from W_1-W_3. The reason of lesser increase between S-4 and S-6 than that between S-3 and S-4 will be discussed in section 7.

5. HYDROLOGICAL CONDITION

The stream temperature may be influenced by several hydrological conditions, such as flow rate alteration which mainly influences the heating or cooling rate due to human and natural heat inputs.

Flow rate and stream temperature in winter and summer (July through September) seasons at selected stations are shown in **Fig. 4** respectively. Flow rate decreased abruptly between S-1 and S-2, because there are two weirs used for water withdrawal for agriculture and drinking purposes, and then it became larger due to wastewater discharge and tributary inflows. Flow rates display similar variation along the mainstream between winter and summer seasons, whereas the stream temperatures are quite different, particularly in the upstream region (S-1-3). This pattern is possibly caused by interactive influence of radiation and flow rate alteration. In summer season, stream temperatures are more sensitive to the heat input by short-wave radiation during low flows[5], thus the upstream temperatures were inversely related to stream flow. On the contrary, stream temperatures in winter season were relatively stable between S-1-3 even the flow rate decreased considerably, probably due to small net radiation inputs.

In winter season, stream temperatures during 1996-2000 were quite similar to those in 2001-2005. This is probably due to the lowest flow rate of 1996-2000, which enhanced the heating by warmer effluents.

6. RELATION BETWEEN AIR AND STREAM TEMPERATURES

The significant stream temperature change found in **Fig. 2** may be partly due to regional warming caused by urban heat islands since the downstream region has been highly urbanized. To separate the influences of other factors from that of regional warming, relationships between air temperature and stream temperature were investigated.

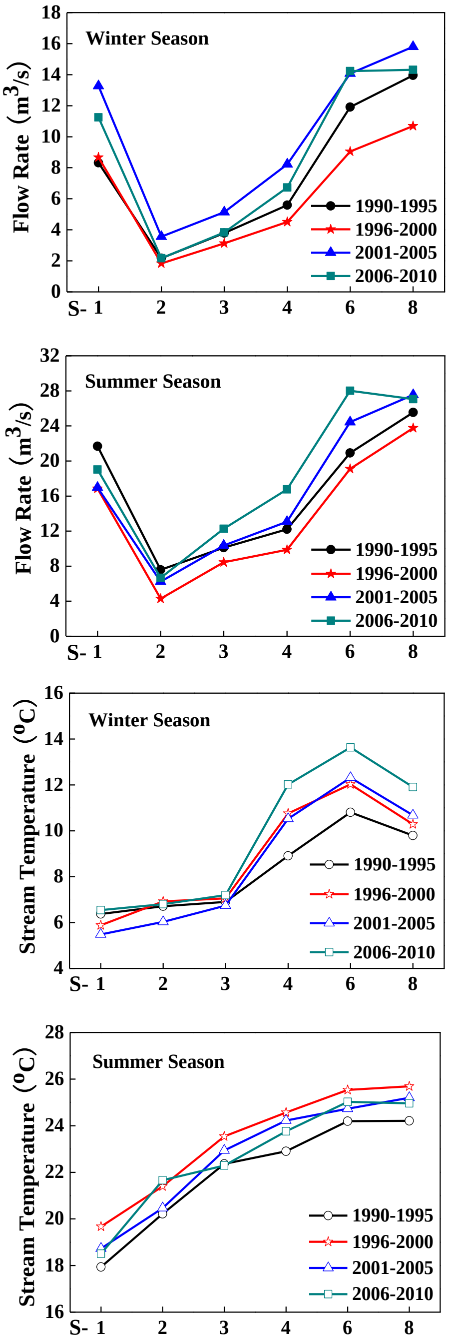

Fig.4 Flow rate and stream temperature in winter and summer seasons respectively. Each plot indicates a 5 or 6-year average of monthly measured data.

The relations between air temperature and stream temperature at S-1, S-4 and S-6 from 1990 to 1995 and from 2005 to 2010 are compared in **Fig. 5**. The data in the figure were based on monthly stream temperature measured at each site and weekly average of air temperature recorded on an hourly basis at Ome (for S-1) and Fuchu (for S-4 and S-6) of AMeDAS. The averaging period for the air temperature was a week prior to the monthly stream temperature measurement, because the weekly average was more strongly correlated with stream temperature than any other intervals[6].

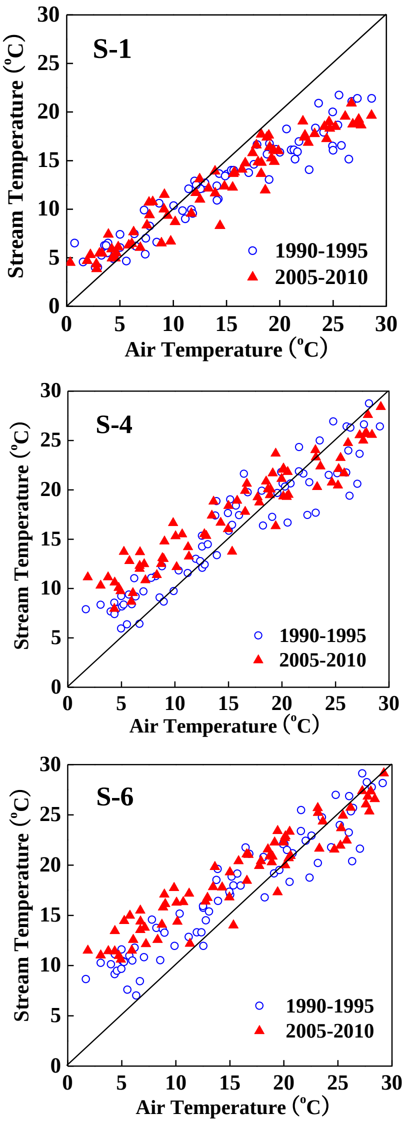

Fig.5 Relations between air temperature and stream temperature at S-1, S-4 and S-6 during two periods.

At S-1, the relations between air temperature and stream temperature were overlapped in these two periods. Stream temperatures were lower than air temperatures at air temperatures above about 15°C, probably due to the shading covers in upstream region and cold water released from the dam in warmer seasons. By contrast, stream temperatures at both S-4 and S-6 were higher in recent years (2005-2010) than those of previous years (1990-1995), particularly at air temperatures below about 15°C. This is likely due to the strong anthropogenic heat inputs caused by the increased wastewater temperature and discharge volume in colder seasons. When air temperatures were above about 15°C, stream temperatures at S-4 and S-6 were more close to air temperatures, which indicates the insensitive change of stream temperature to wastewater influences in warmer seasons because the natural flow is normally larger (**Fig. 4**) and the stream temperature is similar to that of wastewater.

7. WATER AND ENERGY BUDGET

The analysis of water and energy budget for four segments (S-2-3, S-3-4, S-4-6 and S-5-6) was conducted to quantify the processes (**Fig. 6**) that affect the stream temperature.

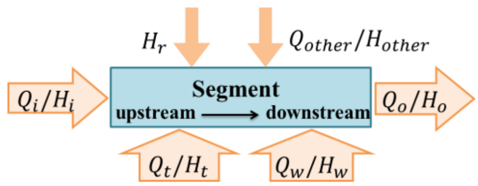

Fig.6 Components responsible for water and energy budget in each segment.

A general description of water budget is given as

$$Q_o = Q_i + Q_t + Q_w + Q_{other} \quad (1)$$

where Q_o is the outflow at downstream section, Q_i, Q_t, Q_w are inflow at upstream section, and from tributaries and WWTPs respectively. Q_{other} indicates integrated flows of other factors (i.e., evaporation, groundwater flow and water withdrawal). In equation (1), Q_o, Q_i, Q_t and Q_w are measured river flow or discharge volume from WWTPs, and Q_{other} is calculated by $Q_{other} = Q_o - Q_i - Q_t - Q_w$.

The balance equation of heat transport in each segment is expressed as

$$H_o = H_i + H_t + H_w + H_r + H_{other} \quad (2)$$

where H_o is the outflowing heat at downstream section, H_i, H_t H_w, H_r are inflowing heat at upstream section and from tributaries, WWTPs and net radiation respectively. H_{other} indicates integrated heat exchanges caused by other factors (i.e., air-water and streambed-water interaction, groundwater flow and water withdrawal, etc.). The heat flux (H_o, H_i, H_t, H_w) is defined as

$$H = C_p \rho Q T \quad (3)$$

where $C_p\rho$ is the heat capacity of water (TJ/m^3/K), Q is the measured river flow (Q_o, Q_i, Q_t) or discharge volume from WWTPs (Q_w) (m^3/h), T is the measured stream or effluent temperature (K). The heat flux caused by net radiation (H_r) is expressed as

$$H_r = R_n * A \quad (4)$$

where A is the water surface area (m^2), calculated from google earth image. R_n is the net radiation, which is derived from equations (5)-(9) [7),8)].

$$R_n = R_s(1-\alpha_s) + \varepsilon_s R_{ld} - R_{lu} \quad (5)$$

$$R_{lu} = \varepsilon_s \sigma T_s^4 \quad (6)$$

$$R_{ld} = [1-(1-\varepsilon_{ac})F_c]\sigma T_a^4 \quad (7)$$

$$\varepsilon_{ac} = 1 - 0.261 exp[-7.77 * 10^{-4}(T_a - 273)^2] \quad (8)$$

$$F_c = 0.826N_c^3 - 1.234N_c^2 + 1.135N_c + 0.298 \quad (9)$$

where R_s is the global short-wave radiation (TJ/m^2/h), α_s is the albedo of the water surface

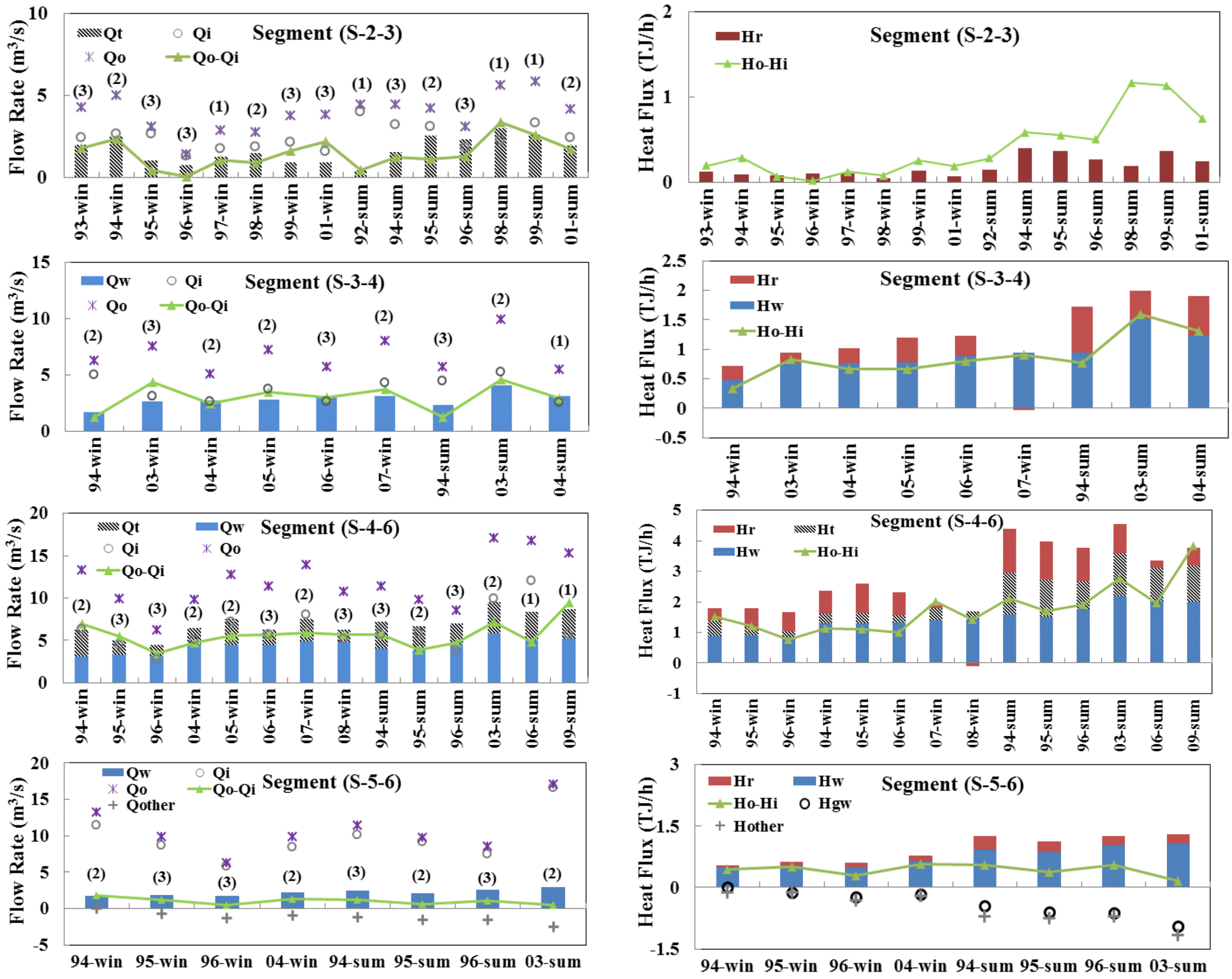

Fig.7 Water and energy budget for each segment in winter and summer seasons.

(0.06), ε_s is the emissivity of the water surface (0.97), R_{ld} and R_{up} are long-wave downward and upward radiation (TJ/m^2/h), σ is the Stefan-Boltzmann constant (TJ/m^2/K^4/h), T_s and T_a are stream temperature and air temperature (K), ε_{ac} is the atmospheric emissivity under clear skies, F_c is the cloud cover ratio, and N_c is the fraction of sunshine hours. The H_{other} in equation (2) is calculated by $H_{other} = H_o - H_i - H_t - H_w - H_r$.

The water and energy budget for each segment (**Fig. 7**) is calculated using equations (1)-(9). The data used for calculation were the monthly measured stream temperature and river flow, monthly effluent temperature and discharge volume from each WWTP along with the short-wave radiation and sunshine duration collected at the central Tokyo and air temperature measured at Fuchu. The number of events that were taken into account in each segment (shown in parentheses in **Fig. 7**) was based on the data availability and all the events selected are under normal flow condition. **Table 1** displays the consideration of factors in our analysis. The numbers on the left/right in the column indicate the number of WWTPs and tributaries that were considered in our analysis/existed in the segment respectively. The other factors such as weirs used for water withdrawal were not directly quantified due to the data limitation. Moreover, the flow rates of tributaries that were not measured tended to be small and negligible.

Table 1 Consideration of factors in each segment.

segment	Q_i, H_i, Q_o, H_o, H_r	Q_w, H_w	Q_t	H_t	Q_{other}, H_{other}
S-2-3	○	○ 0/0	△ 1/2	△ 0/2	×
S-3-4	○	○ 3/3	△ 0/2	△ 0/2	×
S-4-6	○	○ 4/4	△ 3/4	△ 3/4	×
S-5-6	○	○ 1/1	○ 0/0	○ 0/0	×

○: fully considered and calculated using observed data
△: partially considered and calculated using observed data
×: not directly quantified and calculated using Eqs. (1) and (2)

In segment S-2-3, the water budget result indicates that $Q_o - Q_i$ were almost balanced by the tributary inflows. The differences between $H_o - H_i$

and H_r were smaller in winter and comparatively larger in summer, probably due to the larger tributary inflow in summer seasons. Thus, in segment S-2-3, the water and energy transport processes are likely to be dominated by tributary inflow and the net radiation. In segments S-3-4 and S-4-6, which are under strong anthropogenic influences, the discharge volumes and heat inputs from WWTPs occupied large proportions of water and energy increases in most periods, whereas the effects of the net radiation and tributaries were relatively small. In both segments, the H_{other} primarily indicates the energy losses through sensible and latent heat, groundwater recharge and water withdrawal. The heat losses were quite larger in segment S-4-6 than that in segment S-3-4, which may result in the lesser increase in stream temperature between S-4 and S-6. In segment S-3-4, Q_{other} were quite small, which may be caused by tributary inflow, water withdrawal and groundwater recharge. In segment S-4-6, Q_{other} is probably caused by groundwater recharge and water withdrawal.

To better understand the effects of groundwater flow, budgets analysis in segment S-5-6 was also studied. The energy loss caused by groundwater recharge (H_{gw}) is estimated using equation (3), in which, Q is regarded equal to Q_{other} and T is stream temperature. The calculation result shows that H_{gw} is close to H_{other}, which suggests that the groundwater recharges took place and contributed a lot to the water and energy losses in segment S-5-6.

8. CONCLUSIONS

This study mainly investigated the long-term and longitudinal changes in stream temperature in the Tama River system, using data on stream temperatures, flow rates, effluent temperatures and volumes, air temperatures, global short-wave radiations and sunshine durations.

Stream temperature increase in winter season was detected at sites that had considerable increase in both effluent temperature and discharge volume over the study period. The flow rate decreased sharply between S-1 and S-2, resulting in different longitudinal stream temperature changes in the upstream region between winter and summer seasons. The relationships between air temperature and stream temperature at S-1, S-4 and S-6 for two periods indicate that the major cause of stream temperature increase was the wastewater released from WWTPs.

The budget analysis helps to understand the contribution of each component in water and energy transport processes in each segment. Tributary and net radiation were found to be the dominant factors in upstream segment of S-2-3. In segments that under anthropogenic impacts, the water and energy changes were largely contributed by wastewater inputs from WWTPs. Specifically, groundwater recharges were confirmed to be the major cause of water and heat losses in segment S-5-6.

To improve the urban water environment and control on the warming of stream temperature, several countermeasures can be taken. To control the water temperature during wastewater treatment process may be an effective way as most WWTPs value the removal of chemicals and nutrients. The use of warmer wastewater as heat sources and reuse of treated wastewater are also recommended as they can save energy and reduce the effluent release. Other alternative methods for wastewater treatment are also suggested such as man-made wetlands and stabilization ponds[9].

ACKNOWLEDGMENT: This work has been financially supported by the Tokyu Foundation for Better Environment. The authors express sincere gratitude to the Tokyo Bureau of Sewerage for providing data related to WWTPs.

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(Received September 30, 2011)