Journal of Hydrology 489 (2013) 16–25

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Analysis of stream temperature and heat budget in an urban river under strong anthropogenic influences

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ARTICLE INFO

Article history:
Received 7 July 2012
Received in revised form 26 January 2013
Accepted 16 February 2013
Available online 7 March 2013
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of Georgia Destouni, Associate Editor

Keywords:
Human impact
Stream temperature
Wastewater effluents
Water budget
Heat budget

SUMMARY

Stream temperature variations of the Tama River, which runs through highly urbanized areas of Tokyo, were studied in relation to anthropogenic impacts, including wastewater effluents, dam release and water withdrawal. Both long-term and longitudinal changes in stream temperature were identified and the influences of stream flow rate, temperature and volume of wastewater effluents and air temperature were investigated. Water and heat budget analyses were also conducted for several segments of the mainstream to clarify the relative impacts from natural and anthropogenic factors. Stream temperatures in the winter season significantly increased over the past 20 years at sites affected by intensive and warm effluents from wastewater treatment plants (WWTPs) located along the mainstream. In the summer season, a larger stream temperature increase was identified in the upstream reaches, which was attributable to the decreased flow rate due to water withdrawal. The relationship between air and stream temperatures indicated that stream temperatures at the upstream site were likely to be affected by a dam release, while temperatures in the downstream reaches have deviated more from air temperatures in recent years, probably due to the increased impacts of effluents from WWTPs. Results of the water and heat budget analyses indicated that the largest contributions to water and heat gains were attributable to wastewater effluents, while other factors such as groundwater recharge and water withdrawal were found to behave as energy sinks, especially in summer. The inflow from tributaries worked to reduce the impacts of dam release and the heat exchanges at the air–water interface contributed less to heat budgets in both winter and summer seasons for all river segments.

1. Introduction

Stream temperature is a fundamental aspect of water quality and ecosystem health affecting physical, chemical and biological river processes (Caissie, 2006). It affects many aspects of stream and river biota, such as the geographical distribution, growth rate and reproduction of aquatic life. Most aquatic organisms, particularly fish, have specific temperature preferences (Billman et al., 2006). If the stream temperature rises above an upper threshold, biological processes such as growth or reproduction, or even survival itself, are expected to decline or cease (Eaton et al., 1995). An increasing number of studies have focused on the impact of climate change, which can modify the thermal regime of rivers and ultimately affect fish and other aquatic species (Magnuson et al., 1990; Mohseni et al., 2003; Rahel et al., 1996; Stefan et al., 1995). As such, a better understanding of the thermal behavior of river systems under different hydrological conditions and levels of human impact is essential for environmental management and conservation.

The temperature of river water is fundamentally dependent on both natural and anthropogenic energy exchange processes (Fig. 2). Natural processes include heat exchanges across the water surface and streambed, as well as heat advection from tributaries and groundwater flows. Several studies have formulated models to quantify and predict stream temperature behavior, with particular emphasis on heat exchanges across the water surface and streambed (Caissie et al., 2007; Hebert et al., 2011; Sinokrot and Stefan, 1994; Webb and Zhang, 1997). The relative contributions of each natural process such as solar radiation, net longwave radiation, latent and sensible heat fluxes, streambed heat conduction and advective fluxes have been analyzed. Webb and Zhang (1999) demonstrated that heat budget was dominated by radiative fluxes in the River Piddle tributary and the River Bere (both in UK), which accounted on average for close to 90% of the non-advective heat gain in both the summer and winter seasons. Evans et al. (1998) investigated river heat budgets with an emphasis on the streambed–water interaction. In their study, over 82% of the total energy transfers occurred at the air–water interface, with 15% at

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http://dx.doi.org/10.1016/j.jhydrol.2013.02.048

the streambed–water interface. Recent studies regarding stream temperature give particular attention to how human impacts may alter stream and river temperatures (Webb et al., 2008). Kinouchi et al. (2007) found that the stream temperatures increased in winter and early spring at a rate of 0.11–0.21 °C/year in the Tokyo area, with the increase being attributed to the thermal effluents of urban wastewater. Prats et al. (2010) showed that the reservoir release and thermal effluent of a nuclear power plant resulted in an increase of 2.3 °C of the mean annual water temperature in the lower reach of Ebro River, Spain. Other anthropogenic factors that affect stream temperature have been studied including water diversions (Sinokrot and Gulliver, 2000), regional land-use alteration (LeBlanc et al., 1997; Malcolm et al., 2008) and climate change (Mohseni et al., 1999; Tung et al., 2006).

Although several studies have investigated the various gains and losses of energy by analyzing the heat budget, few have actually analyzed urban effects on stream temperatures and heat budgets considering different types of natural and anthropogenic effects. Therefore, our study was designed to provide a better understanding of how human activities alter the stream temperature and heat budget of an urban river. Specifically, the aims of this study were to reveal both the long-term (from 1990 to 2010) and longitudinal (more than 50 km) temperature changes in the mainstream of the Tama River. To identify the major factors that influenced these changes, we analyzed the flow rate changes, the temperature and volume of wastewater effluents from WWTPs, as well as the relationships between air and stream temperatures. We also analyzed the water and heat budgets in selected river segments to quantify the important processes that determine the temperature regime.

2. Study site and data source

We studied the mainstream of the Tama River system, a major river system running through the central Tokyo Metropolitan area (Fig. 1). It originates from forested mountain ranges and flows through the Ogochi reservoir into Tokyo Bay. The Ogochi reservoir was created by the construction of Ogochi Dam. The Tama River watershed has an area of 1240 km^2 with the upstream region largely covered by forest and grassland, whereas downstream areas are highly urbanized. The forest and urban areas accounted for 60.0% and 22.5% of the watershed in 1991, and 58.8% and 26.5% in 2006, respectively. Because the downstream river system is located in one of the most flourishing urban areas in the world, the population density in the watershed is high (3400 person/km^2), which results in considerable anthropogenic influences on the streams. For example, eight wastewater treatment plants (WWTPs) are located in the middle and lower reaches of the river. This sewer network has gradually expanded from 78% coverage of the total population in 1990 to 99% in 2010. A certain volume of water is also diverted from the river at several weirs for drinking, agriculture and industry purposes.

To analyze stream temperature variations and heat budgets in the mainstream, we utilized existing data for stream temperatures and flow rates, wastewater effluents and meteorological conditions. Stream temperatures and flow rates have been measured at 11 sites (hereafter S1–S11) and 9 sites (S1–S9), respectively (Fig. 1). These data consist of monthly measurement records, which were taken two to four times for water temperature and once for flow rate on a particular day each month and are available for the period between 1990 and 2010 from the Ministry of Land,

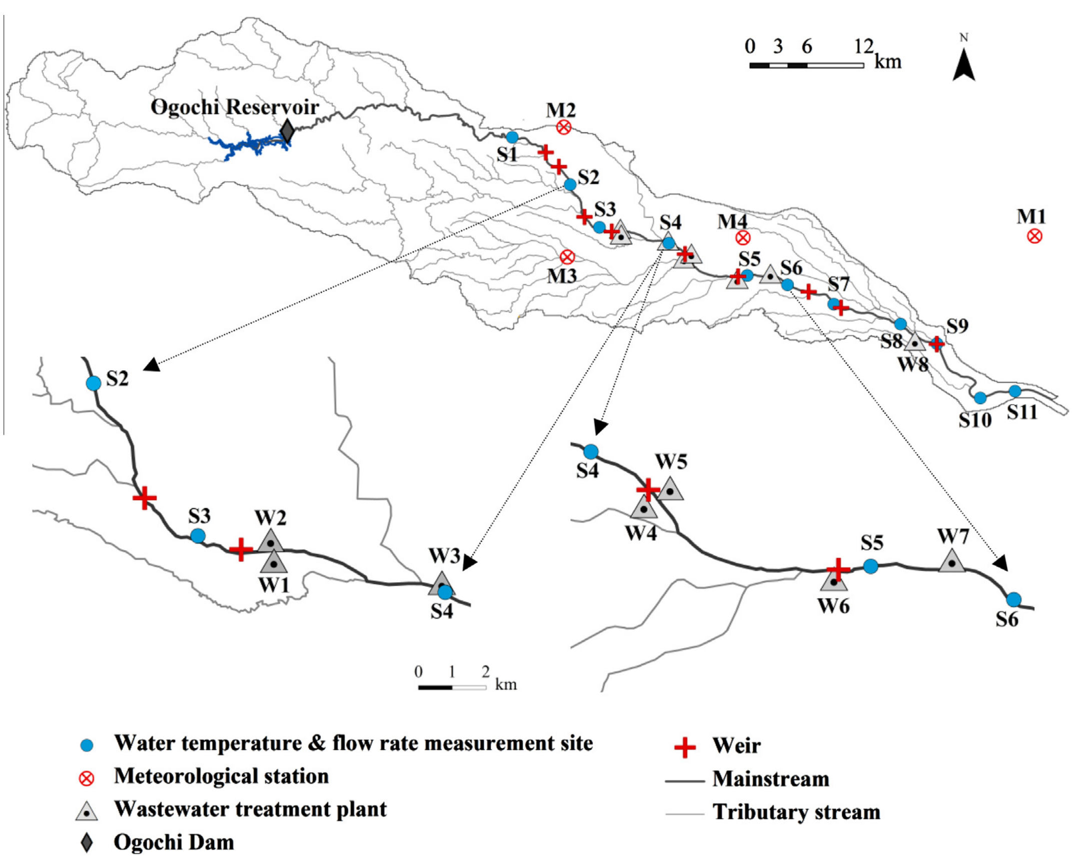

Fig. 1. Study area showing the Tama River system, mainstream, tributary stream, location of Ogochi Dam, wastewater treatment plants, weirs and measurement sites.