

URBAN STREAM TEMPERATURE SIMULATION UNDER STRONG ANTHROPOGENIC INFLUENCES

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Abstract

To simulate watershed scale hydrological and heat transport processes and resulting stream temperatures, a physically based distributed hydrological model (WEP model) was coupled with a physically distributed model of heat transport in river water. This model is designed to investigate factors affecting spatial and temporal variations of the stream temperature by taking anthropogenic heat impacts and urban canopy processes into accounts. Applying the model to the Kanda River Watershed in Tokyo, Japan, stream flow and temperature as well as inflows to a WWTP are well simulated. We found that the urban stream geometry and the riparian vegetation strongly influence the stream temperature in summer. The anthropogenic heat impact on stream temperature was found to be so significant.

Key words: stream temperature, urban hydrology, distributed modeling

1. INTRODUCTION

Streams are thought to have important natural functions such as natural landscaping, conserving habitats, and controlling the micro-climate in urban environments. Such functions can be effective when appropriate stream temperatures and other quality levels are maintained. However, urban streams are vulnerable to thermal pollution due to various direct and indirect anthropogenic impacts such as the effluent from wastewater treatment plants, destruction of riparian vegetation, river channelization, the runoff from paved surfaces and global warming. Increased stream temperature can decrease the environmental importance of urban streams and various ecological impacts have been observed such as the increase in invasive species. Because of increasing urban water and energy waste due to population growth and high energy consumption life-styles, the temperature and magnitude of urban wastewater has increased significantly (Kinouchi, 2007), which may have resulted in the long-term increase in stream temperature. Kinouchi et al. (2007) indicated that the stream temperature in winter and early spring in the central Tokyo increased significantly due to a considerable increase in wastewater heat input.

To conserve environmental values of urban streams, a framework needs to be provided for predicting stream temperatures under various natural and anthropogenic controlling factors. Although there are many physically based in-stream models that are capable of simulating the shading effects, the impact of urbanization and global warming, few studies have modelled and validated stream temperature variations considering hydrological processes in a watershed scale. However, the predictive framework of urban stream temperature needs to include hydrological modeling as the stream temperature is dependent on the hydrological behavior of watersheds as well as on the riparian conditions and anthropogenic heating/cooling factors. In addition, characteristic radiation environment in channels run through highly urbanized areas requires special modeling of air-water heat fluxes. For this purpose, a physically based distributed hydrological model was modified and coupled with a newly developed model of heat transport in river water, and the performance of the model was demonstrated by applying it to a highly urbanized watershed in Tokyo, Japan, where anthropogenic impacts are significant in modifying natural hydrologic cycle and the water temperature.

2. MODEL

2.1. Modeling hydrological system with dual drainage networks

The simulation of hydrological processes in an urbanized watershed with dual drainage system is based on the WEP model, a physically based distributed hydrological model developed by Jia et al. (2001). The main features of this model include coupling simulation of hydrological processes and energy transfer processes, simulation of interactive impact of surface water and groundwater, and the mosaic structure within a grid cell. The simulated hydrological processes include evapotranspiration, infiltration, surface runoff, subsurface runoff, groundwater flow, overland flow, and river flow. The simulated land surface energy transfer processes include short-wave radiation, long-wave radiation, latent heat flux, sensible heat flux, and soil heat flux.

In urbanized watersheds equipped with sewer networks, storm runoff flows down through gutters, lateral pipes and sewer pipes during periods of rainfall. In a combined sewer system, the stormwater mixed with waste from houses and buildings eventually flows into a wastewater treatment plant (WWTP). Untreated wastewater in the sewer system overflows to a river system through combined sewer overflow (CSO) outlets following heavy rainfalls. In no-rainfall periods, the waste water from houses and buildings flows into the WWTP and the treated wastewater is discharged into streams. To take these characteristics of dual drainage networks into account in the WEP model, flows in sewer pipes are routed as an overland flow in underground spaces, instead of directly solving unsteady flows in a sewer network, to reduce modeling complexity. Overland flow routing is carried out by means of the kinematic wave method with equivalent roughness parameters deduced from land use data, while a single value is given for the flow routing in a sewer network.

2.2. Modeling heat transport in streams

A basic equation for heat transport in an open channel is written as

$$\frac{\partial(AT)}{A\partial t} + \frac{\partial(QT)}{A\partial x} = \frac{1}{A} \frac{\partial}{\partial x} (AD \frac{\partial T}{\partial x}) + \frac{W_h}{\rho_w c_{pw} V} + \frac{J_h}{\rho_w c_{pw} H} + \frac{J_s}{\rho_w c_{pw} H} \quad (1)$$

where T = the water temperature [$^{\circ}\text{C}$]; A = the cross-sectional area [m^2]; Q = the flow rate [m^3/s]; D = the longitudinal dispersion coefficient; W_h = the net heat load from surface flow, subsurface flow, groundwater flow, treated wastewater and combined sewer overflow [J/s]; J_h = the air-water heat flux [W/m^2]; J_s = the heat flux from the stream bed to the stream water [W/m^2]; V = the water volume of stream element [m^3]; H = the water depth [m]; ρ_w = the density of water [kg/m^3]; c_{pw} = the specific heat of water [$\text{J}/\text{kg}/^{\circ}\text{C}$]; x = the flow direction [m]; t = the time [s]. The net heat load W_h from sources is computed from the magnitude and temperature of point source (wastewater effluents from WWTPs and CSO) and non-point source (surface flow, subsurface flow and groundwater flow). Thermal runoff may cause a rise of stream temperature to a lethal level during rainfall periods in hot seasons. However, since we mainly focus on stream temperature variations during the low flow periods, the temperature of the surface runoff is assumed to be the same as the air temperature. The observed volume and temperature of the wastewater effluents were used, though it can be computed from Kinouchi (2007). The temperature of subsurface and groundwater flows is assumed to be the same as the ground temperature at a specified depth. The air-water heat flux J_h is computed as

$$J_h = RN - J_c - J_e = I_s^* + J_s^* - J_c - J_e \quad (2)$$

where RN = the net radiation at the water surface; J_c = the sensible heat flux; J_e = the latent heat flux; I_s^* = the net solar shortwave radiation at the water surface; J_s^* = the net atmospheric longwave radiation at the water surface. The net radiation RN is associated with many factors such as the solar zenith angle, the river transversal and cross-sectional dimensions, riparian vegetation and buildings. Here, we take such factors into account, except for the shading effect of buildings. The riparian vegetation and structures crossing the stream modify the shortwave and longwave radiative fluxes. We modelled the attenuation of the solar radiation by the riparian vegetation. The heat flux from the river bed to the stream water (J_s) is calculated from the equation which depends on the stream and river bed temperatures, the thickness, the heat capacity and the thermal diffusivity of the river bed layer. The surface temperature of the river side wall is also calculated from a heat balance equation of the side wall.

3. APPLICATION

3.1. Study area

We applied the hydrological model coupled with the heat energy transport model to the Kanda River watershed located in the heart of Tokyo, Japan (Figure 1). Tributaries run in four open channels and one covered channel in upstream sub-watersheds, and eventually merges to the mainstream. The Momozono River is a covered channel all along the stream (Figure 1). The channels have a trapezoidal cross-sectional shape in most of their reaches. The Kanda River watershed has a combined sewer system and the watershed can be divided into five sewer catchments. Sewage generated in the catchment bounded by a dashed line (Figure 1) flows into two WWTPs within the watershed (the Ochiai WWTP and the Nakano WWTP), where treated effluents are discharged into the Kanda River. In all other catchments, the sewage is transported to WWTPs located outside the Kanda River watershed through the sewer pipes across the watershed boundary. Stormwater flows in the same route during periods of rainfall with relatively light intensity. During periods of heavy rainfall, the CSO in all sewer catchments directly discharges into the Kanda River system from the CSO outlets.

3.2. Input data, parameters and simulation settings

The main input data required to run the model are listed in Table 1. Spatial distribution of correspondent data was prepared using ArcGIS. Stream network data was reproduced on the GIS platform from the digital maps by the Geographical Survey Institute. The watershed was divided into 9 sub-watersheds. River cross-sectional area was approximated as a trapezoidal shape. The orientation of the stream channel was calculated for each river element. Categorized data of riparian vegetation and structures crossing channels, which were prepared

from aerial photographs, are attributed to individual computational element of river channels. The actual sewer network data was not used. Instead, we assumed that the flows in the sewer pipes followed the terrain of the watershed, which was found to be a reasonable assumption.

There are three categories of parameters used in the WEP model: (1) parameters of land surface and river channel system; (2) parameters of vegetation; and (3) parameters of soil and aquifer. Parameters for the heat transport model are additionally specified. All of parameters were initially specified from literatures or estimated according to land cover information, observation data, and some parameters are selected for model calibration. Ratios of the impervious area, four types of pervious areas and water surfaces for each computational mesh (100m by 100m) were given by reclassifying the fine land use data, referring to previous studies (Jia et al., 2005). The spatial distribution data of the topsoil was generated from geological maps. The topsoil in the watershed is mainly the Kanto loam, except for the alluvial soil in riparian zones. The physical properties for each soil type were given from Jia et al. (2005). The air-water heat flux in the Momozono river, a fully covered channel, was computed by setting the direct and diffuse solar radiations as zero and the downward longwave radiation from the cover was assumed to be the same as the downward atmospheric longwave radiation. The model calibration was performed for both stream flows and temperatures at locations where observed values are obtained. For flow simulations, some flood hydrographs and low flows were checked to calibrate parameters such as the Manning's roughness of the river flow and the hydraulic conductivity of the riverbed. Calibration of parameters for the stream temperature was carried out to reproduce its seasonal and diurnal variations.

The coupled model was run for the simulation from January 1 to December 31 of 2005 in a time step of 1 hour (except for overland flow and river flow routing with a time step of 10 minutes) and a grid cell size of 100m×100m. The computational domain includes 9062 grid cells. River channels were divided into computational elements with the longitudinal length of 390m - 450m. The headwater of the stream was maintained by the pumped groundwater. Thus, the upstream boundary conditions were set by the constant stream flow and variable water temperatures deduced from the ground temperature. The temperature of the base flow from the groundwater was likewise set at an equivalent temperature of the ground at the depth of the river bed.

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4. RESULTS

4.1. Streamflow

The simulated results of low streamflows were compared with those observed at Kotobuki and Chitose (Figure 1). Most of the river reaches are covered by a concrete bottom slab and side walls, which prevent water interaction between river flows and groundwater. As a result, the streamflow could be quite low during periods without rainfall. This situation was reproduced well by the simulation (Table 2). Simulated flood discharges during four major storm events in 2005 were compared with hydrographs at Asahi and Honan obtained from observed rating curves and measured water levels. Simulated hydrographs relatively well reproduced observed ones at Asahi for three events (July 9-10, August 15-16 and 25-26) and at Honan for two events (July 9-10 and August 25-26).

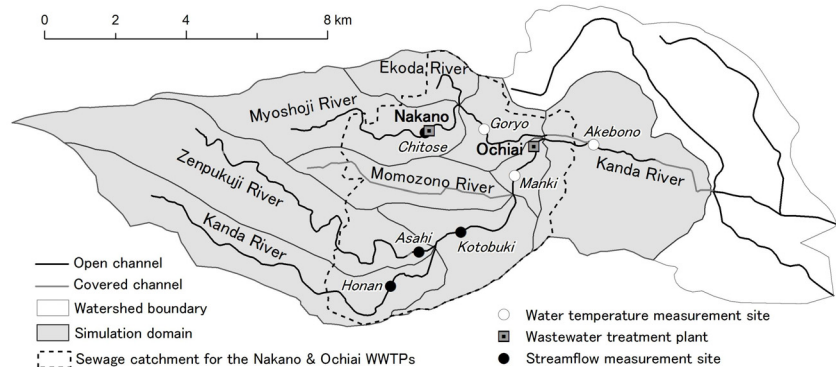


Figure 1. Outline of the Kanda Watershed

Table 1. List of main input data used for the coupled model simulation

Category	Item	Source
Land surface conditions	Watershed boundary	National digital information
	Topography	Digital map (50m by 50m DEM)
	Land use	Fine digital information (13 types of land use, 100m by 100m raster data)
Meteorological and hydrological conditions	Precipitation (19 stations)	Hourly data from the Tokyo Metropolitan Government
	Relative humidity (1 station)	
	Air temperature (3 stations)	
	Wind velocity (3 stations)	
	Sunshine duration (3 stations)	
River network and hydraulic dimensions	Stream channel	Digital Map (1:25,000)
	River profiles	Maps obtained from Tokyo Metropolitan Government
	Riparian vegetation	Aerial photographs
	Crossing structure	Aerial photographs
Anthropogenic conditions	Population	National census data by the Ministry of Internal Affairs and Communications
	Sewer catchment boundary	Maps obtained from the Tokyo Metropolitan Government

Table 2. Simulated and observed stream flow during no-rainfall periods

Location	Period	Observed average flow	Simulated average flow
Kotobuki	2005/1/20-21	0.52 m ³ /s	0.55 m ³ /s
Chitose	2005/1/18-19	0.07 m ³ /s	0.10 m ³ /s

4.2. Water temperature

The simulated stream temperatures are compared with those observed (Figure 2). Modeled stream temperatures matched well with those observed at Goryo throughout the year. Modeled stream temperatures at Manki show larger amplitudes of the diurnal variation than those observed in the fall and winter seasons. Akebono, where we started temperature measurement from November 2005, exhibited flatter temperature variations than those observed at Goryo and Manki. This is mainly because the wastewater effluents from two WWTPs comprise the main portion of the streamflow at Akebono and thus the diurnal temperature variation is dominated by the effluent temperature that has small diurnal amplitudes. Stream temperatures simulated by assuming no wastewater inputs were far below the temperatures simulated with wastewater inputs (Figure 2, bottom), and the maximum difference of stream temperature was found to be approximately 12°C. This suggests that there is a strong influence of wastewater effluents on the stream temperature in the Kanda River, and potential impacts on the habitat for fish and invertebrates and algae growth. The dependency of the stream temperature on the sky view factor is shown in Figure 3. The sky view factor, as an indicator of the channel geometry and the riparian vegetation, strongly influence the stream temperature in summer.

5. CONCLUSION

A framework was presented for the water temperature prediction in urban streams under distributed anthropogenic and natural heat sources in the urbanized watershed. The predictive model developed in this study is based on a model of heat transport in river water incorporated into a physically based distributed hydrological model (WEP model). This model was applied to the Kanda River watershed in Tokyo, and showed that it could reproduce well low flows and flood runoff. Overall magnitudes of the simulated stream temperature agreed well with those of observed. Impacts of anthropogenic heat input from WWTPs and riparian conditions were found to be very significant.

Acknowledgment

This work has been financially supported by CREST of JST (Japan Science and Technology Corporation).

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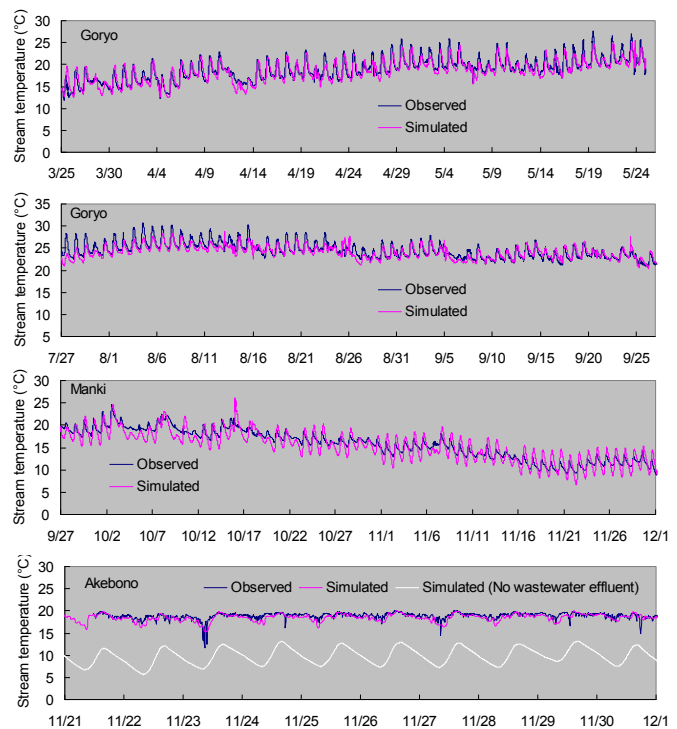


Figure 2. Comparison of simulated stream temperatures with observed.

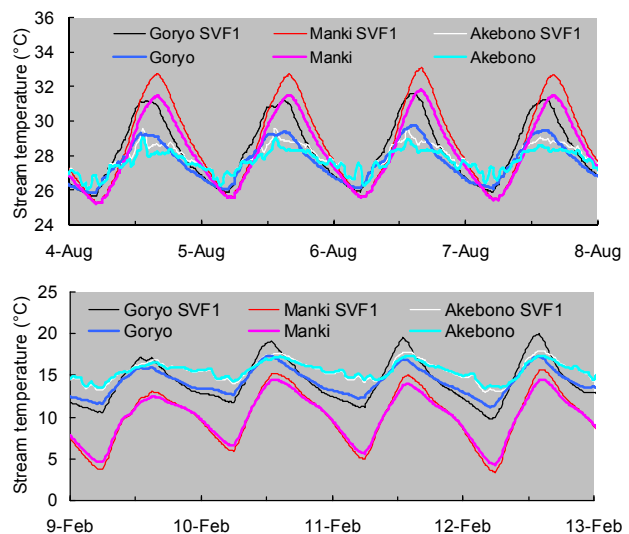


Figure 3. Effect of sky view factor on stream temperature