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ANALYSIS OF LONG-TERM CHANGE IN THERMAL FORCING TO RECEIVING WATER DUE TO URBAN WATER AND ENERGY CONSUMPTION

By

Tsuyoshi Kinouchi

Hydraulic Engineering Research Group, Public Works Research Institute, Tsukuba, Japan

SYNOPSIS

In a highly urbanized watershed, a huge amount of water consumed and heated by urban activities is eventually drained into natural streams and oceans through sewage treatment plants, and it could be a thermal forcing that affects the temperature of receiving water. To investigate the effluent temperature from the outlet of sewage treatment plants, a watershed-scale water and heat budget model that accounts for water and energy supply, consumption and transport processes within urban areas is used in the 23 special-ward area of Tokyo. It is verified by both measured data and model calculation that the effluent temperature and heat efflux at the outlet of treatment plants have been increasing considerably during the past 30 years. The rise in the effluent temperature was mostly due to the increase in the supply water temperature and the added heat energy associated with residential, business and commercial sectors. For the residential sector, the rise in drain temperature mostly results from the increase in the water use for bathing. As for the business and commercial sectors, the rise in drain temperature is due to the increasing floor area and resulting energy consumption.

INTRODUCTION

A huge amount of water and energy consumed for urban activities is eventually released into the atmosphere and hydrosphere. Although the impact of the anthropogenic heat emission on the urban boundary layer has been drawing research and practical attention for improving urban atmospheric environment (e.g., Kimura and Takahashi 1991), typical artificial heat inputs into a natural hydrologic system are believed to occur as effluents from electric power generating stations and industrial facilities (e.g., Erickson and Stefan 2000). Thus, even though many studies have been conducted to predict stream temperature (e.g., Sinokrot and Stefen 1993, LeBlanc et al. 1997, Chen et al. 1998, Younus et al. 2000), effluent from urbanized areas has been a negligible factor. However, information about temperature and volume of effluents from urbanized areas is important for evaluating the thermal impact on aquatic habitats in streams, estuaries and bays located along cities with considerable activities. As cities grow into metropolitan areas such as Tokyo, Shanghai, Singapore and others, the thermal impact of enormous effluents from urban areas to the receiving water cannot be negligible, yet it will be increasingly important. Accordingly, the quantification of thermal forcing of urban effluents into

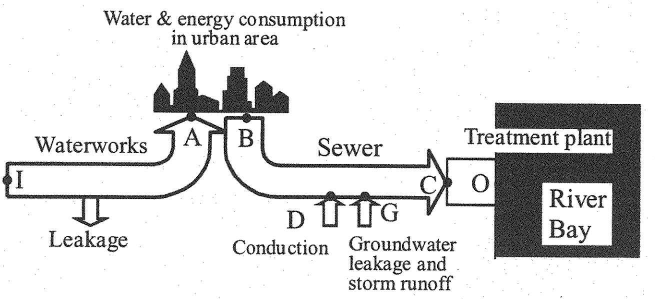

Fig. 1. Schematic Diagram of the Artificial Water and Energy Flow in the Urban Area

the receiving water, which is represented by the amount and temperature of effluent, is quite valuable. For this purpose, a watershed-scale water and heat balance model is required to quantify the temperature of heated effluents from urbanized watersheds, as the temperature of effluents from urbanized watersheds is determined by supply water temperature, water and energy consumption by urban activities, heat exchange between water and ground, etc.

In this paper, a watershed-scale water and heat budget model that accounts for urban water and energy supply, consumption and transport processes was constructed to quantify the effluent temperature via treatment plants in highly urbanized areas, and the model was applied to the sewerage system in the 23 special-ward area of Tokyo to investigate the long-term change of effluent temperature and relevant factors in determining the effluent temperature.

MODEL DESCRIPTION

In typical urbanized cities, water flows into the city area through waterworks and is used for various purposes. The water gains heat by energy consumption for some specific purposes such as bathing and kitchen, and it eventually drains into a sewerage system. Furthermore, the sewage flows into sewer pipes which mixes with leaking groundwater and storm runoff (this is the case for a combined sewerage system during rainfall events), which change sewage temperature along with the heat conduction into the ground surrounding sewer pipes. Finally, the sewage is dumped into rivers or bays as appropriate treatment processes are finished. Fig. 1 represents the artificial water and energy cycle in urbanized areas in which sewer networks are fully developed.

These water and heat transport processes in urbanized areas via waterworks and sewer networks are modeled to quantify the effluent temperature from sewage treatment plants. The upstream boundary condition of supply water volume and temperature is defined at point A in Fig. 1, which is located just before the entry to residential houses, business and commercial buildings, and manufacturing factories. The temperature change between point A and B is dependent on the net heat energy added to the water. Temperature change in the sewer networks by heat conduction into the surrounding ground and advection with groundwater leakage and storm runoff into sewers occurs between point B and C. The annual mean temperature of the sewage into treatment plants is defined at point C. The effluent temperature and heat efflux is defined at the outlet of treatment plants (point O).

A set of basic equations used in the model is described by the heat and water budget as shown in equations (1)~(5). The heat influxes by groundwater leakage and storm drain into sewers are considered in equation (4) to give mean water temperature flowing to sewage treatment plants. The water temperature change along with sewer networks by heat conduction into the surrounding ground is expressed by equation (6).

$$Q_A = Q_B \quad (1)$$
$$Q_C = Q_B + Q_{GW} + Q_R = Q_O \quad (2)$$
$$Q_A(T_A - T_r) + H/c_p\rho = Q_B(T_B - T_r) \quad (3)$$
$$Q_C(T_C - T_r) = Q_B(T_{BC} - T_r) + Q_{GW}(T_{GW} - T_r) + Q_R(T_R - T_r) \quad (4)$$
$$Q_O(T_O - T_r) = Q_C(T_C - T_r) + \Delta H_C/c_p\rho \quad (5)$$
$$T_{BC} - T_G = (T_B - T_G)\exp(-kt_f) \quad (6)$$

where Q_A = volume of supply water (m^3/day); Q_B = volume of wastewater (m^3/day); Q_C = volume of influent at the inlet of treatment plants (m^3/day); Q_{GW} = volume of groundwater leakage into sewers (m^3/day); Q_R = volume of storm drain into sewers (m^3/day); Q_O = volume of effluent at the outlet of treatment plants (m^3/day); T_A = temperature of supply water (°C); T_B = temperature of wastewater (°C); T_C = influent temperature at the inlet of treatment plants (°C); T_{GW} = temperature of groundwater leaking into sewers (°C); T_R = temperature of storm drain into sewers (°C); T_{BC} = temperature of wastewater at the inlet of sewage treatment plant (°C); T_G = ground temperature (°C); T_O = the effluent temperature at the outlet of treatment plants (°C); ΔH_C = net heat gain by sewage through the treatment process between points C and O (J/day); H = energy consumed to heat supply water (J/day) defined in equations (7)~(9); $c_p\rho$ = heat capacity (J/m^3/K); T_r = reference temperature (°C); k = constant for heat conduction (1/hour); and t_f = mean travel time of sewage flow (hour). It is assumed that the volume of supply water (Q_A) is equivalent to the volume of wastewater (Q_B). The ground temperature (T_G) is assumed to be the same as air temperature when quantifying the annual mean effluent temperature.

There are two alternative methods to quantify the energy consumed to heat supply water H in equation (3). The one is represented by equation (8), which requires specification of the volume (Q_{ij}) and temperature (T_{ij}) of drain from building type j for individual purposes i such as bathing and cleaning. Another method is to sum up the heat added to water for each purpose h_{ij} (J/day), as shown in equation (9).

$$H = \sum_j H_j \quad (7)$$
$$H_j = c_p\rho \sum_i Q_{ij}(T_{ij} - T_A) \quad (8)$$
$$H_j = \sum_i h_{ij} \quad (9)$$

where H_j (J/day) = energy used to heat supply water for building type j (i.e. residential houses, business and commercial buildings, or manufacturing factories).

For residential houses, it is practical to apply equation (8) specifying Q_{ij} and T_{ij} based on existing information. On the other hand, there is little information about the temperature of wastewater from individual purposes for business and commercial buildings, while the energy consumption rate for each purpose can be obtained from several sources (e.g., Ojima 1995). Thus, equation (9) is applied to quantify H_j for business and commercial buildings. Equations (1) through (9) are used to give the mean influent temperature at the inlet of treatment plants, assuming H_j for industrial facilities is negligible.

In fact, the sewage temperature changes through the treatment process and heat loss within a treatment plant (Sedory and Stenstrom 1995). In this model, the net heat gain ΔH_C is assumed zero as the difference of T_C and T_O is found to be small on average according to the data provided from the Sewerage Bureau of Tokyo Metropolitan Government.

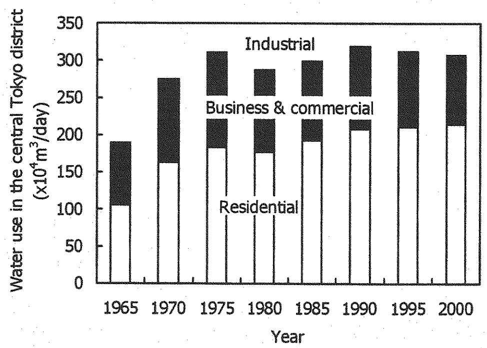

Fig. 2. Water Use in the 23 Special-ward Area of Tokyo

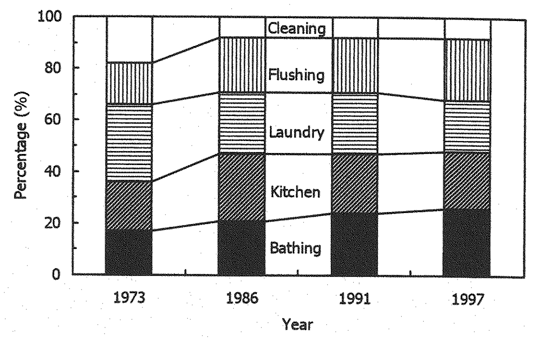

Fig. 3. Transition of the Ratio of Water Use by Each Category in the Household

APPLICATION TO 23 SPECIAL-WARD AREA OF TOKYO

Overview of sewerage system

A combined sewerage system has been adopted for the most part of the 23 special-ward area of Tokyo, while a separated sewerage system is partially provided. In 1965, sewer networks in the 23 special-ward area of Tokyo covered 35% in population of its total. The ratio gradually increased to 63% in 1975 and 83% in 1985. Almost all areas were linked to sewer networks in 1994. As of March 2000, the total number of households connected to the sewage system reached 8.2 million, the total length of sewer pipes was about 1000 km for main pipes and more than 14,000km for branches, and daily mean sewage volume was 4.76 million m^3. The 23 special-ward area of Tokyo is currently divided into 10 sub-basins, and each has one or more sewage treatment plants at the downstream end.

Supply water volume and temperature

The total amount of water consumed for residential houses, business and commercial buildings, and manufacturing factories is recorded by the General Affairs Bureau of Tokyo Metropolitan Government on monthly basis. Each percentage to the total is provided from the Waterworks Bureau of Tokyo Metropolitan Government (unpublished data) as shown in Fig. 2. The percentages of water volume consumed in residential houses for bathing, laundry, kitchen, flushing, cleaning and other purposes are given by the Waterworks Bureau of Tokyo Metropolitan Government (unpublished statistic for 1991 and 1997) and the Ministry of Welfare (1977, 1990) as shown in Fig. 3. The percentages of bathing and flushing have been increasing, while cleaning and kitchen decreasing. From these findings, it can be inferred that the water use increase for bathing is resulted from the diffusion of shower and bigger bathtubs. The water use for flushing increased by 5 points in percentage between 1973 and 1986, which may be due to the diffusion of flush toilet due to the provision of sewer networks.

There is no direct measurement data of supply water temperatures, even though the Tokyo Metropolitan Government measures hydrant temperatures periodically. Thus, the average of measured hydrant temperatures at 30 ~ 60 locations is used for the annual mean supply water temperature. As shown in Fig. 4, the supply water temperature has been

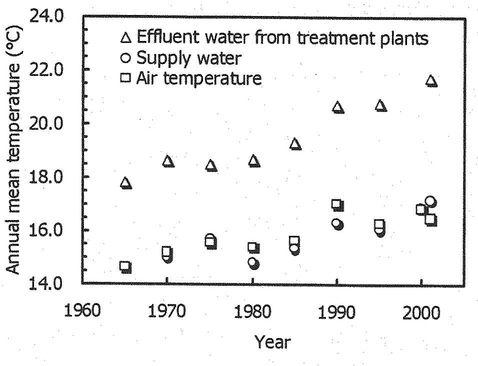

Fig. 4. Time Variation of the Annual Mean Supply Water Temperature

Table 1. Water temperature for each purpose of water use

Item	Temperature
Drain from shower	40°C
Bathtub filling water	40°C
Hot water for kitchen	40°C
Unheated water for kitchen	Hydrant water temperature
Drain from washing machines	Hydrant water temperature
Drain from toilets	Hydrant water temperature
Drain from other utilities	Hydrant water temperature

increasing 2°C since 1970, and is quite close in magnitude to the annual mean air temperature measured at the Ootemachi Observatory of the Japan Meteorological Agency located in a business district of the 23 special-ward area of Tokyo.

Heat energy added to supply water

For residential houses, the temperature of drains for each water use is specified as shown in Table 1. For bathing, the temperature of drains from bathtubs and showers are given separately. The temperature of drains from showers was set to 40°C. The drain water temperature of bathtubs $T_{bath\text{-}drain}$ (°C) is estimated by equation (10) that depends on the temperature of filling water $T_{bath\text{-}filling}$ (°C), mean air temperature T_{air} (°C), constant for heat conduction k' (1/hour) and the interval between filling and draining t_d (hour).

$$T_{bath-drain} - T_{air} = (T_{bath-filling} - T_{air})\exp(-k' t_d) \qquad (10)$$

The ratio of water volume used for bathtub filling and shower is set to 60:40 after the Ministry of Welfare (1990). For kitchens, there seems no distinct data available for determining the drain water temperature. For convenience, it is assumed that the supply water has a temperature of 40°C for hot water and hydrant temperature for unheated water, each comprising a half of the total volume used in the kitchen. The temperature of drains from washing machines, toilets and other utilities is assumed to be the same as the supply water temperature.

Information on the energy consumed for each purpose in several building categories (see Table 2) is necessary to quantify the mean temperature of drains from business and commercial buildings. It is assumed that 70% of the energy used for hot water supply turns into heat added to the water and the rest is emitted into the atmosphere as the anthropogenic heat, whose percentage is determined by the energy efficiency of typical appliances. The whole energy used for other purposes is assumed to turn into heat that is emitted into the atmosphere. The integration of energy used to heat supplied water in each category is carried out by using the constant energy consumption rate of hot water supply and kitchen for each building category as shown in Table 2 (Ojima 1995) and the total floor area of each building category in the Tokyo district provided by the Environment Bureau of Tokyo Metropolitan Government. The energy consumption rate in Table 2 is further processed to give energy consumption rate for hot water supply only by multiplying constant ratio

Table 2. Energy Consumption Rate of Hot Water Supply and Kitchen for Individual Buildings

Kind of Building	Category	Energy Consumption Rate ($MJ/m^2/year$)
Office building	Business	3.1
Department store	Commerce	5.5
Retail store	Commerce	5.5
Restaurant	Commerce	5.5
Hotel	Lodging	74.1
School	Education	0.0
Hospital and medical facilities	Medical service	49.2
Other services	Leisure	15.3

given by Energy Data and Modeling Center (1999) as 0.87, 0.87, 0.84, 0.81, 0.79, 0.76 and 0.76 for 1970, 1975, 1980, 1985, 1990, 1995 and 2001, respectively.

The temperature of industrial wastewater is set at the same temperature as the supply water temperature, resulting in the zero additional heat. The sensitivity of this assumption is quite small as the volumetric percentage of industrial wastewater is only about 2 ~ 10% of the total water used in the whole area.

The data on the volume of groundwater leakage and storm runoff into sewers within the 23 special-ward area of Tokyo are obtained from the Sewerage Bureau of Tokyo Metropolitan Government. The annual mean temperature of the leaked groundwater and storm runoff is assumed to be the same as the annual mean air temperature near the ground at the Ootemachi Observatory.

Parameter setting

The constant for heat conduction k (1/hour) in equation (6) is set to 0.048 after Miyoshi et al. (1990). The mean travel time of sewage t_f in equation (6) was estimated by the following manner. First, the time lag between the occurrence time of least water consumption rate in houses and buildings (approximately 3 *a.m.*) and the occurrence time of minimum influent to a treatment plant, which is given by the operational record of four largest treatment plants, is determined. Thus, the relation between the time lag and the area of sub-basin was derived to obtain the travel time for all sub-basins in the 23 special-ward area of Tokyo. Weighing the travel time with the volume of effluent from each treatment plant yields the mean travel time as about 5 hours.

The interval between filling and draining (t_d) which is expressed in equation (10) was set to 7.5 hours according to the survey conducted by Tokutomi et al. (1999). The constant for heat conduction k' (1/hour) in equation (10) is set to 0.052 according to the time variation data of bath water temperature provided from the Tokyo Gas Co. LTD.

RESULTS

The proposed model with aforementioned settings is applied to the 23 special-ward area of Tokyo to quantify the annual mean effluent temperature from treatment plants and validate with measured data during the past three decades. The factors affecting the effluent temperature and heat efflux are also discussed.

The annual mean effluent temperature is quantified for 1970, 1975, 1985, 1995 and 2001, and compared with measured data as shown in Fig. 5. The measured data stands for weighted averages of monthly mean effluent temperature by the sewage volume for each treatment plant. The original effluent temperature data was recorded by the Sewerage Bureau of Tokyo Metropolitan Government based on the once-a-day measurement at each plant. The estimated

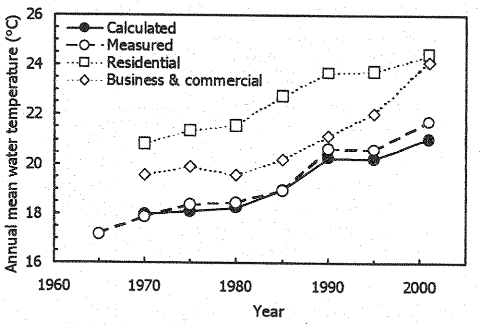

Fig. 5. Computed and Measured Annual Mean Temperatures of Effluent from Treatment Plants

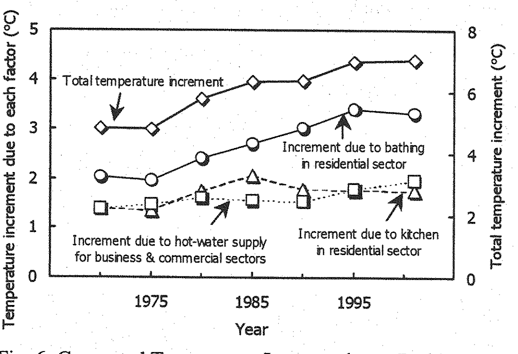

Fig. 6. Computed Temperature Increase due to Bathing and Kitchen for Residential Houses, Hot Water Supply for Business and Commercial Buildings, and Their Total

temperatures of drain from residential houses, and business and commercial buildings are also plotted in Fig. 5. It should be noted that the considerable increase in the annual mean effluent temperature in the past three decades was revealed by measured data, and that the effluent temperature is well reproduced by the model. This marked rise can be attributed to the temperature increases of drain from both residential and commercial sectors, and the increase in the supply water temperature. The increment between estimated drain water and measured supply water is shown in Fig. 6 for individual factors. The sum of the increment for each factor yields a total temperature increment. The largest impact on the total increment is caused by bathing, which is 2°C in 1970 and 3.3°C in 2001. The difference in the increment between 1970 and 2001 is due to the increased percentage of volume used for bathing to the total water demand. In contrast, the increment of kitchen outflow has been decreasing since 1985, which is due to the shrunken ratio of water use by kitchen (see Fig. 3). The temperature increment due to hot water supply in business and commercial buildings has been gradually increased up to 1990. The temperature increase since 1990 is attributed to the recent abrupt enlargement of the total floor area for business and commercial buildings (the total area increment between 1998 and 1990 is almost the same as that between 1990 and 1975). The discrepancy between measured and calculated effluent temperature in recent years shown in Fig. 5 may be the result of the constant energy consumption rate and temperature set points for every subjected year, and possibly due to the fact that the temperature of groundwater and storm runoff differs from air temperature.

Fig. 7 illustrates heat flux components associated with urban water and heat exchanges together with measured and estimated mean effluent heat fluxes from all treatment plants for long-term variation. The heat flux components H_A, H_B, H_D, H_G and H_O are defined by

$$H_A = c_p\rho Q_A(T_A - T_r);\quad H_B = c_p\rho Q_B(T_B - T_r);\quad H_D = H_O - H_B - H_G;\quad H_G = H_{GW} + H_R;$$
$$H_{GW} = c_p\rho Q_{GW}(T_{GW} - T_r);\ H_R = c_p\rho Q_R(T_R - T_r);\quad H_O = c_p\rho Q_O(T_O - T_r)\quad (11a,b,c,d,e,f,g)$$

where H_A = heat influx through water works (J/day); H_B = heat efflux from houses and buildings (J/day); H_D (J/day) = conduction heat along with the flow in sewer pipes (being negative outward); H_G = sum of heat influx by groundwater leakage H_{GW} (J/day) and storm runoff H_R (J/day); H_O = heat efflux from sewage treatment plants (J/day); T_r = reference temperature (°C).

The actual supply water temperature and effluent temperature are put into equation (11) to calculate H_A and H_O, while estimated water temperatures are used in quantifying H_B and H_G. As the Tokyo Bay receives effluents, the surface seawater temperature at a standard monitoring point in the bay is taken as the reference temperature T_r, which is given by the 25-year (1975 ~ 2000) mean of the surface seawater temperature measured once a month (the 25-year mean annual surface seawater temperature is 17.6°C). The entire added heat energy H can be given by extracting H_A from H_B.

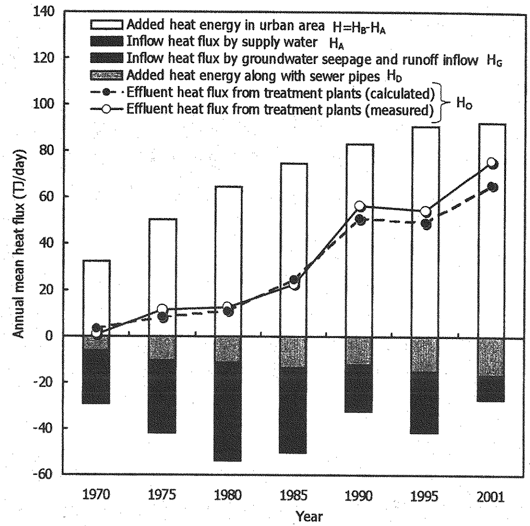

Fig. 7. Computed Annual Mean Heat Flux from Treatment Plants and Each Heat Flux Component

Fig. 7 shows that the effluent heat flux from sewage treatment plants has been considerably rising in the past three decades and is doubled between 1985 and 2001. It can be seen that major factors causing the rise are the heat energy added in the residential, business and commercial sectors. The influx of heat by supply water is another factor of the rising as it shows an increasing trend since 1980. At least in the last 10 years, the influx of heat associated with groundwater leakage and storm runoff into sewers has not been changing much comparing to other heat fluxes.

As is previously mentioned, the increasing trend of the supply water temperature is relevant to the rise in temperature of effluents from sewage treatment plants. As the supply water temperature corresponds well to the annual mean air temperature recorded at the Ootemachi Observatory, it is likely that the urban heat island phenomena has a certain influence on the heat transport associated with the supply water flow through waterworks in the shallow ground. On the contrary, it is confirmed by the data provided from the Waterworks Bureau of Tokyo Metropolitan Government that annual water temperature at filtration plants had no significant long-term change.

Although it was found that an enormous amount of water and energy is consumed for urban activities, it has never been verified that how much ratio of the heat energy is dumped with sewage into the hydrosphere. The total heat energy drained with sewage from residential, business and commercial sector is calculated by $c_p \rho Q_A(T_B - T_A)$, where actual records of Q_A, T_A and estimated temperatures of wastewater T_B are used. As a result, the heat energy added to the whole sewage is found to be 99 (TJ/day) on an annual average, which accounts for 11% of energy used for residential, business and commercial sectors in the 23 special-ward area of Tokyo as of 1998 (880TJ/day). This means that 89% of the energy used in the 23 special-ward area of Tokyo is released to the atmosphere as the sensible and latent heat.

No clear evidence exists that shows the relationship between the increasing thermal impact from coastal urban areas and the environmental change in the Tokyo Bay. However, the average of surface seawater temperature taken once a month since 1972 at eight locations within 8km off the coast of the 23 special-ward area of Tokyo confirms that the area has been apparently warming particularly in winter despite the different meteorological conditions year by year, as shown in Fig. 8. Other plausible factors related to the seawater temperature increase include wastewater from electric power generating plants along the coastal area and the air temperature variation over the Tokyo Bay. Thus, further studies are necessary to investigate major factors that have caused the seawater temperature to change in the Tokyo Bay using a sophisticated ocean model with actual artificial heat inputs.

CONCLUDING REMARKS

A watershed-scale water and heat budget model was constructed to quantify annual mean effluent temperature from sewage treatment plants as a result of water and energy supply, consumption and transport processes within urban areas. This model was applied to the 23 special-ward area of Tokyo, and measured effluent temperatures were reproduced accurately by the model. In addition, a considerable increase in the annual mean effluent temperature in the past three decades is revealed by both measured data and model calculation. This marked rise is attributed to the increase in the supply water temperature and the added heat energy associated with residential, business and commercial sectors.

Annual mean supply water temperature well corresponds to the annual mean air temperature near the ground recorded in the 23 special-ward area of Tokyo. This implies that the heat island phenomenon has been affecting the supply water temperature through the increase in the shallow ground temperature.

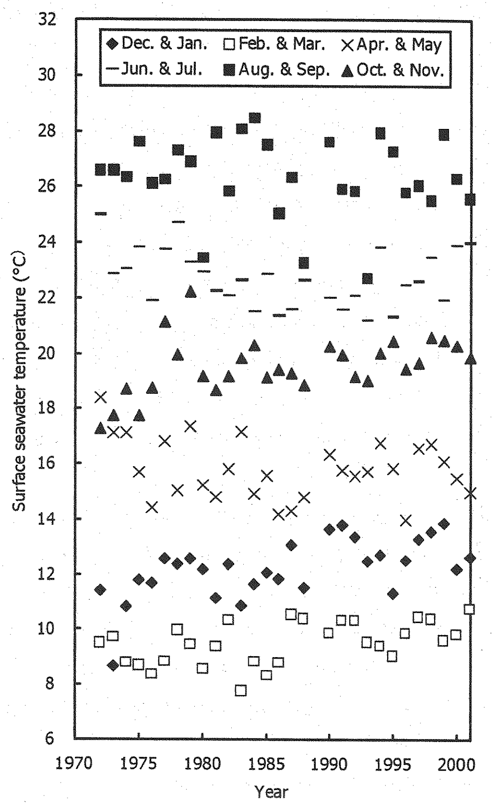

Fig. 8. Long-term Variation of Average Surface Seawater Temperature

For the residential houses, the rise in estimated drain temperature results from the increase in the water use for bathing, which is most likely due to the diffusion of shower and bigger bathtubs. As for the business and commercial sectors, the rise in calculated drain temperature is originated in the fact that the total amount of energy consumption has been increasing as the floor area of business and commercial buildings has been enlarged. However, the substantial thermal impact from business and commercial sectors is found to be small compared to the residential sector.

It is also confirmed by quantifying annual mean heat flux components in the process of water supply, use and transport that the major factors causing the rise in heat flux from treatment plants are the heat energy added in the residential, business and commercial sectors, and the increase in the influx of heat through waterworks.

This paper also addressed the quantification of the ratio of heat energy released with sewage to the total energy consumed. It is estimated that the ratio of the heat energy added to the entire wastewater to the total energy used for residential, business and commercial sectors as of 1998 accounts for 11% on an annual average.

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