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SIMULATION OF HYDROLOGICAL CYCLE IN AN URBANIZED WATERSHED AND EFFECT EVALUATION OF INFILTRATION FACILITIES WITH WEP MODEL

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SYNOPSIS

A distributed hydrological model, WEP (Water and Energy transfer Processes) model, is introduced at first. The WEP model is grid-based and able to model spatially variable water and energy transfer processes with complex land covers. Using the WEP model, a simulation of 5 years from 1992 to 1996 is performed in the Ebi river watershed ($27km^2$) with a grid size of 50m and a time step of 1 hour. To validate the model, both simulated river discharges and groundwater levels are compared with the observation. The comparison of water balance at present (1993) with that in the future (2035) is also conducted and it shows the impact of urbanization. To conserve hydrological cycle in the watershed, implementation of infiltration trenches is suggested and its effect is evaluated. It is found that the hydrological cycle in the future can be improved at the same level with or even better than now if infiltration trench is implemented to infiltrate storm water from urban canopies.

INTRODUCTION

The hydrological cycle is greatly changed with the rapid urbanization in watersheds. The groundwater outflow decreases and groundwater levels become lower while the river flood become bigger and quicker because of increased impervious area. The purpose of this study is to make clear the hydrological cycle and groundwater flow in the rapidly urbanized Ebi river watershed, and to provide basic information for the conservation countermeasures of hydrological cycle in the watershed.

Distributed physically-based hydrological models can take account of spatial variations of all variables and parameters involved in the basic mathematical equations of the water flows for a watershed. In addition, the used parameters are physically measurable. Therefore, they give a detailed and potentially more correct description of the hydrological processes in the watershed than empirical and conceptual hydrological models. With more available data, especially with the development of GIS and remote sensing technology, the study and application of this type of models will surely be promoted. Today, several popular models are of this type, like SHE (1), IHDM (3) and MIKE SHE (11) etc.

In this paper, the WEP model is developed which adds more detailed energy balance analysis in hydrological modeling. The model is based on Jia and Tamai (6) and it is improved by adding simulation of multi-layered aquifers, direct computation of groundwater outflow to rivers and simulation of infiltration trenches. Although the WEP model simulates most of the hydrological processes by the similar methods as the distributed physically-based models mentioned above, its main differences from those models are as follows. **1)** The energy transfer processes are also simulated in details in addition to hydrological processes. Because of its detailed consideration of heat flux partitions on land surface, the model not only enhances the computations of interception and evapotranspiration but also is easy to be coupled with atmospheric models. **2)** The subgrid heterogeneity of land use is considered by using the mosaic method (2), which is believed to be more reasonable than the usual dominant land use method, especially in urbanized area with complex land covers. **3)** The generalized Green-Ampt model (7) is developed to simulate infiltration and infiltration excess during heavy rains to save computation time. **4)** The infiltration trenches are simulated in the model, which makes it possible to evaluate their effect on hydrological cycle.

MODEL STRUCTURE

The diagram of the model structure within a grid cell utilized in this study is shown in Fig.1(a). To consider the subgrid heterogeneity of land use, the mosaic method is used which reflects composition of different land uses within a grid cell. The areal average of water and heat fluxes from all land uses in a grid cell produces the averaged fluxes in the grid cell. Land use is at first divided into 3 groups, namely a water body group, a soil-vegetation group and an impervious area group. The soil-vegetation group is further classified into bare soil, tall vegetation (forest or urban trees) and short vegetation (grass or crops). The impervious area group consists of impervious urban cover and urban canopy. For the soil-vegetation group, 9 vertical layers, namely an interception layer, a depression layer, 3 upper soil layers, a transition layer, an unconfined aquifer and 2 confined aquifers, are included in the model structure. The energy balance of each land use is also analyzed. The interaction of radiation between soil and vegetation is considered by use of the fraction of transmitted short-wave radiation of vegetation, whereas the interaction between urban cover and urban canopy is considered by using the sky view factor of urban cover. As for the modeling of land surface processes (10), evapotranspiration is computed by the Penman-Monteith equation (9), infiltration and its excess on land surface during heavy rains are simulated by a generalized Green-Ampt model whereas water movement in unsaturated soil layers during the remaining periods is simulated by using

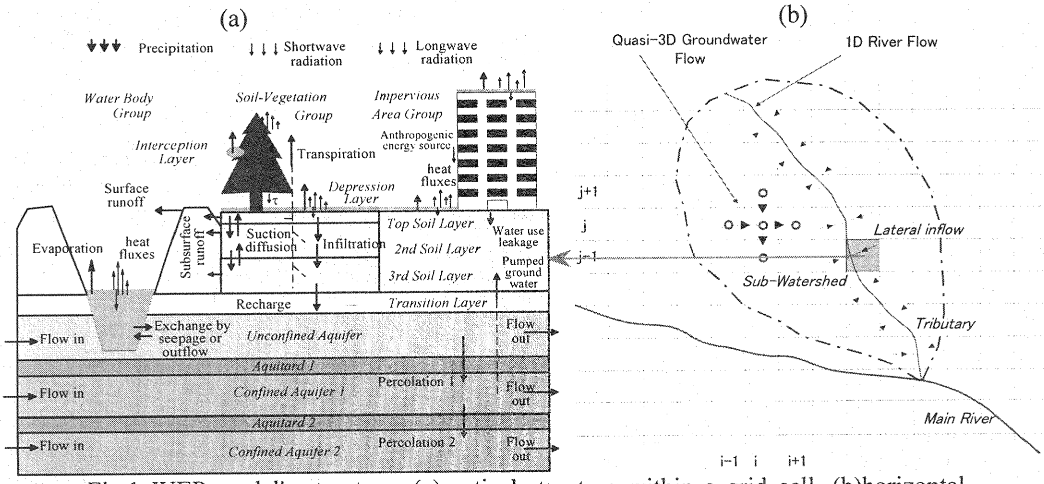

Fig.1 WEP model's structure: (a)vertical structure within a grid cell, (b)horizontal structure

the Darcy's law. The generalized Green-Ampt model for modeling infiltration into multi-layered soil profiles during unsteady rains is referred to Jia and Tamai (7). Computation time is much decreased through applying the Green-Ampt model to infiltration simulation instead of solving the Richards equation. However, the Green-Ampt model is adopted only during heavy rains considering the application limitation of the Green-Ampt model, i.e., its assumption of a wetting front occurred in soil columns during the infiltration process. In addition, short wave radiation is based on observation or deduced from sunshine duration, long wave radiation is calculated according to temperatures, latent and sensible fluxes are computed by the aerodynamic method and surface temperature is solved by the force-restore method (5). Moreover, artificial components, e.g., water supply, groundwater lift, sewerage drainage and anthropogenic energy source etc., are also taken into account.

The diagram of the model horizontal structure within a watershed is shown in Fig.1(b). River flow routing is conducted for every tributary and a main river by using the kinematic wave method. Overland flow is simplified as lateral inflow to rivers because the concentration time is estimated to be shorter than the simulation time interval in this study. In addition, a two-dimensional simulation of multi-layered aquifers, i.e., quasi-3D simulation is performed for groundwater flow.

The detailed descriptions of equations in the WEP model are referred to Jia and Tamai (6). The 2 main modifications in the WEP model are described as follows.

One modification is concerned with the simulation of groundwater flow and its interaction with river water. In the Jia and Tamai's model, an unconfined aquifer and a confined one are considered in the simulation of groundwater flow and its outflow to rivers is simulated by using the storage function method. In the present WEP model, another confined aquifer is added and the groundwater outflow to rivers (or river seepage to groundwater) is directly computed for the grid cells in which there are river channels by using the Darcy's law. The equations are as follows.

Groundwater flow in the unconfined aquifer:

$$C_u \frac{\partial h_u}{\partial t} = \frac{\partial}{\partial x}(k_u h_u \frac{\partial h_u}{\partial x}) + \frac{\partial}{\partial y}(k_u h_u \frac{\partial h_u}{\partial y}) + (Q_3 + WUL - RG - Per - E) \qquad (1)$$

Groundwater flow in confined aquifers:

$$C \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}(kD \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(kD \frac{\partial h}{\partial y}) + (Per - GWP - Perc) \qquad (2)$$

Water exchange between river and groundwater (see Fig.2):

$$RG = \begin{cases} k_b A_b (h_u - H_r)/d_b & h_u \geq H_r \\ -k_b A_b [1 + (H_r - Z_b)/d_b] & h_u < H_r \end{cases} \qquad (3)$$

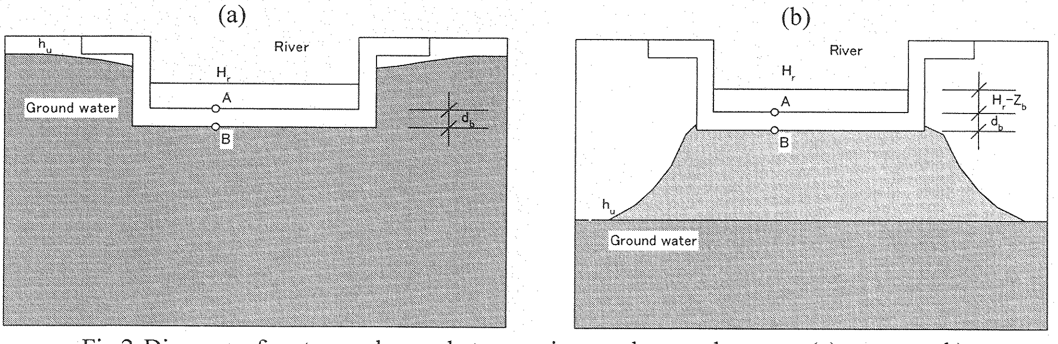

Fig.2 Diagram of water exchange between river and groundwater: (a) $h_u \geq H_r$, b) $h_u < H_r$. The water exchange depends on the water head difference between the point A and the point B.

where C_u is the specific yield of the unconfined aquifer, C the storage coefficient of confined aquifers, h_u and h the groundwater heads in the unconfined aquifer and confined aquifers respectively, k_u and k the hydraulic conductivities of the unconfined aquifer and confined aquifers respectively, D the thickness of confined aquifers, Q_3 the recharge from unsaturated soil layers, RG the groundwater outflow to rivers, WUL the water use leakage, GWP the pumped groundwater, Per and $Perc$ the percolation to the aquifer below, E is the evapotranspiration from groundwater (when groundwater level is high), k_b the hydraulic conductivity of riverbed material, H_r the river water stage, A_b is the seepage area of riverbed, Z_b the elevation of riverbed and d_b is the thickness of riverbed material.

The other modification is the adding of the following infiltration trench simulation equations (4):

$$\partial S_t / \partial t = Q_{in} - Q_{\inf} - Q_{ovf} \tag{4}$$

$$S_t = nLWH \tag{5}$$

$$Q_{\inf} = K_0 L(aH + b) \tag{6}$$

$$Q_{ovf} = cL(H - H_m)^{3/2} \tag{7}$$

where S_t is the storage in infiltration trenches, Q_{in} the inflow discharge, Q_{inf} the infiltration, Q_{ovf} the overflow, n the porosity of filled material in the trench, L the length of infiltration trenches, W the width, H the depth, H_m the maximum design depth, K_0 the saturated hydraulic conductivity of the soil below the trench, a, b and c the constants.

APPLICATION

Study Area and Input Data

The map of the Ebi river watershed is shown in Fig.3. It is located in the Funabashi and Kamagaya cities, Chiba prefecture, Japan. It is one of the pilot watersheds set by the Ministry of Construction to study hydrological cycle in details. It has an area of 27 km^2. There are 6 rain gauges within or near the watershed, one of which is the Funabashi AMeDAS (Automated Meteorological Data Acquisition System) station with the observations of temperature, wind and sunshine duration besides precipitation. The annual average precipitation over the past 10 years is 1360 mm. The Thiessen method, namely the nearest gauge station method is used to estimate the meteorological data for each grid. In addition, there are 2 gauges of river water stage and discharge, one of which is the Yasakaebashi station of the Ebi main river and another is the Ichiba station of the Maehara tributary.

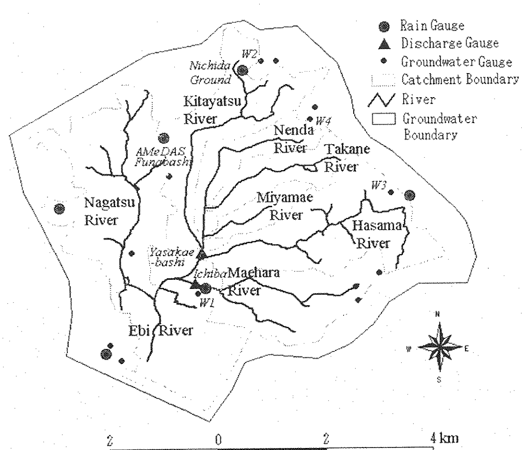

Fig.3 The map of the Ebi river watershed

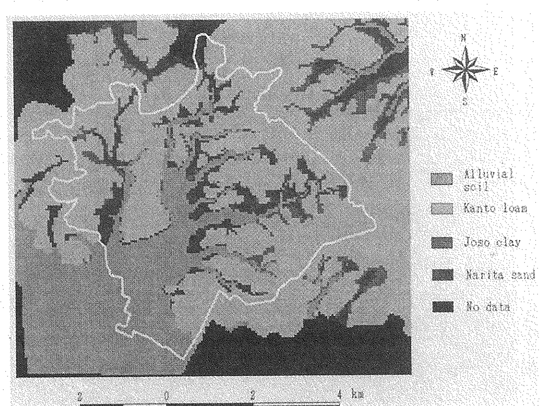

Fig.4 The classification of surface soils

The land use and elevation data are based on the Fine Digital Information System (FDIS) prepared by Geographical Survey Institute of Japan, which is raster type data of 3 big cities with a resolution of 10m by 10m. The watershed is adjacent to the Tokyo bay and land elevations are quite low (0~33m). There are 4 kinds of soils (see Fig.4) considered in the study, the dominant ones being the Kanto loam and the alluvial soil. The geological boring data indicates that the aquifers in the watershed have a multi-layered structure. The boundary of groundwater flow is a little larger than the watershed boundary according to the measurement of groundwater levels as shown in Fig.3.

The distributions of land use at present and in the future are shown in Fig.5. According to the prediction by the local government, forest, paddy or drought farmland of about 5.7 km^2 will be developed to housing area from 1993 to 2035, the population will reach 261,000 from 203,000 and the coverage rate of sewer system will attain 100% from 10% (in population).

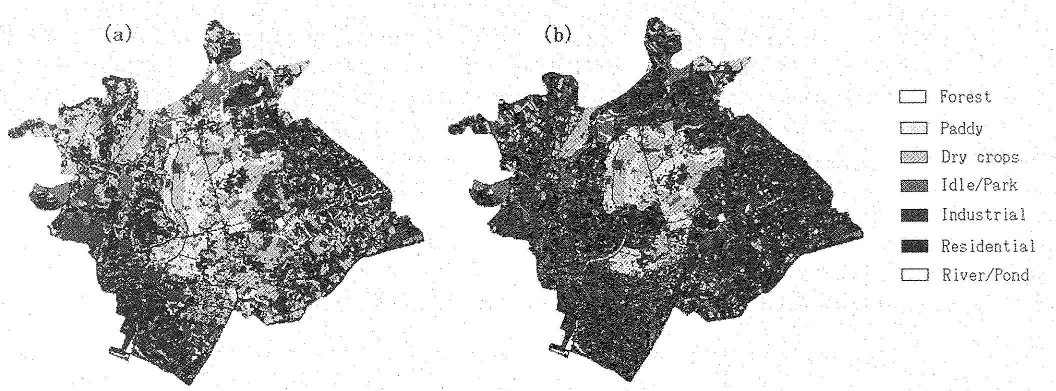

Fig.5 The distributions of land use: (a) at present (1993) and (b) in the future (2035)

Model Parameters

Many parameters are used in the model. The setting of main parameters is summarized as follows.

Soil parameters and aquifer parameters are shown in Table1 and 2 respectively. The soil parameters are referred to Herath (4) who conducted on-site borehole tests for representative soils within or near the watershed. In addition, the depths of top, second and third soil layers in the model are set as 0.2m, 0.4m and 1.4m respectively considering the variation characteristic of soil moisture, the distribution of vegetation roots and the damping depth of diurnal temperature wave in the watershed. Aquifer parameters are based on geological investigations in the watershed although there are some adjustments after model calibration.

Vegetation parameters are species-dependent and referred to Wilson et al. (12) etc. Their seasonal variations are considered in this study according to growing characteristic of trees and crops in the watershed.

Furthermore, the area fractions of land use classification are specified through sample analysis using a residential map of large scale. The aerodynamic and thermal parameters of land covers are referred to Kondo (8).

Table 1 The soil parameters

Parameter	Kanto loam	Joso clay	Narita sand	Alluvial soil
Saturated moisture content	0.772	0.394	0.400	0.707
Residual moisture content	0.589	0.120	0.077	0.598
Field capacity	0.676	0.384	0.174	0.622
Saturated hydraulic conductivity (m/s)	5.0×10^{-6}	5.0×10^{-7}	2.0×10^{-4}	3.0×10^{-6}

Table 2 The aquifer parameters

Parameter	Unconfined aquifer	Aquitard 1	Confined aquifer 1	Aquitard 2	Confined aquifer 2
Permeability (m/s)	5.0×10^{-6}	$1\sim10\times10^{-8}$	5.0×10^{-6}	2.0×10^{-9}	5.0×10^{-6}
Specific yield／specific storage (1/m)	$0.01\sim0.1$	—	5.0×10^{-4}	—	5.0×10^{-4}
Thickness (m)	$2.0\sim16.7$	$2.0\sim7.8$	$80.6\sim96.0$	10.0	$391\sim424$

Calibration and Verification

To reduce the impact of initial conditions of soil moisture and groundwater etc., the data in 1992 are used to warm up the model. Then, the model simulation is continuously carried out till the end of 1996. The observation discharge data in 1993 are used to calibrate the model. The data from 1994 to 1996 are used to carry out the model verification. Fig.6 shows the comparison of simulated discharge with the observed one at the Yasakaebashi station, which is located at the middle reach of the Ebi river and has a control area of 8.3 km^2. It can be seen that the simulated discharge show overall agreement with the observed one.

Fig.7 shows the comparison of simulated groundwater level with the observed one at the W1 well (its position is referred to Fig.8). It can be seen that the variation patterns are almost the same. Here the groundwater level is the elevation above the sea level of the Tokyo bay.

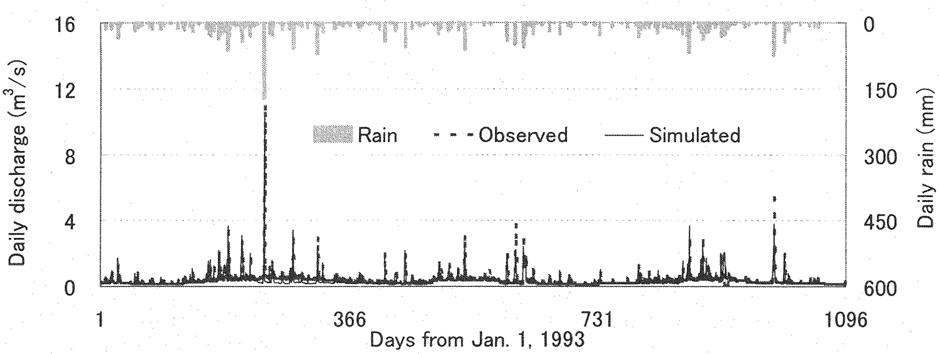

Fig.6 Daily discharges at the Yasakaebashi station of Ebi river

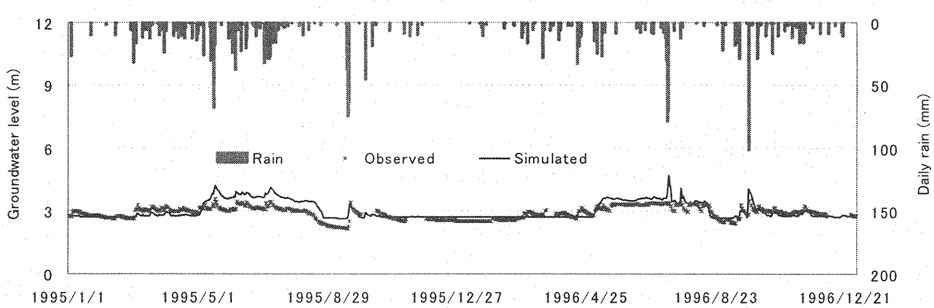

Fig.7 Groundwater levels at the W1 well (Mark label interval of horizontal axis: 120 days)

Contour lines of groundwater level in the watershed are shown in Fig.8. The simulated result of the top confined aquifer is compared with the measurement at 112 private wells in winter of 1996. Though there are obvious differences between them, the distribution patterns are similar, namely the groundwater level become lower from upstream area to downstream area (refer to Fig.3 at the same time).

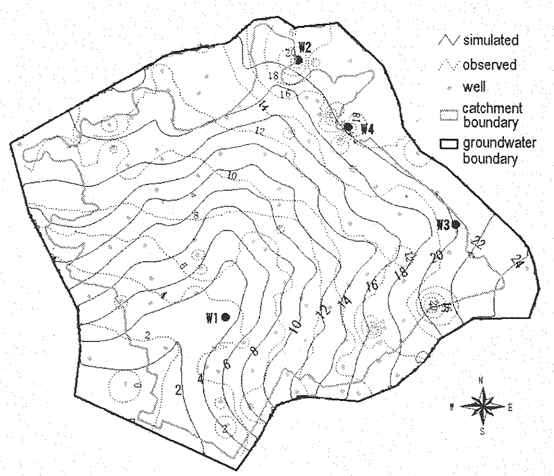

Fig.8 Contour lines of groundwater level on Jan.25, 1996 (Unit: m)

Impact of Urbanization and Effect of Infiltration Trenches

The comparison of water balance at present with that in the future in the whole watershed is shown in Fig.9 (a) and (b). The land use and population data in 1993 are used in the simulation of water balance at present whereas those data predicted in 2035 is used for that in the future. The land use and population data in 2035 are prepared based on the urban development plan and the population density control plan of Chiba prefecture as well as the data in 1993. The meteorological data in 1993 are used for both cases. It can be seen that with the further urbanization in the future, evapotranspiration will be decreased by 90mm, infiltration lessened by 97mm and groundwater outflow reduced by 21mm. On the other hand, surface runoff will be increased by 140mm. In the case with separate sewer system installed and the sewage drained directly to the sea, a great change of river flow is predicted, namely the river base flow will be decreased to 178mm (the value within brackets in the figure), which means the deterioration of water environment. In the case without sewer system, though the river base flow can be increased from 992mm to 1197mm, the water environment will also be deteriorated because the sewage will account for 85% in the base flow. Therefore, to conserve the hydrological cycle and the water environment, infiltration facilities, sewer system and wastewater treatment plant should be installed, and the treated wastewater should be drained back to local rivers.

The installation effect of infiltration trenches for the storm water from urban canopies (building roofs) is studied by using the present model. In the Ebi river watershed, the urban canopies account for about 20% of the whole area. The guideline promulgated by Japan Association for Rainwater Storage and Infiltration Technology is followed to make a layout and design scheme of infiltration trenches. It is required that the land slope should be lower than 10%, the soil should not be clay, ground water table should be 2 m or more below the land surface and the trench density should be less than 450m/ha etc. Assuming an installation density of 450m/ha, the trench length is computed as $450 \times 0.25 \times$ area fraction of urban canopies for every grid cell where the above guideline requirements are satisfied. In addition, every trench is assumed to have a lateral section of 1.5m(width)$\times$1.0m(depth) for the simulation using Eqs.4 to 7. Fig.10 shows the computed infiltration trench length in every grid cell.

The installation effect of infiltration trenches is shown in Fig.9 (c) and Fig.11. Fig.9(c) shows that, compared with the case without infiltration trenches, the annual surface runoff shows a decrease of about 200mm, the groundwater outflow shows an increase of 25mm though the evapotranspiration shows less difference. In a general sense, the hydrological cycle in the watershed can be much improved with the installation of infiltration trenches for storm water from urban canopies. From Fig.11, it can be seen that the discharge peak in the future is about 20% higher than that at present at the Yasakaebashi of the Ebi river, however, it can be improved to the present level or even better if infiltration trenches are implemented for the storm water from urban canopies.

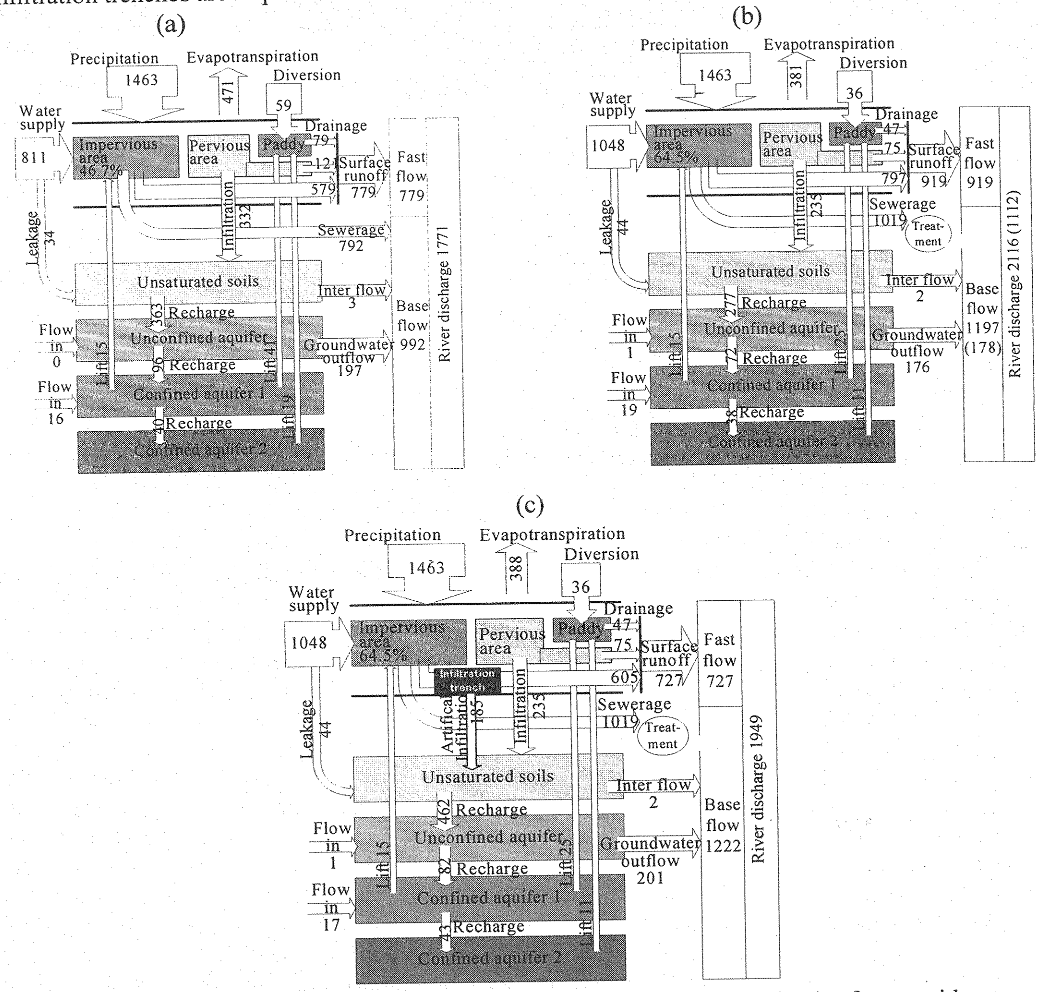

Fig.9 Water balances in the whole watershed: (a) at present, (b) in the future without infiltration trenches and (c) in the future with infiltration trenches (Unit: mm/year)

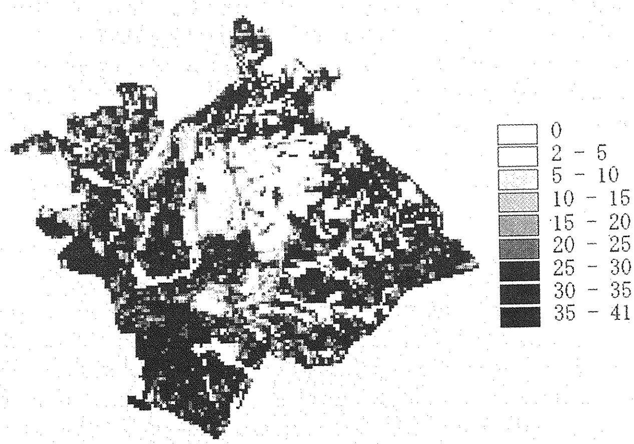

Fig.10. Computed infiltration trench length in every grid cell (Unit: m)

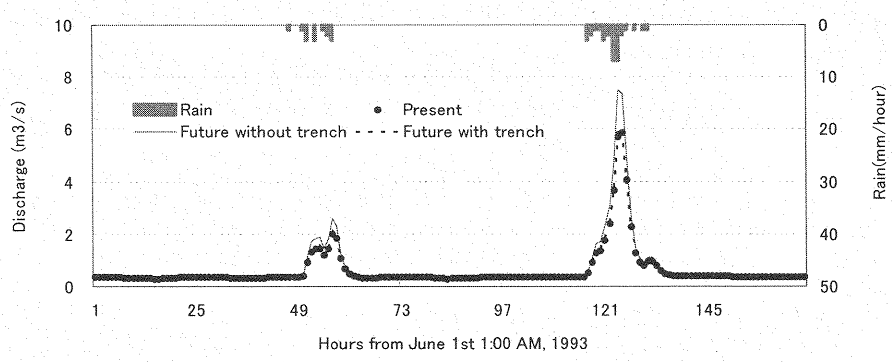

Fig.11 Comparison of river discharges at the Yasakaebashi of Ebi river

CONCLUSIONS

To ensure sustainable developments in urban areas, it is required to adopt an integrated analysis of the hydrological and energy processes and to evaluate the effects of countermeasures. In this study, a model for this purpose (WEP model) is developed. The model is grid-based and able to simulate spatially variable water and energy processes in watersheds with complex land covers.

The model is applied to the Ebi river watershed with reasonable results obtained. The model is verified through comparisons of simulated river discharges and groundwater levels with the observed values. The comparison of water balance at present (1993) with that in the future (2035) is conducted and it shows the impact of urbanization. The effect of infiltration trenches is also studied. It is found that the hydrological cycle in the future can be improved to the same level with or even better than now if infiltration trenches are implemented for the storm water from urban canopies. In addition, to conserve water environment in rivers, sewer system and wastewater treatment plant should also be installed, and the treated wastewater should be drained back to local rivers.

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REFERENCE

1. Abbott, M. B., J.C. Bathurst, J.A. Cunge, P.E. O'Connell and J. Rasmussen: An Introduction to the European Hydrological System - Systeme Hydrologique Europeen, "SHE", 2: Structure of a physically-based distributed modelling system, Journal of Hydrology, Vol.87, pp.61-77, 1986.
2. Avissar, R. and R. A. Pielke: A parameterization of heterogeneous land-surface for atmospheric numerical models and its impact on regional meteorology, Mon. Wea. Rev., Vol.117, pp.2113-2136, 1989.
3. Beven, K., A. Calver, and E.M. Morris: The Institute of Hydrology Distributed Model, Institute of Hydrology Report 98, Wallingford, UK, 1987.
4. Herath, S.: Unsaturated zone hydraulic property estimation and applications to infiltration facility analysis, Doctoral dissertation submitted to the Univ. of Tokyo, p.305, 1987.
5. Hu, Z. and S. Islam: Prediction of ground surface temperature and soil moisture content by the force-restore method, Water Resour. Res., Vol.31 No.10, pp.2531-2539, 1995.
6. Jia, Y. and N. Tamai: Integrated analysis of water and heat balances in Tokyo metropolis with a distributed model, J. Japan Society of Hydro. Water Resour., Vol.11 No.2, pp.150-163, 1998.

7. Jia, Y. and N. Tamai: Modeling infiltration into a multi-layered soil during an unsteady rain, Ann. J. Hydraul. Eng., JSCE, Vol.41, pp.31-36, 1997.
8. Kondo, J.: Meteorology of Water Environment (in Japanese), Asakura Press, Tokyo, p.348, 1994.
9. Monteith, J. L.: Principles of Environmental Physics, Edward Arnold Press, p.236, 1973.
10. Noilhan, J. and S. Planton: A simple parameterization of land surface processes for meteorological models, Mon. Wea. Res., Vol.117, pp.536-549, 1989.
11. Refsgaard, J.C. and B. Storm: Chapter 23 MIKE SHE in V. J. Singh (Ed) Computer Models of Watershed Hydrology, Water Resources Publications, p.1113, 1995.
12. Wilson, M. F., A Henderson-Sellers, R. E. Dickinson and P.J. Kennedy: Sensitivity of the biosphere - atmosphere transfer scheme (BATS) to the inclusion of variable soil characteristics, J. Climate Appl. Meteorol., Vol.26, pp.341-362, 1987.

APPENDIX - NOTATION

The following symbols are used in this paper:

A_b = seepage area of riverbed;
Ae = artificial energy consumption;
C = storage coefficient of confined aquifers;
C_u = specific yield of the unconfined aquifer;
d_b = riverbed material thickness;
D = confined aquifer thickness;
E = evapotranspiration;
GWP = pumped groundwater;
H = groundwater head in confined aquifers;
h_u = groundwater head in the unconfined aquifer;
H = water depth in infiltration trench;
H_m = maximum design water depth in infiltration trench;
H_r = river water stage;
k = hydraulic conductivity of soils/aquifers;
k_b = hydraulic conductivity of riverbed material;
K_0 = hydraulic conductivity of the soil below infiltration trench;
L = infiltration trench length;
n = porosity of the material filled in infiltration trench;
Per = percolation from the unconfined aquifer to the confined aquifer;
$Q3$ = recharge from unsaturated soil layers;
Q_{in} = inflow discharge to infiltration trench;
Q_{inf} = infiltration from infiltration trench to soil below;
Q_{ovf} = overflow of infiltration trench;
RG = groundwater outflow;
S_t = infiltration trench storage;
W = infiltration trench width; and
WUL = leakage of water.

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