Distributed hydrological modeling in the Yata watershed using WEP model and propagation of rainfall estimation error

YANGWEN JIA

Department of Water Resources, Institute of Water Resources & Hydropower Research (IWHR), Che-Gong-Zhuang West Road 20, Beijing 100044, China

e-mail: jiayw@iwhr.com

TSUYOSHI KINOUCHI and JUNICHI YOSHITANI

Hydrologic Engineering Team, Hydraulic Engineering Research Group, Public Works Research Institute (PWRI), Minamihara 1-6, Tsukuba City 305-8516, Japan

Abstract The WEP model is validated in the Yata watershed (166km^2) using the observation data in 2000 and 2001. The simulation is carried out in a time step of one hour and a grid cell size of 100m. The impact of rainfall estimation error on annual water budgets is studied by carrying out a sensitivity analysis and that of rainfall spatial distribution on discharge prediction is investigated by using gauged rainfall data and radar rainfall data. It is found that the spatial distribution of rainfall during typhoon seasons has a great impact on river discharge prediction. It is concluded that the WEP model is applicable to both short-term prediction of flood and long-term prediction of water budgets with satisfied accuracy.

Key words hydrological model; urbanization; water balance; groundwater level; WEP; Yata watershed; rainfall estimation error; radar

INTRODUCTION

Distributed hydrological modeling is highly required for hydrological predictions in watersheds with heterogeneous land surfaces, soils and aquifers under uneven distribution conditions of rainfall. A robust distributed hydrological model should be applicable to both long-term prediction of water budgets and short-term prediction of flood with satisfied accuracy. However, long-term simulations using distributed hydrological model are very few in the literature of the study field.

The Yata watershed is located in the northwest of Ibaraki prefecture, Japan, and has an area of 166km^2 of which agricultural land use and forest accounts for about 70%. Several institutions had ever carried out some field investigations of groundwater and river discharges in the watershed in 1970's (Ichikawa et al.1976). PWRI and the local government began to monitor water and heat fluxes, river discharges and groundwater levels in 1999. However, there is no continuous long-term observation in the watershed, therefore a hydrological simulation is required to understand the continuous variations of water budgets, river discharges and groundwater levels.

The WEP (Water and Energy transfer Processes) model is based on that of Jia and Tamai (1998a, 1998b) and is improved at the Public Works Research Institute (Jia et al. 2001). Although the WEP model simulates most of the hydrological processes using the methods similar to the physically-based spatially distributed (PBSD) models like MIKE SHE (Refsgaard and Storm 1995), its computation time is decreased through applying the Green-Ampt model to infiltration simulation during heavy rains and conducting multi-layered modeling of aquifers.

The purposes of this study are to simulate the hydrological changes in the Yata watershed in the past 24 years (1978-2001) by applying the WEP model and to evaluate the impact of rainfall estimation error and rainfall spatial distribution on river discharge prediction.

MODEL DESCRIPTION

Model structure

The vertical structure of the WEP model within a grid cell is shown in Fig.1. The state variables include depression storage on land surfaces and canopies, soil moisture content, land surface temperature, groundwater level and water stage in rivers etc. A brief description of modeling approaches of hydrological processes follows with equations and modeling approaches of energy transfer processes referred to Jia and Tamai (1998a) and Jia et al. (2001).

Modeling approaches of hydrological processes

Evaporation is calculated with the Penman equation and transpiration is calculated by using the Penman-Monteith equation. The average evapotranspiration in a grid cell is obtained by areally averaging those from each land use.

Infiltration during heavy rains is calculated utilizing the generalized Green-Ampt model for infiltration into multi-layered soil profiles suggested by Jia and Tamai (1998b) whereas soil moisture movement in unsaturated soils during other periods is solved using the Richards model. A heavy rainfall period is defined as a period during which the rainfall intensity is larger than the saturated soil hydraulic conductivity.

Surface runoff from the soil-vegetation group consists of two parts, namely the infiltration excess during heavy rainfall periods and the saturation excess during the other periods. The infiltration excess occurs when the depression storage on land surface surpasses its maximum value. The depression storage is balanced with rainfall as inflow and infiltration, evaporation and infiltration excess as outflows. The saturation excess during the remaining periods may occur if the groundwater level in the unconfined aquifer rises and the topsoil layer becomes nearly saturated. It is deduced by applying the Richards model. Subsurface runoff is calculated according to land slopes and unsaturated soil hydraulic conductivities in those grid cells adjacent to rivers.

Groundwater flow in multi-layered aquifers is simulated using the Boussinesq equation and the interactions between surface water and groundwater of the unconfined aquifer are considered through a source term. The source term includes the recharge from unsaturated soil layers, the groundwater outflow to rivers, the water use leakage, the pumped groundwater, the percolation to the lower aquifer and the evapotranspiration from groundwater. Groundwater outflow is calculated according to the hydraulic conductivity of riverbed material and difference between river water stage and groundwater head in the unconfined aquifer.

Treated as overland flow, runoff from a grid cell is routed along the steepest downward one among 8 directions to its adjacent cells using the kinematic wave method in 1D scheme and the downhill Newton method. The computation sequence is decided as from the lowest flow accumulation number (headwater area) to the biggest flow accumulation number (river mouth). River flow is routed for every tributary and a main channel using the kinematic wave method or the dynamic wave method in 1D scheme and the Newton-Raphson method.

MODEL VALIDATION

The Yata watershed, input data and parameters

A diagram of the Yata watershed is shown in Fig.2. There are three main rivers in the watershed, which flow into the Ushiku Lake. Inside or around the watershed, there are two meteorological gauge stations managed by local meteorological bureau and one by PWRI. In October 2000, three continuous water stage gauge stations were installed and periodical discharge observations are carried out to obtain the relation of water stage and discharge. Hourly meteorological data from January 1978 to December 2001 were collected.

The land use data at four periods are shown in Table 1. Data of year 1994 shows that 14%

of the watershed is paddy field, other farmland and forest occupy about 50%, and the rest is covered by buildings, river etc.

For aquifer data, borehole geology data at 119 sites within or near the watershed were picked up to clarify the soil stratigraphy of the watershed. The ground soil is divided into five layers, i.e. three aquifers and two aquitards to separate each aquifer from another. Hydrogeological parameters of each aquifer and aquitard, i.e. hydraulic conductivity, specific yield, were set up referring to the results of in situ pumping tests (Geological Survey of Japan, 1988). The topsoil is mainly Kanto loam, except for alluvial silt in riparian zones. Experiments were carried out to obtain the characteristic curve of soil moisture and suction.

In addition, ground elevation and population were obtained from available databases; domestic water use, agricultural water use (mainly pumped from rivers outside the watershed) and industrial water use were deduced from the reports of the local government and organizations; and data of river sections were also collected.

Model validation

To validate the WEP model in the watershed, simulation was first performed for the period from January 1998 to December 2001. The initial and boundary conditions were determined according to the field observation results and "warming up" simulation of one year (1998) was first carried out to eliminate the possible effect of initial condition setting. The results after January 1999 were used for model validation.

Fig.3 shows comparison of simulated discharge with observed one at the Kojirabashi (see Fig.2). The Kojirabashi with a command area of 47.6 km^2 is located at the middle-reach of Yata river. Fig. 4 shows comparison between simulated and observed groundwater levels for all the simultaneous observation wells within the watershed. Although there are some differences between the simulated and the observed results, all the comparisons show that the model gives quite satisfactory results.

Influence of parameter estimation errors

The main parameters of the WEP model includes the saturated hydraulic conductivity of soil layers, the permeability and specific yield of unconfined aquifer, the hydraulic conductivity and thickness of riverbed material, the Manning's roughness of river flow and overland flow, the vegetation parameters and the paddy field parameters. As for the influence of parameter estimation errors of the WEP model, it had ever been performed in previous studies. For example, it was found that annual water budgets are quite sensitive to the saturated hydraulic conductivity, the annual groundwater outflow is very sensitive to the hydraulic conductivity of riverbed material and the groundwater level is sensitively influenced by the aquifer permeability. In this study, we also analyzed the influence of the Manning's roughness on the river discharge hydrograph at the Kojirabashi station. It is found that the increase of the Manning's roughness of overland flow will obviously decrease the peak discharge and delay the occurrence of the peak discharge whereas the influence of the Manning's roughness of river flow is not so obvious in the Yata watershed. It is believed that the concentration time of overland flow is much longer than that of river flow in this watershed.

PROPAGATION OF RAINFALL ESTIMATION ERROR

Sensitivity of annual water budgets to rainfall input data

It is investigated by increasing/decreasing the hourly rainfall in 2000, which is equivalent to the case that systematic errors occur in rainfall observation data. The result is shown in Fig. 5. The relative error here means the estimation error of some budget divided by the budget correspondent to the precipitation in 2000. It can be seen that estimation errors of runoff and groundwater outflow are bigger than rainfall estimation error though those of evapotranspiration and infiltration are smaller than rainfall estimation error. This is because that evapotranspiration is influenced also by energy budgets and infiltration is effected also by soil conductivity and groundwater level.

Impact of rainfall distribution on river discharges

To study the impact of rainfall distribution on river discharges, hourly radar rainfall data from August to October 2001 were obtained from the Ministry of Land, Infrastructure and Transport (MLIT), Japan. The radar rainfall data has a resolution of about 1km. During typhoon seasons, rainfall distribution is very uneven. Fig.6 shows an example of distribution of radar rainfall from 20:00 to 21:00 on 10 October 2002 in the watershed.

Simulation results using the radar rainfall data are compared with those using two gauge stations (Shimotuma and Nagamine) and the Thiessen method, and with those using three gauge stations (Shimotuma, Nagamine and PWRI) and the Thiessen method. Fig.7 shows the comparisons of three rainfall events at the Kojirabashi in 2001: (a) from Aug. 21 00:00 to Aug. 23 24:00, (b) from Sept. 10 00:00 to Sept.12 24:00 and (c) from Oct. 10 00:00 to Oct. 12 24:00. It can be seen that in general, the results using radar rainfall data and those using three gauge stations have better matching with the observed than those using two gauge stations. The results using two gauge stations give simulation error as big as 152% for the flood peak on 22 August, 4% for the flood peak on 11 September and 40% for the flood peak on 10 October respectively. The reason why the results using radar rainfall data do not show better matching with the observed is that gauge stations in the downstream of or outside the watershed rather than the three gauge stations mentioned above were utilized by MLIT in the radar rainfall calibration against ground-gauged rainfall. The averaged discharges from August 1 to October 31 and relative simulation errors are shown in Table 2, from which the same remarks as above can be concluded but the results using two gauge stations do not show too big errors. It means that rainfall distribution may have less impact on the estimation of long-term water budgets.

Therefore, rainfall distribution in the watershed is quite uneven during typhoon seasons and has a big impact on river flood predictions. However impact of rainfall distribution on seasonal averaged discharges become smaller than that on flood discharges.

It should be mentioned that the estimation errors of radar rainfall also influence river discharges. The radar rainfall errors can come from both radar observation and calibration based on gauge stations and they include the systematic error and the random error. The influence of radar rainfall errors on river discharges is closely related to the location of storm center and the direction in which the storm comes to the watershed, and it will be carried out in the study of the next step.

CONCLUSIONS

In this study, through analyzing the sensitivity of annual water budgets to rainfall estimation error and investigating the impact of rainfall spatial distribution on river discharges, it is found that the spatial distribution of rainfall during typhoon seasons has a great impact on river discharge prediction. It is concluded that the WEP model is applicable to both short-term prediction of flood and long-term prediction of water budgets with satisfied accuracy and distributed hydrological modeling needs distributed rainfall data to give accurate predictions.

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FIGURES CAPTIONS

Fig. 1 Schematic illustration of WEP model structure

Fig. 2 The Yata Watershed

Fig. 3 Model validation using observed and simulated river discharges at the Kojirabashi

Fig.4 Model validation using observed and simulated groundwater levels. T.P. means elevation above the averaged sea water level in the Tokyo bay.

Fig.5 Sensitivity of annual water budgets to rainfall input data. E is evapotranspiration, I infiltration, R direct runoff, G groundwater outflow to rivers and P precipitation.

Fig.6 Distribution of radar rainfall from 20:00 to 21:00 on 10 October 2002

Fig.7 Discharge comparisons during three rainfall events at the Kojirabashi in 2001: (a) from Aug. 21 00:00 to Aug. 23 24:00, (b) from Sept. 10 00:00 to Sept.12 24:00 and (c) from Oct. 10

00:00 to Oct. 12 24:00.

Fig. 1

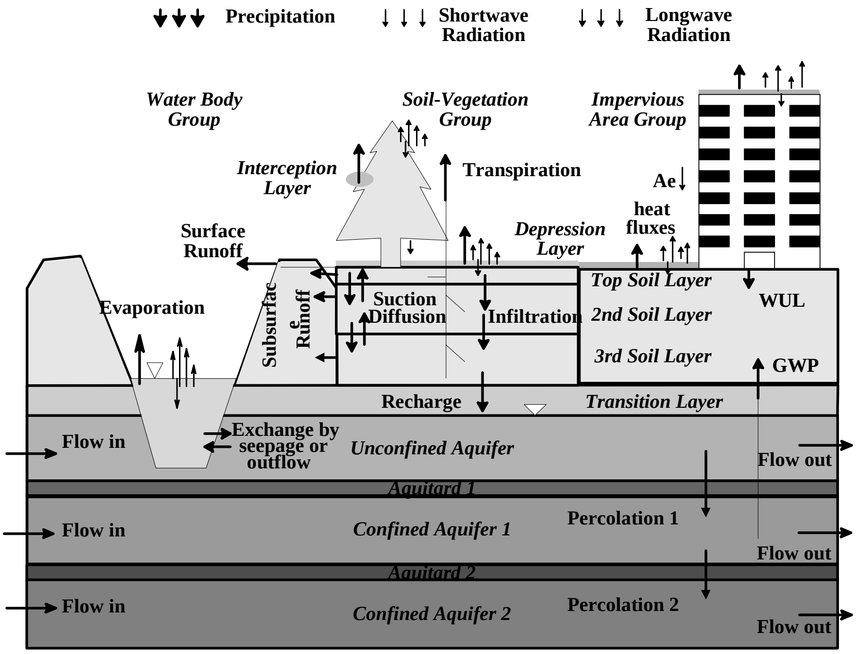


Fig. 3

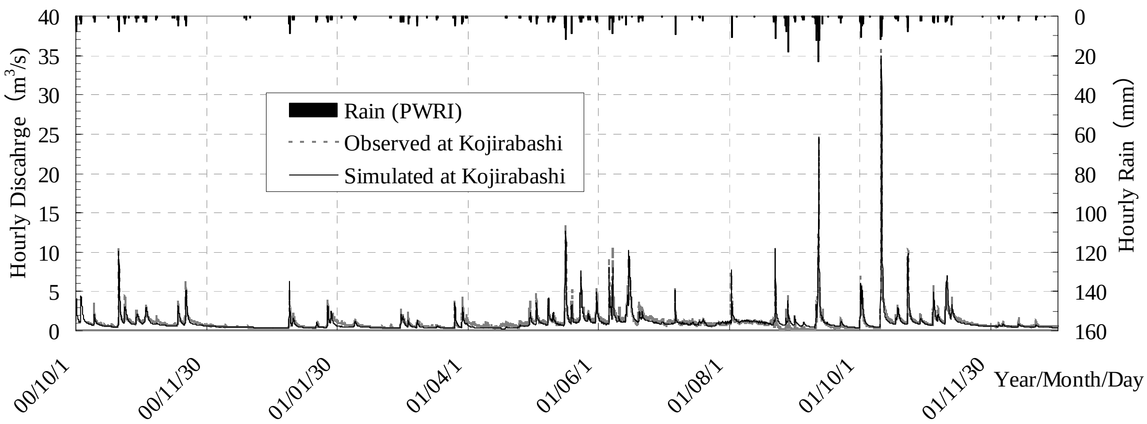


Fig. 4

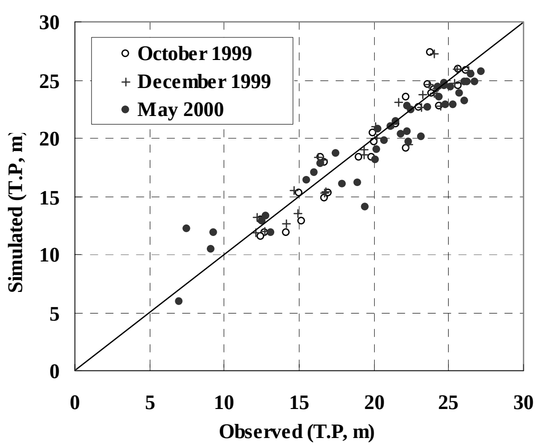


Fig. 5

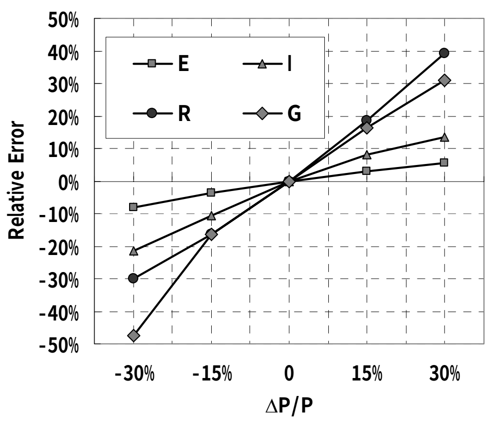


Fig. 2

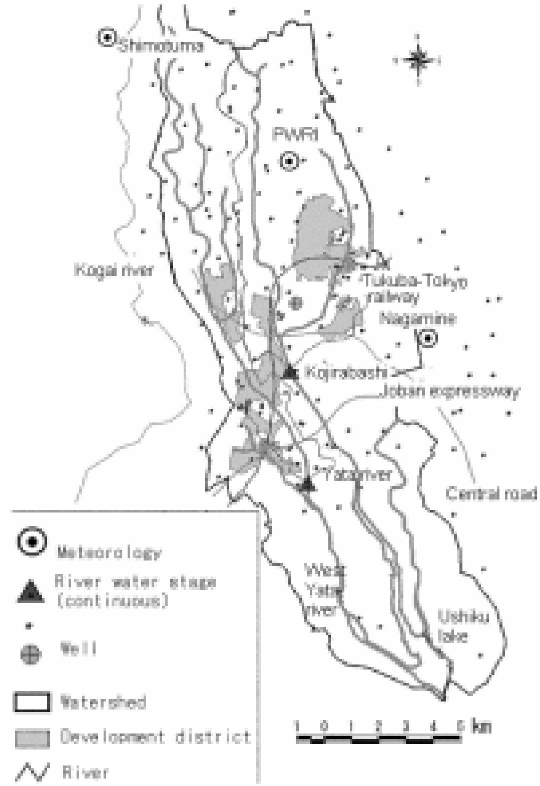


Fig. 6

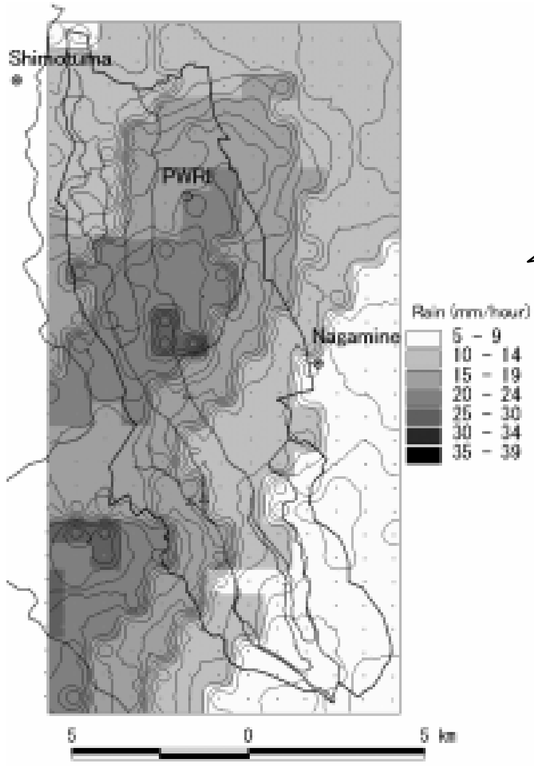


Fig. 7 (a)

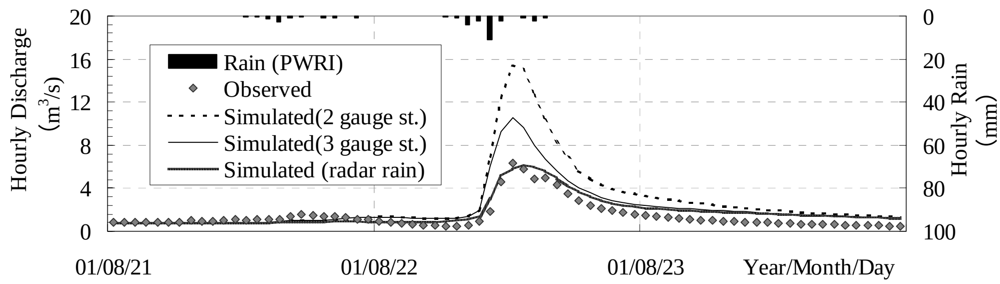


Fig. 7 (b)

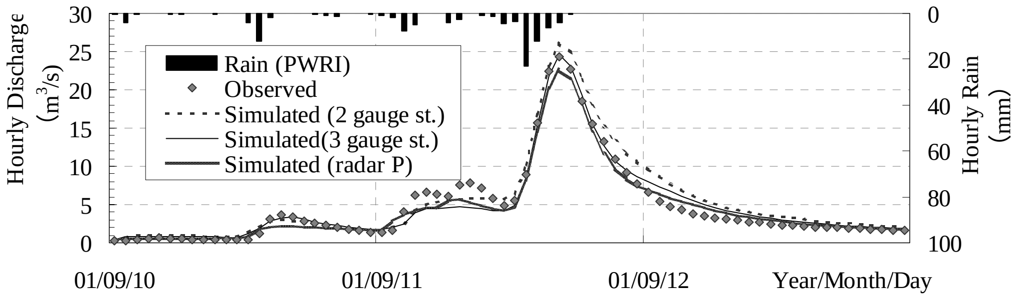
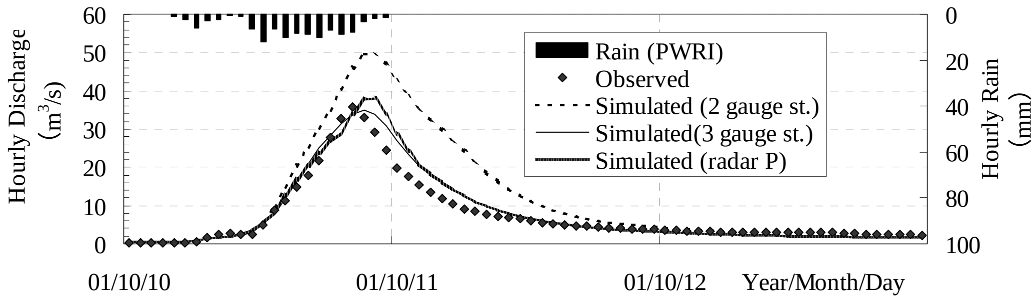


Fig. 7 (c)



TABLE

Table 1 Land use in the Yata watershed (km^2)

Types	1976	1984	1989	1994
forest	36.13	29.00	27.06	26.63
paddy	24.32	24.62	24.55	23.66
field	65.56	56.96	57.23	55.39
under preparing	0.00	0.38	0.30	0.30
vacant land	19.55	4.23	2.88	3.45
industrial use	0.00	2.48	2.87	3.01
housing area	12.45	20.44	21.40	21.71
road	0.78	5.52	5.87	6.86
park	0.00	1.00	1.40	1.39
public works	0.00	12.22	12.60	12.69
river/lake	7.82	6.66	6.69	6.81
sum	166.61	166.61	166.61	166.61
impervious rate	0.079	0.157	0.165	0.177

Table 2 Averaged discharges (m^3/s) from August 1 to October 31, 2001 at three sites.

Site	Observed	Simulated using 2 gauge st. rainfall	Simulated using 3 gauge st. rainfall	Simulated using Radar rainfall
Kojirabashi	1.332	1.698	1.499	1.547
		(27.5%)	(12.5%)	(16.5%)
Sakaimatu	1.125	1.302	1.161	1.226
		(19.9%)	(3.2%)	(9.0%)
Takaoka	0.196	0.241	0.244	0.21
		(23.0%)	(24.5%)	(7.1%)

Note: Values in brackets are relative errors compared with the observed.