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Development of the hourly hydrological model for mountainous basins using the storage function method and the Diskin-Nazimov infiltration model

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Abstract This study aims to improve the daily hydrological model to an hourly hydrological model by combining the storage function method, the Diskin-Nazimov infiltration model and the groundwater recharge and runoff calculation procedure. The hourly hydrological model in this study was evaluated by estimating the runoff in the Sameura Dam basin (472 km^2), located in the mountains of Shikoku in western Japan, using 16 years series of hydrological rainfall data. The results indicated satisfactory to good model performance in terms of obtaining an accurate monthly mean hydrograph as well as daily and hourly mean hydrographs.

Key words hourly hydrological modelling; 50 m-resolution DEM; Diskin-Nazimov infiltration model; groundwater and surface runoff

INTRODUCTION

In Japan Hydrological models for mountainous basins are considered to be important for planning water resources and the management of river flow, because water resources depend on mountainous areas, which occupy about 70% of the land area. The daily hydrological model for a hilly or mountainous basin was proposed by Ando (JHHE, 5, 1988), and was based on earlier studies by Ando *et al.* (1983, 1984). In recent years, advances in computer and gauging technology have promoted the development of new methods for analysing hydrological processes. Climate change is a serious global problem, and it is necessary to devise effective adaptation strategies at the local level and also for urban areas. Downscaling climate-change scenarios to the local level and predicting the variation of water resources and flood runoff in local areas are important so that local governments can formulate policies for adapting to climate change. The accurate prediction of reservoir inflow using an hourly hydrological model is required for the management of water resources. As a basic study on this subject, a hydrological model with an hourly time scale for a mountainous basin is developed and applied to the Sameura Dam basin located in Kochi Prefecture, in the mountains of Shikoku in western Japan.

STUDY AREA AND DATA

The Sameura Dam basin, in the upper Yoshino River basin, is located in the mountains of Shikoku in western Japan (Fig. 1). The basin area is 472 km^2 and the land is completely covered with forest. The elevation in the Sameura Dam basin ranges from 324 to 1880 m a.m.s.l. and its average elevation is 910 m a.m.s.l. Approximately 15% of the basin is above 1500 m a.m.s.l. and 85% of the basin is above 600 m a.m.s.l. (Fig. 2). The water resources for agricultural, industrial and urban use, as well as the household water supply for the four prefectures on the island of Shikoku (Kochi, Ehime, Tokushima and Kagawa), are dependent on Sameura Dam. Another role of Sameura Dam is to regulate the downstream discharge of flood water by storing storm flood water. To analyse the hydrological process with an hourly time step, hourly rainfall, temperature and dam inflow

Fig. 1 Map of the Sameura Dam basin and hydrological stations referred to herein.

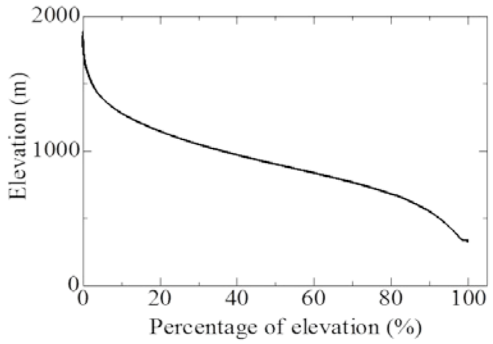

Fig. 2 Elevation of the Sameura Dam basin.

data are used in this study. The rainfall data at seven stations in the basin and the dam inflow data are measured by the Ministry of Land, Infrastructure and Transport. The temperature data at Motoyama station obtained by the Automated Meteorological Data Acquisition System (AMeDAS) of Japan

Meteorological Agency is used. The day length data at the Dam site is used in the calculation of the potential evapotranspiration rate. This data are obtained from the Website of the Ephemeris Computation Office, Public Relations Center, National Astronomical Observatory of Japan (NAOJ). The DEM data with 50 m resolution were obtained from the Geospatial Information Authority of Japan. The period of analysis is the 16 years from 1991 to 2006.

MODELLING METHODS

The basin was divided into a 50-m mesh, and at each grid the rainfall was estimated by an inverse distance weighting method using the seven rainfall gauges in the basin. At each grid the infiltration rate and then the excess rainfall were calculated by the Diskin-Nazimov model (Diskin & Nazimov, 1995, 1996). The flood runoff was calculated by summarising the excess rainfall using the storage function method, and the groundwater recharge and runoff were calculated by summarising the infiltration rate using the lumped conceptual model.

Diskin-Nazimov infiltration model

The schematic structure of the Diskin-Nazimov model is shown in Fig. 3. The model comprises two simple elements: the reservoir element and the input-regulating element of the reservoir. The reservoir element represents the moisture content in the upper soil layer. The relationship between the storage in the reservoir and the infiltration capacity is assumed to be specified by a decreasing linear relationship.

Diskin and Nazimov proposed a method of computing the variation of infiltration for unsteady rainfall that involves carrying out calculations for successive time intervals. The procedure involves consideration of the following three cases that depend on the relationship between the rainfall intensity and infiltration capacity.

- Case (a) The infiltration capacity is lower than the rainfall intensity.
- Case (b) The infiltration capacity is higher than the rainfall intensity.
- Case (c) The infiltration capacity varies from higher to lower than the rainfall intensity in a signal time interval.

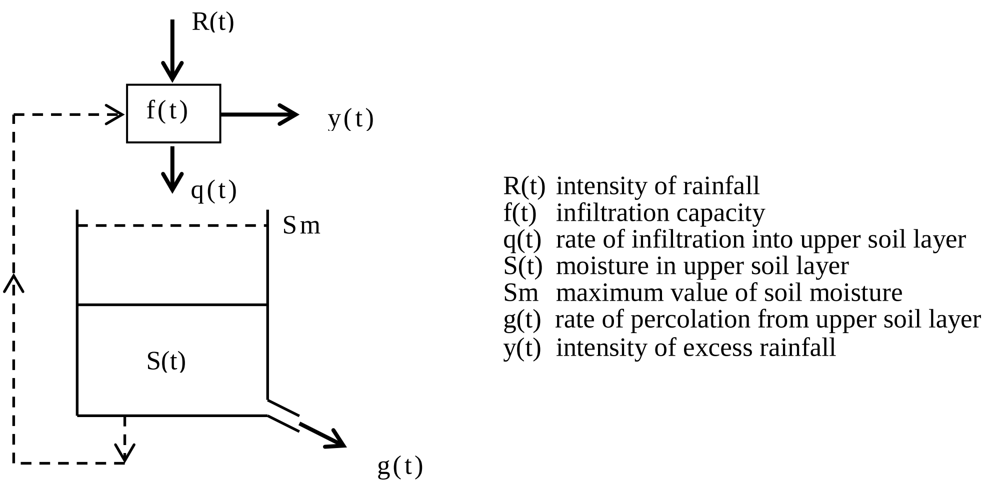

Fig. 3 Schematic structure of the Diskin-Nazimov model.

Figure 4 shows each of the above relationships between the infiltration capacity and rainfall intensity.

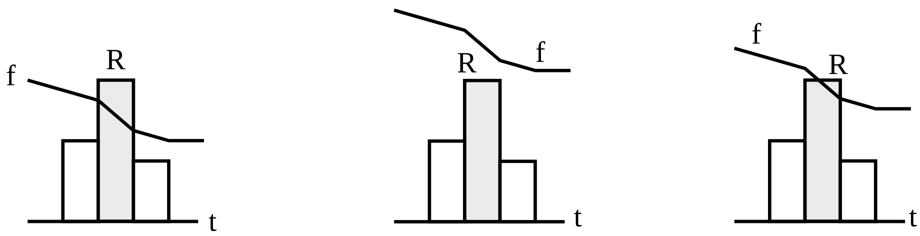

Fig. 4 Three cases of the relationship between infiltration capacity and rainfall intensity for analysing the infiltration variation for unsteady rainfall.

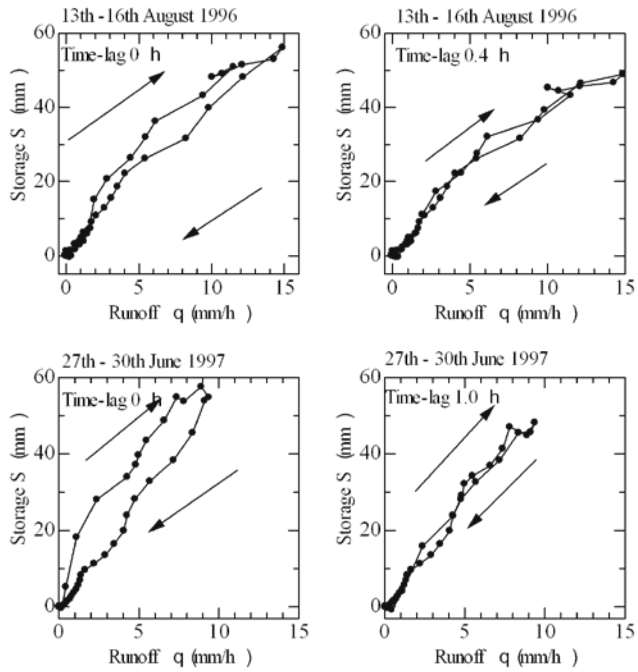

Fig. 5 Two examples of the graphical method used to define the time lag between storage and runoff.

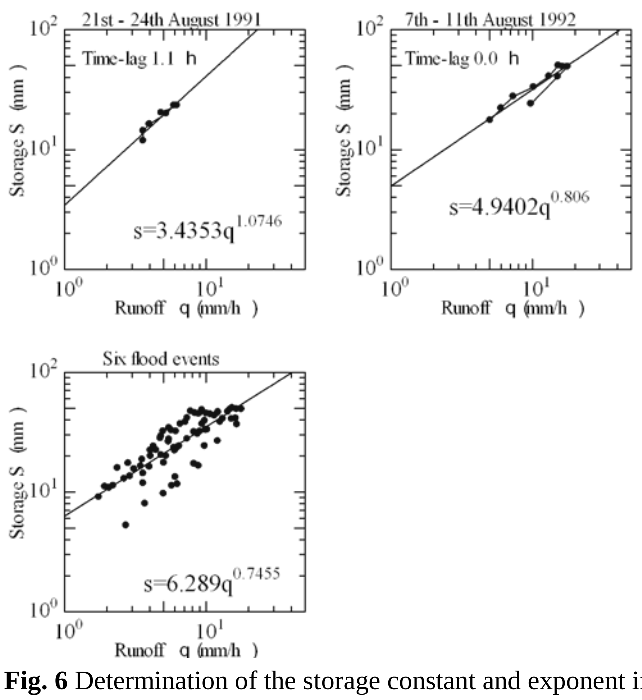

Fig. 6 Determination of the storage constant and exponent in the storage function equation.

Storage function method

The excess rainfall calculated by the Diskin-Nazimov infiltration model is used as input data for the storage function method in order to calculate the flood runoff from the basin. The equation is expressed as:

$$S = k\,q^{p} \qquad (1)$$

where *S* is the storage, *q* is the runoff, *k* is the storage constant and *p* is an exponent.

To define the parameters in the storage function method, six isolated flood events were selected from the study period. The time lag between storage and runoff was derived from a graphical method as shown in Fig. 5. The mean storage constant *k* and exponent *p* were determined using a log-log plot graph for the six flood events as shown in Fig. 6. Table 1 shows the flood events used for parameter calibration and the parameter values.

Table 1 Flood events for parameter calibration and their values.

Date of flood	Total rainfall volume (mm)	Values of parameters		Time lag (hour)
		k	*p*	
21–25 August 1991	257.20	3.4353	1.0746	1.1
7–11 August 1992	265.30	4.9402	0.806	0
24–27 August 1992	292.31	12.544	0.4044	0
22–25 September 1995	193.41	2.043	0.9921	0.5
13–16 August 1996	359.34	6.745	0.7742	0.4
27–30 June 1997	227.02	5.594	0.9923	1
Calculated means		5.884	0.8406	0.5
Means obtained graphically		6.289	0.7455	

g(t), f(t): Calculated by Diskin-Nazimov model

$Ms'(t)=Ms(t)+g(t)-E(t)$

$$G(t)=\begin{cases} 0 & Ms'(t)\leqq Mn \\ \beta\,(Ms'(t)-Mn) & Ms'(t)>Mn \\ gg & h\leqq Ms'(t)-Mn \end{cases}$$

$Ms(t+1)=Ms'(t)-G(t)$

$Sg(t+1)=Sg(t)+G(t)-Qg(t)-SP$

$Qg(t)=Au^2\cdot Sg(t)^2$

Sg:	Groundwater storage (mm)
f:	Infiltration rate of upper soil layer (mm/h)
Qg:	Groundwater runoff (mm/h)
q:	Infiltration rate into upper soil layer (mm/h)
g:	Infiltration rate into unsaturated soil layer (mm/h)
Ms:	Soil moisture storage (mm)
β:	Constant of groundwater recharge
Mn:	Normal soil moisture
gg:	Capacity of groundwater recharge (mm/h)
E:	Evapotranspiration (mm/h)
h:	Constant of excess soil moisture (mm)
G:	Groundwater recharge (mm/h)
SP:	Groundwater runoff to outside the basin (mm/h)
t:	Time step (in this case, 1 hour)
Au:	Recession constant of groundwater runoff from unconfined aquifers

Fig. 7 Sequence of the groundwater recharge and runoff model.

Groundwater recharge and runoff

The infiltration rate calculated by the Diskin-Nazimov model is used in the model proposed by Ando *et al.* (1983, 1984) for calculating the groundwater recharge and runoff. The infiltration into the unsaturated soil layer increases the moisture in the unsaturated soil layer (Ms), and evapotranspiration from the infiltration area (E) decreases the moisture in the soil. Groundwater recharge (G) is proportional to the excess moisture in the soil. Groundwater runoff (Qg) is proportional to the square of the volume of stored groundwaters (Sg). The total runoff (Q) is the sum of direct runoff and groundwater runoff. A flow chart of the model is shown in Fig. 7.

RESULTS

A simulation for the 16 years between 1991 and 2006 was carried out. The result was compared with the mean monthly, mean daily and hourly hydrographs. Figure 8 shows the mean monthly hydrograph. Scatter plots of the mean monthly and mean daily hydrographs are shown as log-log graphs in Fig. 9. The calculated hydrographs approximately agree with the observed hydrographs. The model was assessed using the Nash-Sutcliffe efficiency coefficient and the square of the correlation coefficient (R^2) as shown in Table 2. The values for the mean monthly hydrograph as well as those for the other hydrographs show good applicability for use as long-term hydrological data. Figure 10 shows the results for two flood events calculated using the model in this study, which reproduces the flood hydrographs reasonably well.

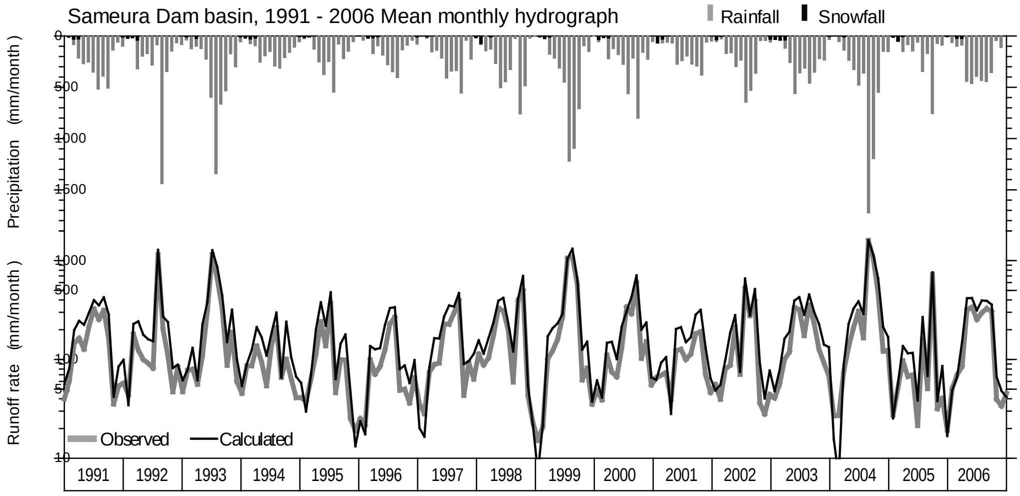

Fig. 8 Mean monthly hydrograph simulated by the hourly hydrological model in this study.

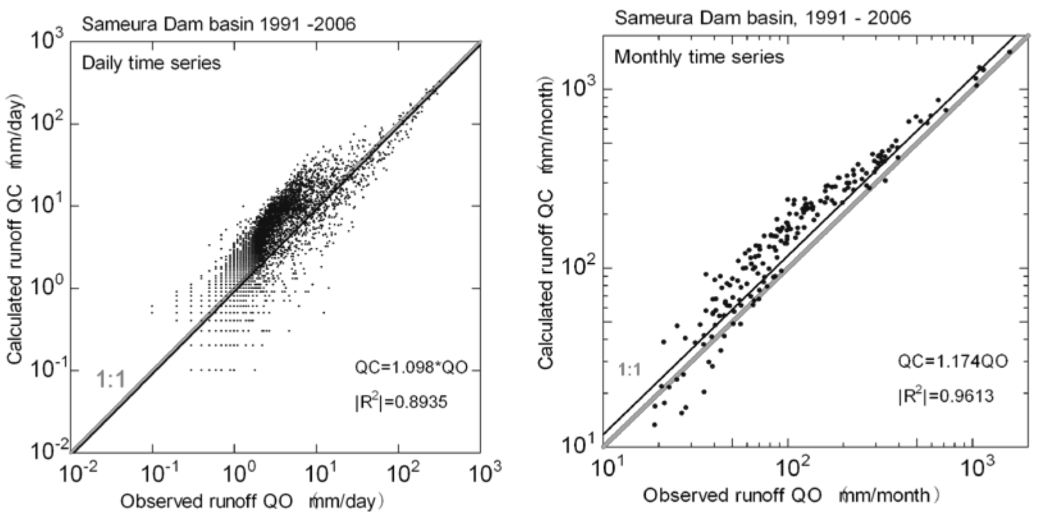

Fig. 9 Comparison between the observed and calculated runoffs shown as log-log graphs.

Table 2 Nash-Sutcliffe and correlation coefficients for mean monthly, mean daily and hourly hydrographs.

	Nash-Sutcliffe coefficient	Correlation coefficient (R^2)
Mean monthly hydrograph	0.9023	0.9613
Mean daily hydrograph	0.8726	0.8935
Hourly hydrograph	0.8666	0.8772

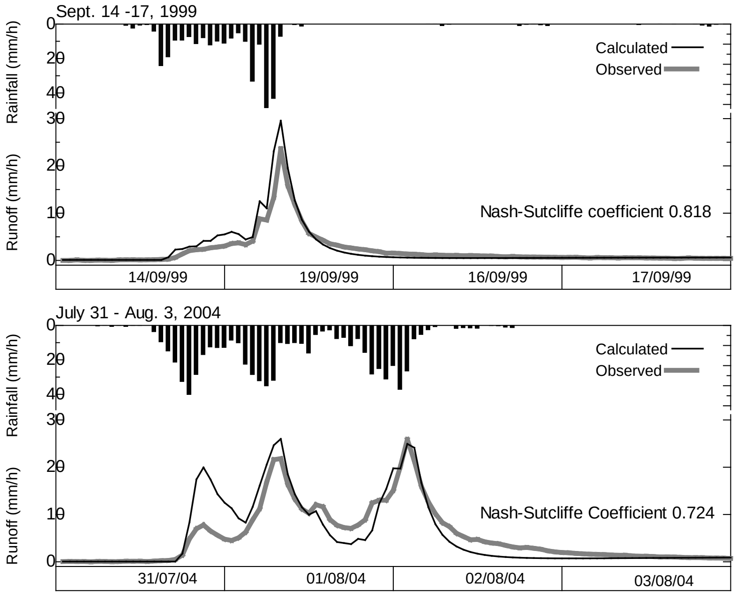

Fig. 10 Hydrograph results for two flood events.

CONCLUSIONS

A newly proposed hydrological model based on the storage function method and the Diskin-Nazimov infiltration model is applied to 16 years data for the Sameura Dam basin in a mountainous region in western Japan. The model shows satisfactory to good performance in terms of obtaining accurate long-term hydrographs. Furthermore, the model can be used to reproduce the hydrographs for flood events. Its applicability to the hydrological analysis of both long-term and short-term events will make it useful for the management of water resources and flood control, especially for the development of climate change adaptation policies by local governments.

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