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Predictions of Heavy Floods in 2004 and 2005 in Japan and PUB

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Introduction

In 2004, record-high ten typhoons and severe rainfall fronts caused heavy rainfall disasters with 232 casualties in Japan. In 2005, a severe typhoon, which brought historical rainfall with more than 1,000 mm in two days in the eastern part of the Kyushu region, claimed 19 lives. The heavy rainfall events caused slope failures in many parts of mountainous areas and inundations along rivers, which mainly occurred at tributary catchments with several hundreds square km. River managements of these catchments are usually conducted by prefectural governments. In most situations, the river improvements are hard to realize in the near future.

In these catchments, to assess safety level at the current state of river basins is the basis to design a river development program for the future. To develop a real-time flood runoff prediction system to issue a flood warning is also an urgent task to save lives. To achieve these purposes, hydrologic predictions by a reliable rainfall-runoff model are fundamental. However especially for small-scale catchments with several hundreds square km organized by local governments, accumulations of hydrologic data to develop and validate hydrologic models are quite insufficient. Generally, floods at small-scale catchments is sensitive to space and especially time distributions of rainfall patterns. Therefore, flood runoff predictions for small-scale catchments need more detailed hydrologic information rather than for large-scale catchments with more than several thousand square km. In addition, flood data with a magnitude of a design flood level or above the level does not exist in most situations. Thus, rainfall-runoff models for small-scale size (several hundreds square kilometers) should be closely examined their predictive performances especially for historical largest-ever floods under limitations of available hydrologic data.

In this paper, we test a physically based distributed rainfall-runoff model for historical large floods, which is based on topographic representations by grid based DEMs and kinematic flow routing (Shiiba *et al.*, 1999; Ichikawa *et al.*, 2001; Tachikawa *et al.*, 2004). The hydrologic model is applied to the upper part of the Asuwa River basin (351km^2) to examine the predictability of the distributed runoff model for the 2004 Fukui flood. The same model is also applied to the Kamishiiba Dam basin (210 km^2) for the Kyushu heavy rainfall in 2005. Then, we analyze the causes of the differences between predicted and observed floods; discuss the sources of flood prediction uncertainty and a direction to improve flood discharge predictions.

Physically based distributed rainfall-runoff model

Figure 1 illustrates the catchment topographic model using DEMs processed with the algorithms by Shiiba *et al.* (1999). A slope segment is represented by a rectangle formed by the adjacent two grid points determined to have the steepest gradient. In Figure 1, three flow lines (two inflows and one outflow) connect to the grid point A and two flow lines (one inflow and one outflow) connect to the grid point B; thus 1/3 of the grid area A and 1/2 of the grid area B are allocated to form the area of the slope segment AB. The slope width is determined by dividing the area by the slope length AB. The catchment topography is represented as a set of these slope segments. Figure 2 shows the topography model for the Maruyama River basin (1,115km^2) using a DEM with 250m grid resolution. According to the flow directions shown in Figure 2, the slope flow is routed one dimensionally. Then the slope discharge is given to the river flow routing model, and finally the river flow is routed to the catchment outlet.

In each slope segment, the slope is assumed to be covered by a soil layer composed of a capillary soil layer and a non-capillary soil layer above bed rocks (Fig. 3). In the capillary soil layers, sub-surface flow is modelled as saturated-unsaturated Darcy flow with variable hydraulic conductivity, and saturated Darcy flow is assumed in the non-capillary soil layer. If the depth of water exceeds the soil water capacity, overland flow happens. These processes for each slope segment are represented with a kinematic wave model using a function of the discharge-stage relationship (1) as illustrated in Fig. 3 (Tachikawa *et al*., 2004) and the continuity equation (2):

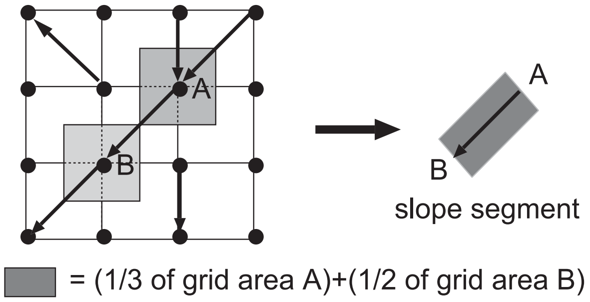


Fig. 1 Catchment topography modeling by Shiiba *et al*. (1999).

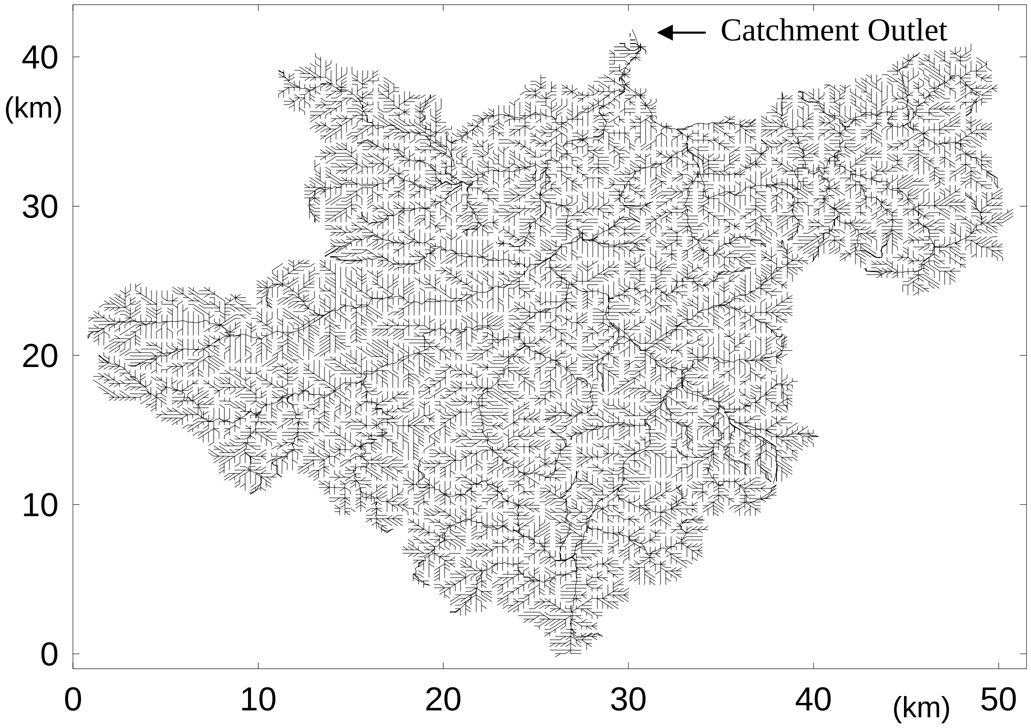


Fig. 2 Watershed model with 250m grid DEM for the Maruyama River basin (1,115km^2).

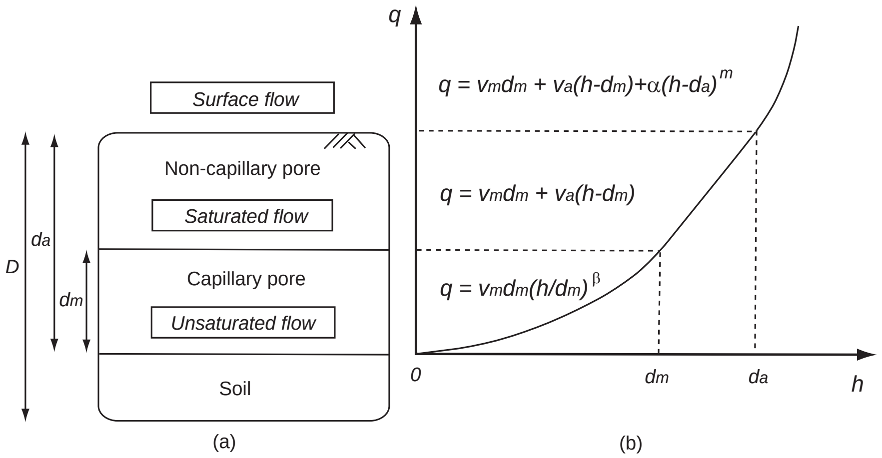


Fig. 3 Slope soil model and discharge stage relationship (Tachikawa *et al.*, 2004).

$$q=\begin{cases} v_m d_m (h/d_m)^{\beta}, & 0 \le h < d_m \\ v_m d_m + v_a (h-d_m), & d_m \le h < d_a \\ v_m d_m + v_a (h-d_m) + \alpha (h-d_a)^m, & d_a \le h \end{cases} \qquad (1) \qquad \frac{\partial q}{\partial x}+\frac{\partial h}{\partial h}=r \qquad (2)$$

where q is discharge with unit width; h is flow depth; r is rainfall intensity; $v_m = k_m i$, $v_a = k_a i$, $k_m = k_a/\beta$, $\alpha = \sqrt{i}/n$; i is gradient of slope segment; k_m is saturated hydraulic conductivity for the capillary soil layer; k_a is hydraulic conductivity for the non-capillary soil layer; n is surface roughness coefficient; d_m is the capacity of water depth for the capillary soil layer; and d_a is the capacity of water depth including capillary and non-capillary soil layers. The model parameters to be determined are n (m$^{-1/3}$s), k_a (m/s), d_a (m), d_m (m), and β. For channel flow routing, surface flow with rectangular cross section is assumed for kinematic wave approximation.

Discussion on Fukui 2004 flood simulations and predictions (Tachikawa *et al*, 2006)

The nine floods with more than 400 m^3/s peak discharge were selected from the discharge data since 1978. For each flood, spatial distributions of hourly rainfall with 3 km gird resolution were generated from the ground gauged rainfall measurements using the nearest neighbor method; then the five model parameters above mentioned that define the stage-discharge relationship are determined. The initial water depth at each slope segment is determined from the initial river discharge at the outlet assuming a steady state condition. Table 1 summarizes the results of parameter identifications. To evaluate appropriateness of the simulated discharges, the peak discharge ratio and the Nash-Sutcliffe efficiency are used. The evaluation results suggest that the identified model parameter sets are classified into three groups: group 1 with the 1993, 1981 and 1982 flood; group 2 with the 1985, 1983 and 1979 flood; and group 3 with the 1989, 1990 and 2004 flood. The parameter sets in the group 1 have tendency to overestimate and the group 3 to underestimate floods; the group 2 shows both tendencies. The estimated peak discharges are widely distributed from 2500 to 4200 m^3/s, and it is larger than the estimated peak discharge 2400 m^3/s obtained by the Construction Ministry from hydraulic river flow simulations with the high flood stage marks.

Table 1 Model parameter values fitted to each year flood and the characteristics of each year heavy rainfall and flood discharge.

Properties	Group 1: (overestimating peak discharge)			Group 2: (over/underestimating peak discharge)			Group 3: (underestimating peak discharge)		
Parameters	1993	1981	1982	1985	1983	1979	1989	1990	2004
n (m$^{-1/3}$s)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
k_a (m/s)	0.01	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
d_a (m)	0.25	0.4	0.2	0.2	0.6	0.17	0.25	0.325	0.26
d_m (m)	0.18	0.35	0.15	0.1	0.15	0.1	0.18	0.2	0.16
d_a-d_m (m)	0.07	0.05	0.05	0.1	0.45	0.07	0.07	0.125	0.10
β (-)	24	24	12	8	12	4	4	8	4
Peak discharge (m^3/s)	548	1117	676	542	758	622	608	447	2400
Initial discharge (m^3/s)	11	65	18	86	36	37	44	17	25
6 hours rainfall R_{6h} (mm)	60	73	42	43	54	84	67	56	265
2 days rainfall R_{2d} (mm)	116	163	136	116	169	103	174	127	297
Rainfall ratio R_{6h}/R_{2d}	0.52	0.45	0.31	0.37	0.32	0.82	0.39	0.44	0.89
Station number	10	4	7	10	4	6	10	10	12

Within a group, the values of model parameters are close, and floods simulated with any parameter sets show good scores of the peak ratio and the Nash efficiency. The clear difference among the groups is that the value of β is larger and the capacity of non-capillary layer d_a-d_m is smaller in the group 1 as compared to the group 3. The difference of parameter values represents the difference of hydrologic characteristics. In the group 1, rainfall stored in soil layer flows quite slow, therefore at the beginning of floods, river discharge is insensitive to rainfall intensity. Then the soil layer is easily saturated and once the water depth at slope segments exceeds the capacity of the capillary soil layer, river discharge rises up suddenly. On the contrary, the parameter sets in the group 3 tends to show opposite characteristics that a hydrograph rises up from the beginning of rainfall and its peak discharge is smaller when the same rainfall is given to the runoff model with parameter sets in the group 1. The group 2 shows the middle feature of the group 1 and 3.

The question is why the difference is observed in the same catchment. Each group includes various scales of floods and there are no distinguished characteristics in the rainfall and discharge data to form three groups. One of clear difference is the number of rainfall observatories. All floods in the group 3 were observed with more than 10 rainfall stations. It is inferred that the accuracy of rainfall observations affects the value of the tuned model parameters and makes large prediction uncertainty. Another possible reason that makes the large prediction uncertainty is the setting of initial condition for prediction simulations. The groups 1 and 2 have a flood observed with 10 rainfall stations. The difference among the floods with more than 10 rainfall observations is the initial discharge. The 1993 flood has the smallest initial discharge; while the 1985 flood has the largest initial discharge in these floods. For the 1985 flood, the recession of river discharge is clearly observed. This implies it was not correct for the 1985 flood to assume the steady state condition at the beginning of simulation. Rainfall is spatially distributed and the distributions are memorized in the spatial distribution of soil moisture, therefore if the initial condition setting is inappropriate the resultant model parameter values are obtained wrongly.

For the 1993 flood, a sudden rising up of river discharge followed dry condition. To simulate the flood with the runoff model used here, the value of parameter β is needed to be set in a large value to keep water in soil layer for lasting small discharge at the outlet. If the low flow observation in 1993 is correct, the improvement of model structure including the refinement of the discharge stage relationship and the initial condition setting are the key to improve the flood runoff prediction for the rainfall-runoff model.

Discussion on Kamishiiba 2005 flood simulations and predictions

The peak discharge of the 2005 heavy rainfall at the Kamishiiba Dam site (Fig. 4, 210 km^2) is estimated about 1,800 m^3/s by Kyushu Electric Power Co., Inc. The estimated peak discharge value is the highest record after the dam was constructed in 1955, which is more than 1.5 times larger than the floods recorded in recent ten years. The catchment mean rainfall in two days is 831 mm and the highest hourly rainfall is 45 mm. We applied the same distributed hydrologic model to predict the floods in this catchment. The rainfall data used is observed by radar with 2.5 km spatial resolution calibrated by ground gauged rainfall measurements. The discharge data was estimated at the Kamishiiba Dam site with the relation between the water stage at the dam reservoir and the dam release.

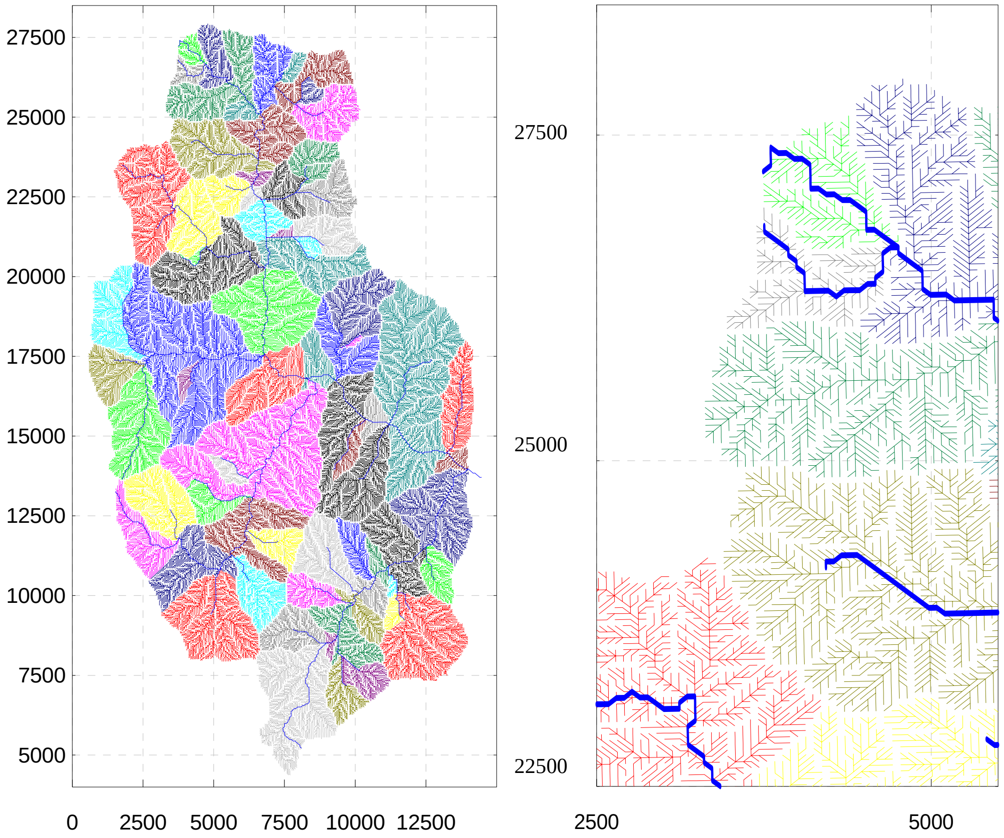
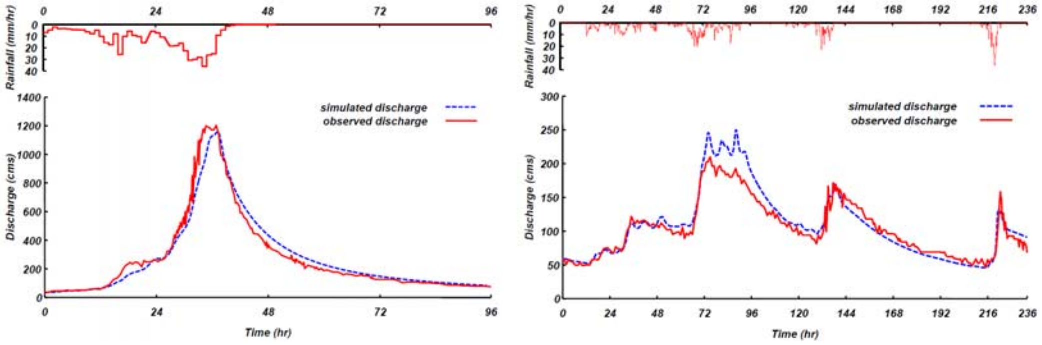


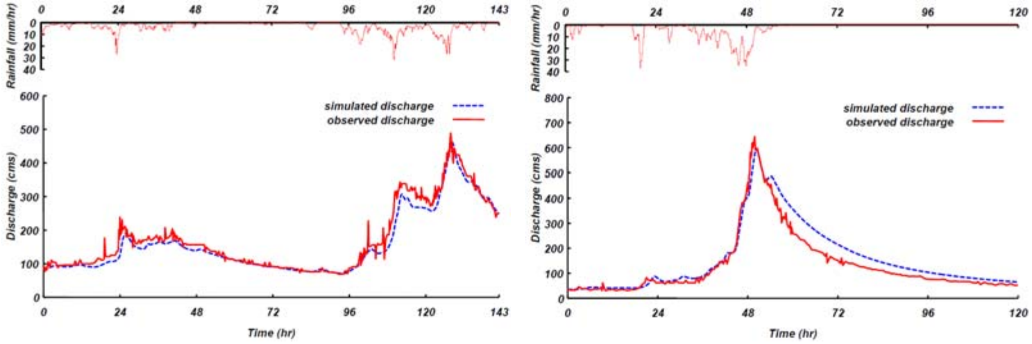
Fig. 4 Watershed model for the Kamishiiba basin (210 km^2). The location is specified using UTM coordinate with m unit. The right figure shows enlarged illustration.

Table 2 Model parameter values fitted to floods and the characteristics of each year heavy rainfall and flood discharge at Kamishiiba catchment.

Parameters	Sept. 1997	June 1999	Aug. 1999	Sept. 1999	Sept. 2005
n ($m^{-1/3}s$)	0.3				
k_a (m/s)	0.01				
d_a (m)	0.55				
d_m (m)	0.45				
d_a-d_m (m)	0.10				
β (-)	4				
Peak discharge (m^3/s)	1203	210	489	644	1840
Initial discharge (m^3/s)	33	59	82	34	11
Total amount of rainfall (mm)	496	463	473	339	831
Total amount of discharge (mm)	415	238	237	256	780
Runoff ratio	0.84	0.51	0.50	0.77	0.94



(a) 1997 September flood (b) 1999 June flood



(c) 1999 August flood (d) 1999 September flood

Fig. 5 Observed and simulated hydrographs for the Kamishiiba basin in 1997 and 1999.

Table 2 summarizes the characteristics of the floods used and identified model parameters. Figure 5 shows the observed and simulated floods in 1997 and 1999. The model parameter set was determined using the flood in 1997 and it was successfully applied to reproduce the floods in 1999. Figure 6 represents the observed and simulated hydrograph for 2005 largest ever flood. For the discharge simulation, the ground-gauged rainfall was used, because the radar rainfall was much underestimated the ground-gauged rainfall and the spatial distribution pattern of the event was not significant. In contrast to the simulation results at the Asuwa River basin, one parameter set is applicable to predict the floods with the peak discharges ranging from 210 to 1,800 m^3/s and runoff ratio from 0.50 to 0.94. The simulation results support that the model structure well reflects the characteristics of runoff properties for the mountainous catchment.

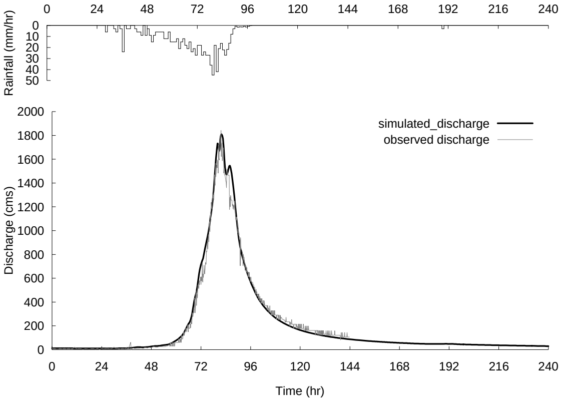


Fig. 6 Prediction of the 2005 flood with identified parameter values.

Discussion on sources of prediction uncertainty and a direction to improve flood discharge predictions

The state of the art physically based rainfall-runoff model shows large uncertainty to predict the largest ever 2004 flood in the Asuwa River basin, while quite good prediction is observed for the largest ever 2005 flood in the Kamishiiba basin. We also obtained good simulation results applying the same model at the Yura River basin (1,860 km^2, Kobayashi *et al*, 2006) and the Maruyama River basin (1,115 km^2, Tachikawa and Furuichi, 2006). Through the experiments of the hydrologic simulations in these mountainous catchments, we think the cause of prediction uncertainty mainly comes from the insufficiency of the observed hydrologic data. At the Asuwa River basin, the number of the rainfall observations would be a key factor to make better prediction; while at the Kamishiiba basin, rainfall data is obtained by radar with ground measurement calibration, and all the study floods are well reproduced by the same model parameter set.

If we use erroneous hydrologic observed data, we misunderstand the hydrologic characteristics and it leads to develop a hydrologic model with an ill-chosen hydrologic model structure. The identified model parameters also become erroneous, which results in large prediction uncertainty. We cannot avoid the input data insufficiency. Therefore, the important research themes are:

1. Development of a method to diagnose observed and simulated data to identify input data uncertainty; and
2. Analysis of the behaviors of hydrologic models and prediction uncertainty through uncertainty of identified model parameter and model structure that comes from input data uncertainty.

Input data, model structures and model parameters are not free from errors. The important is to access the prediction error ranges, to understand the causes of the errors and to reduce the width of the error range. To make better predictions in ungauged basins, we need to make efforts to use the knowledge obtained at gauged basins to transfer to ungauged basins. The research topics to be addressed include:

1. Development of a method to transfer model structures and parameters across scales and regions;
2. Development of a method to diagnose input uncertainty;
3. Development of methods for estimating frequencies of hydrologic extreme events in ungauged basins by using scaling, regionalization, and historical record analysis;
4. Development of assessing methods for hydrologic model performance through a development of uncertainty evaluation indices;
5. Hydrological modeling considering interaction between natural variation and anthropogenic activities; and
6. Downscaling of global hydrologic information for local scale watershed managements in ungauged basins

Concluding remarks

In this paper, we have demonstrated the prediction uncertainty through the hydrologic simulations at two mountainous catchments using a physically based distributed hydrological model. The simulation results suggest that input data insufficiency would be a main source of prediction uncertainty. Further works need to deal with a diagnostic way to examine input data uncertainty and to analyze the hydrologic model behaviors that comes from input uncertainty through parameter and model structure uncertainty. In addition, to develop transferable hydrologic models and estimating methods for hydrologic extremes across scales and regions are significant research themes.

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