IMPROVEMENT OF INTERNAL BEHAVIOR IN DISTRIBUTED HYDROLOGICAL MODEL

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Distributed hydrological models are capable of predicting the internal behavior at any point within a study basin. However, most cases, models are calibrated only at the catchment outlet and prediction accuracy at ungauged points inside is not assured. In this study, we investigate the capability of a physically based distributed hydrological model for predicting internal behavior by calibrating only using discharge observations at the basin outlet. It is found that the prediction ability for internal discharges is different depending on the initial condition; and especially the prediction accuracy of the floods with dry initial condition is low. This is due to a spatially uniform parameter setting for satisfying the calibration at the catchment outlet. Incorporating spatial heterogeneity of the parameter value for easily generating surface flow along the channel network improves the discharge prediction inside for different initial conditions.

Key Words: internal behavior of a basin, distributed hydrological model, flood prediction, ungauged basins

1. INTRODUCTION

Predicting floods at stream flow gauging stations can be achieved by a calibrated hydrological model using observed flow data. However, availability of stream flow data for model calibration is limited and making prediction not only at the stream flow gauging stations but also at strategically important ungauged places inside a basin is necessary to take better actions before and during the disaster for reducing the risk and the damage. Therefore, utilizing available measured data at a gauging station and making better prediction at ungauged locations inside a basin is vital.

Modeling the actual hydrological response of a basin is a difficult task as the actual basin processes are complicated and basin properties change temporally as well as spatially. However, this difficulty can be addressed to some extent by using distributed hydrological modeling approach, which is capable of incorporating the basin heterogeneity to model the basin hydrological responses. The main objective of distributed hydrological modeling is to represent the characteristics of a basin spatially and temporally. Difficult problem is a lack of measurement technology at the scale required by the model and the approximations made in the process

modeling. Therefore, calibration of the model parameters using observed hydrological response is required [1,2].

In general, distributed hydrological models use conservation equations to describe the flow at each slope element due to rainfall and then routed through the channel network. Therefore, theoretically it is possible to predict stream flow at any interior location. However, as the model calibration and validation is done at the basin outlet, there is no guarantee of the prediction accuracy at inside locations. Therfore, in the application of a distributed hydrological model, a question arises whether it is possible to use the calibrated model at the basin outlet to predict the internal behavior at any place within the basin, in other words, how accurately predictions can be made at ungauged sub-basins inside, using a distributed hydrological model. Hence, it is important to study the reliability of a distributed hydrological model prediction at different ungauged places within a gauged basin outlet. This fact was highlighted in the distributed model intercomparison project (DMIP) as well [3].

Ajima *et al.*[1] applied a semi distributed sacramento soil moisture accounting model for the Illinois River basin in USA and analyzed the internal prediction accuracy of the model for

different calibration strategies. They found that the model dose not predict well the stream flow at internal locations. Andersen *et al.*[2] applied a modified version of MIKE SHE model to the Senegal River basin and they calibrated the model for one station and validated against eight internal locations. They also found significant disagreements of the predictions with observed data at some upstream locations. Several studies[1),4),5)] concluded that calibration against additional internal gauge improves the prediction accuracy at some internal locations. Vieux *et al.*[6] observed that their physically based hydrological model is capable of making reliable predictions at some interior points. However, it is not clear in what situations, the hydrologic model well predict or not well predict internal hydrologic behavior.

In this study we investigate the prediction accuracy of internal behavior of a distributed hydrological model, OHDIS-kwmss, OHyMos based distributed hydrologic model with kinematic wave method including surface-subsurface runoff.(http://hywr.kuciv.kyoto-u.ac.jp/index.html# products). Even though the model calibration and validation at a basin outlet gives good agreement for different flood events it is observed that the prediction accuracy of internal locations is low for some flood events. The main objective of this study is to investigate in detail on the model internal behavior for different flood events to clarify the hydrologic condition that internal prediction is failed, and to improve the internal prediction accuracy without using the internal observations for model calibration.

Section 2 describes the distributed hydrological model used in this study. Details for the study basin and the internal prediction accuracy of the model are given in section 3. Section 4 presents the model improvement and discussion.

2. MODEL DESCRIPTION

OHDIS-kwmss is based on the one dimensional kinematic wave theory and developed by Ichikawa *et al.*[7]. The basin topography in the hydrologic model is represented according to the methodology described in Shiiba *et al.*[8]. In the model, it is considered that the basin consists of number of rectangular slope elements which drains to the deepest gradient of its surrounding (**Fig.1**). Each arrow corresponds to rectangular slope element.
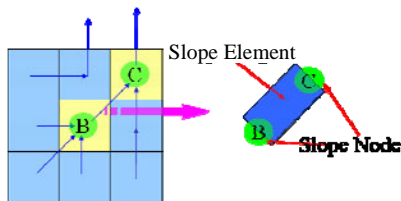

Fig.1 Representation of the topography.

The area of each element depends on the number of connections it has. In **Fig. 1**, when the area of grid cell is a, the slope element connected to Node B is assigned 1/4 of a and element connected to Node C is assigned 1/3 of a; thus the area of the slope element BC is 7/12 a according to Eq.(1). Slope flow produced due to rainfall is routed one dimensionally. Then it flows to the channel network and routed to the basin outlet.

$$
\left.
\begin{aligned}
&\text{Area of grid cell} = a, \\
&\text{Area of slope element assigned from Node B}(a_b) = a/4 \\
&\text{Area of slope element assigned from Node C}(a_c) = a/3 \\
&\text{Area of the slope element BC} = a_b + a_c
\end{aligned}
\right\} \quad (1)
$$

It is assumed that the each slope element of the basin is covered with a permeable soil layer and a stage-discharge relationship for unsaturated, saturated and overland flow defined by the threshold d_c and d_s [9] is adopted. **Figure 2** shows the flow process and the stage discharge relationship used in the OHDIS model given in Eq.(2).
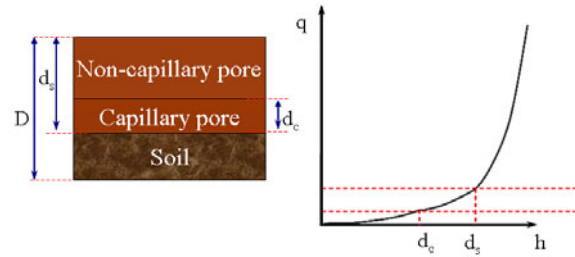

Fig.2 Flow process and Stage-discharge relationship

$$
q = \begin{cases}
V_c d_c (h/d_c)^\beta & 0 \le h \le d_c \\
V_c d_c + V_a(h - d_c) & d_c < h \le d_s \\
V_c d_c + V_a(h - d_c) + \alpha(h - d_s)^m & d_s < h
\end{cases} \quad (2)
$$

where, q is the discharge per unit width; h is the stage; V_a and V_c are flow rates in the capillary pore and non capillary pore respectively.

OHDIS model demands detail channel network information based on Japanese GIS data sets. Unfortunately, detail channel network information is not available for many countries in the world especially in developing countries where the water related problems hindered their development. Therefore, a preprocessor for topographic information, OHDIS-PreTOP[10](http://hywr.kuciv. kyoto-u.ac.jp/hunu/) was developed to apply OHDIS to any catchments on the globe only using globally available digital elevation models and it was used for this study.

3. INTERNAL BEHAVIOR OF DISTRIBUTED HYDROLOGIC MODEL

(1) Study basin and data
The Maruyama River basin in Japan having area

of about 909 km^2 was selected for this study and four internal stream flow measuring stations was used for analysis of internal hydrologic behaviors. **Figure 3** shows the stream flow gauging locations, rainfall measuring stations and sub-basins at each internal gauging location. Brief physical details about each sub-basin are given in **Table 1**.
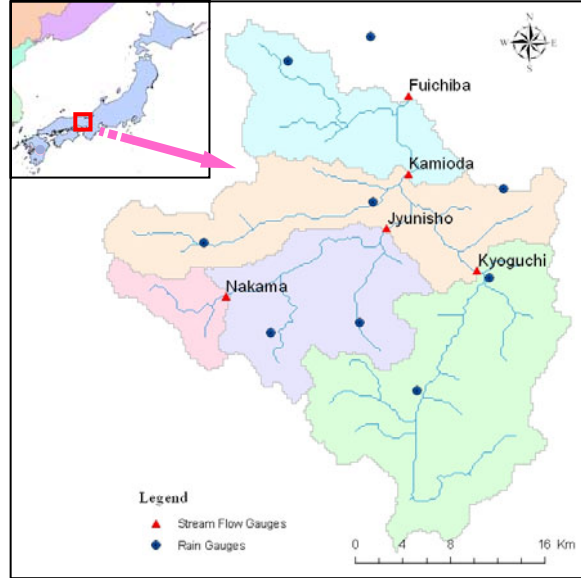

Fig. 3 Maruyama Basin at Fuichiba.

Table 1 Physical properties of sub basins.

Property	Basin Name				
	Fuichiba	Kamioda	Kyoguchi	Jyunisho	Nakama
Area (km^2)	909	766	318	216	45
Stream Length (km)	240	202	82	55	12
Mean Slope(deg)	13.80	14.19	13.51	15.54	17.05

According to the Japanese land use and land cover data set [11], the basin covered with different land use types comprise of 85% forest, 7 % rice, 2% buildings, 1% inland water and 5% other. To represent the basin topography, the SRTM 90m digital elevation model (http: //seamless. usgs.gov/) was used. Considering the time taken for automatic calibration of the distributed hydrological model, the original digital elevation model (DEM) was resampled to 200m x 200m grid size.

Table 2 Details of the selected flood events at Fuichiba.

Flood event	Date	Peak flow (m^3/s)	Minimum flow before to the flood (m^3/s)	Initial river flow of the event (m^3/s)
Event1	10/ 19 – 10/24, 2004	4782	32	32
Event2	09/ 28 – 10/02, 2004	2634	67	95
Event3	07/ 11 – 09/19, 2003	545	46	47
Event4	08/ 23 – 09/02, 2004	2021	5	27

Rainfall data at ten stations within and nearby the Maruyama basin was used for the study. Three flood events in 2004 and one event in 2003 were selected and the details are given in **Table 2.** Event 1, 2 and 3 are occurred after a rainy period and the initial status of the basin can be considered as wet. Event 4 occurred after reasonably dry period (about 25 days) and therefore the status of the basin before to the flood is considered as dry. Initial condition of the basin was set up using the initial river flow and assuming the steady state condition.

(2) Methodology

Overall objective of this study is to investigate the accuracy of representation of the internal behavior of a distributed hydrological model and improve the internal prediction accuracy. Even though distributed hydrological models are capable of predicting some internal state variables of the basin, most of the cases, measured stream flow data is the only information for model calibration and validation due to lack of internal spatio-temporal observed data of the other hydrological responses. Here in this study also we used stream flow data for model calibration, validation and to evaluate how accurately the OHDIS model can predict the internal behavior of the basin.

The Shuffled Complex Evolution Algorithm (SCE)[12),13)] is used for calibrating the model using the observed stream flow data at the basin outlet at the Fuichiba station. The SCE algorithm is a single-objective global optimization method widely used to find the best fitted parameter set for nonlinear hydrological models. Here, in this study, Nash Sutcliffe coefficient (N_c) is used as the objective function for model calibration. Calibration of a distributed hydrological model with large number of spatially distributed model parameters is time consuming and computationally intensive [5]. Even though the OHDIS model is capable of representing the heterogeneity of the basin land use and soil properties, it is rather difficult for automatic calibration of fully distributed parameters in the basin. Therefore, it is assumed that the whole basin has uniform properties and optimized for one set of model parameters, *β, d_c , d_s , Saturated hydraulic conductivity and Manning's coefficient.*

At first, the OHDIS model was calibrated for Event 1, which is the biggest recorded flood in the basin in recent history, by using the observed data at the basin outlet at Fuichiba. A best fit parameter set for the basin was obtained with the help of the SCE algorithm and the other three events were used for model validation. After the model was verified, at the outlet, the optimum parameter set was used to simulate the flood hydrographs at each internal gauging station. Finally, the model simulated flood hydrographs and the observed flood hydrographs at each internal gauging location were compared. The

Nash Sutcliffe coefficient was used for quantitative comparison of the prediction accuracy for all flood events at each internal stream flow gauging stations.

(3) Results and discussion

Table 3 shows the performance of the model at the basin outlet for calibration and validation. It is clear that the optimized parameter for Event 1 predicts the other flood events to a reasonable accuracy at the basin outlet. Notably, the flood event starts after a dry period (Event 4) shows low prediction accuracy than other two events in the model validation. However, by looking at the model prediction accuracy only at the outlet of the basin, we can conclude that the uniform parameter set can capture range of flood events to a reasonable accuracy at the outlet.

Table 3 Nash Sutcliffe coefficient for model calibration and validation.

Calibration	Validation		
Event 1	Event 2	Event 3	Event 4
0.99	0.97	0.91	0.73

The values of Nash efficiency for four events are shown in **Figure 4** for Fuichiba at the catchment outlet and internal stations Kamioda, Kyoguchi, Jyunisho and Nakama. According to **Figure 4**, the model gives good prediction accuracy at all internal locations for Event 1, 2 and 3, where the events starts with wet initial condition. Therefore, the model calibrated for very high floods with wet initial condition can even predict the internal behavior of small flood with wet initial condition. It is a good evidence to prove that the OHDIS model is capable of predicting the internal behavior to a reasonable accuracy for wide range of floods with wet initial conditions. In contrast to this, the model shows very low prediction accuracy at all internal locations for Event 4 (medium flood after a dry period) even though it gives fairly reasonable accuracy at the outlet at Fuichiba.

Figure 5 shows the observed and model predicted hydrographs for Event 4 at each internal gauging station. When we look at the predicted and observed hydrographs, the model predictions are slower than the observed hydrographs at all internal locations. Having longer concentration time for flood events after a dry period is normal. However, in the case, the model is requested to generate faster flow at all internal locations when compared to observed flow. That is the main reason for giving low prediction accuracy at these places. Thus the model is requesting more fast flow. The parameter set used to predict the flow at these internal locations is the best fit parameter set obtained for the flood Event 1 at the basin outlet. Hence, there is no chance to change the parameters to improve the prediction accuracy inside the basin. Therefore,

setting uniform parameters for whole basin is not sufficient to reproduce the internal behavior for floods which begin especially after a dry period. Heterogeneity of a natural basin (e.g. temporal gullies) produces faster flows even though the rainfall intensity is weak. By considering all these facts and figures, we decided to include catchment heterogeneity and investigate whether it is possible to see any improvement.
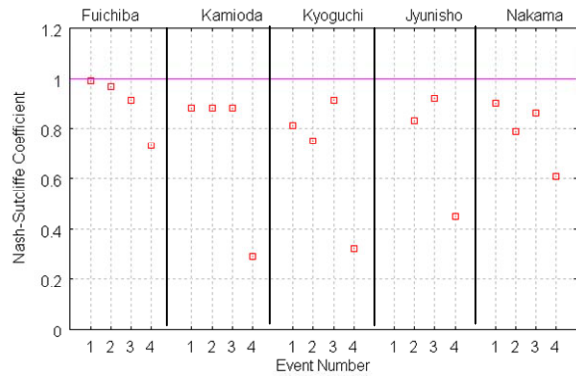

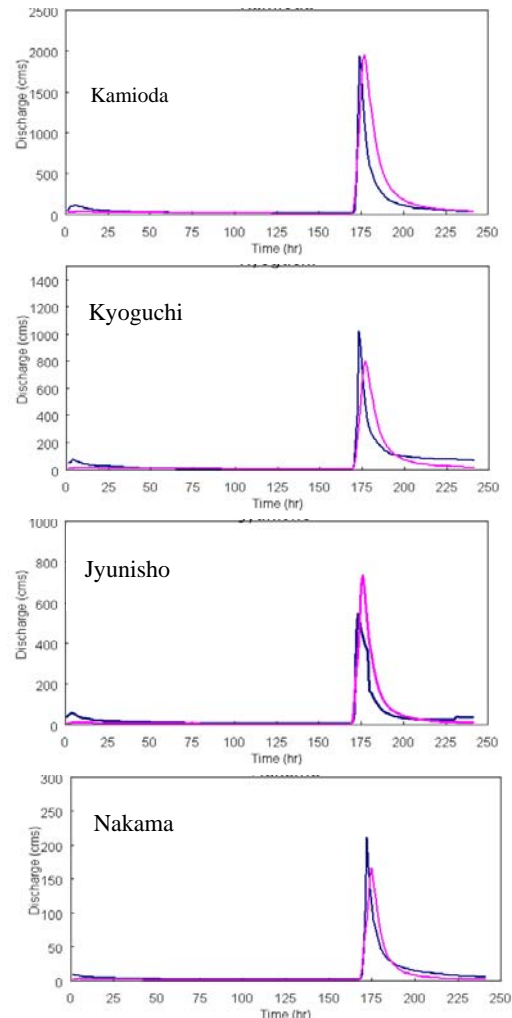**Fig.4** Internal prediction accuracy of the OHDIS model.

Fig.5 Observed and model predicted hydrographs at Kamioda, Kyoguchi, Jyunisho and Nakama for Event 4.

4. IMPROVEMENT AND DISCUSSION

In general, area along the river has high moisture content and the mountainous area has low soil depth. Therefore both places tend to produce quick flow during a rainfall event. The OHDIS model structure is flexible and it is possible to generate quick flow component easily by setting the thresholds d_c and d_s to zero. Here it is decided to check the effects on the internal prediction accuracy by setting the threshold d_c and d_s to zero at two different places within the basin,

      a. Along the river (Case II)
      b. At the higher mountains (Case III)

Case (I) represents the situation in the previous section as using only the optimized uniform parameter set for the basin. We kept the total modified area of nearly 10% of the total basin area for both cases. **Figure 6** shows the schematic diagrams of the test modifications.
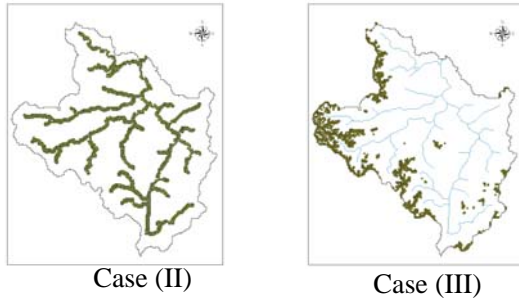

Case (II)	Case (III)

Fig.6 Schematic diagrams for modifications. The model parameters d_c and d_s are set to zero for dotted slope elements. Both cases, the area is 10% of the total catchment area.

Figure 7 shows the model performance for each modification case at each internal gauging location for all flood events. According to the figure, model perf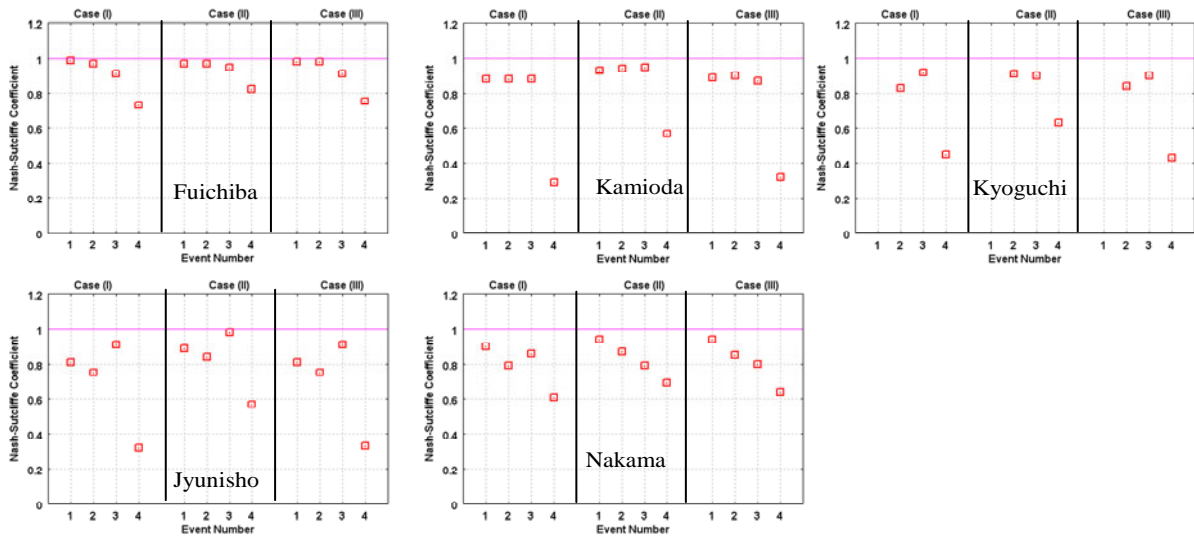ormance at all the internal places for all events was improved for Case (II), where the soil depth is set to zero near to the river. The improvement is significant for the flood Event 4 at Kamioda, Kyoguchi and Jyunisho and percentage improvements of these locations with respect to Case(I) are 94%, 75% and 41%, respectively. On the other hand no significant improvement can be seen in Case (III) modification. In Case (II), the flow produced due to the modification directly flows to the river and hence it is more effective than the Case (III) where the produced flow go through slope elements with soil layer.

To investigate further on these findings, the model was calibrated independently for the other three events (Event 2, 3, 4) using the data at the basin outlet, Fuichiba. Then the best fit parameter sets were obtained for each event and predictions at internal locations were obtained for all three cases. Nash efficiency values at Fuichiba and all internal location for each parameter set for Case (I), (II) and (III) are shown in **Figure 8**. According to the figure corresponding to the basin outlet at the Fuichiba station, the model gives nice predictions for all events regardless of the parameter set used. It means that the model calibrated for any event can successfully use to predict the flow at the basin outlet for all other events. However, when look at the inside locations, Event 4 predictions shows low Nash efficiency values than the other events for all parameter sets.

It is clearly noticed that the model performance at internal locations improve significantly for the Case (II) modification while Case (III) gives little improvement. This pattern can be observed for all independent best fit parameter sets obtained at the basin outlet for each flood event. It confirms that the internal behavior of distributed hydrological model can be improved by setting the soil depth parameter to zero to easily generate surface flow.
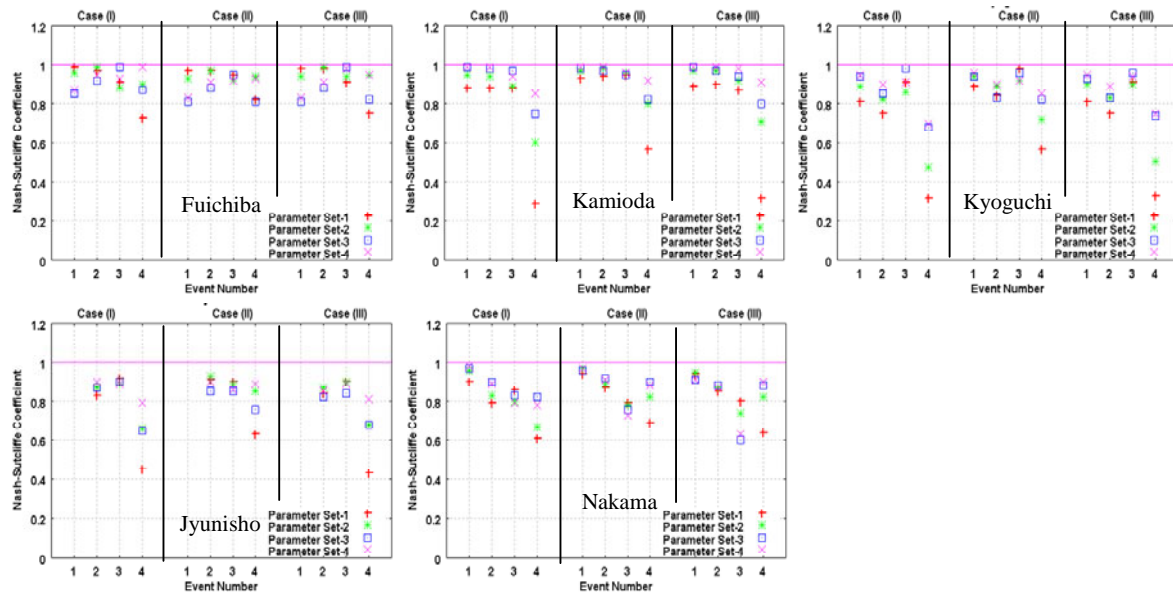

Fig. 7 Model performance at internal locations and the outlet at Fuichiba for Case (I), Case (II), and Case (III).

Fig. 8 Model performance at internal locations and Fuichiba for different optimized parameter sets (Parameter sets, 1,2,3,4 corresponds to the optimum parameters obtained from SCE algorithm for event 1,2,3,4 respectively).

5. CONCLUSIONS

Capability of a distributed hydrologic model OHDIS for predicting the internal behavior was studied in detail. The findings are summarized below:

- The model is capable of predicting the internal behavior of floods with wet initial conditions to a reasonable accuracy.
- The internal prediction accuracy of floods occurs after a dry period is not good and it is not possible to capture the internal behavior only using a spatially uniform parameter set.
- Significant improvement can be achieved by including basin heterogeneity. The model structure for easily generating quick flow along the river improves the internal hydrologic behavior.
- Setting out a saturated zone at arbitrary places does not give significant improvement at the internal locations.

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