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Parameter Determination of a Distributed Runoff Model Considering the Surveyed Ground Surface Conditions

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ABSTRACT:
Though distributed runoff models can take spatial variability of ground surface condition into consideration, there are few studies in which the model parameters are determined considering the surveyed ground surface conditions. The Yanase Dam catchment located in the Nahari River, Southwest Japan was modelled using the object-oriented hydrologic modelling system, OHyMoS, and the Cell Based Distributed Runoff Model developed by Kyoto University. The model was manually calibrated in two ways: one is to allocate one common parameter set to the whole catchment; another is to allocate two parameter sets to two sub-catchments considering proportion of the land with damaged vegetation. The simulated hydrographs of 12 representative flood events obtained by the latter way of calibration showed better coincidence with observation than ones obtained by the former way of calibration. This result suggests that the performance of the runoff model can be improved by parameter calibration considering the actual land surface condition of the catchment. It was also confirmed that time and manpower for this manual calibration can be drastically reduced by introduction of automatic calibration based on SCE-UA algorithm.

Keywords: cell based distributed runoff model, actual ground surface conditions, land with damaged vegetation, SCE-UA algorithm

1. INTRODUCTION

As the result of global warming, frequency of abnormal rainfall and flood is increasing all over Japan. This trend is expected to be accelerated in the coming decades. In order to continue hydropower business under such circumstance, it is more and more required to operate the dams accurately in advance of occurrence of abnormal flood. Electric Power Development Co. Ltd (J-Power), the largest wholesale power company in Japan, is developing a real-time inflow prediction system based on a distributed runoff model for its hydropower dams.

In application of a distributed runoff model, it is ideal to survey the actual environment of the catchment and allocate different parameters to each slope segment. However, there are few studies in which the model parameters are determined considering the surveyed ground surface conditions. In order to improve accuracy of runoff analysis and objectiveness of analysis conditions, the authors are trying to determine the model parameters as far as they reflect actual environment of the catchment. This paper explains that accuracy of runoff analysis is improved when the parameters are determined considering the surveyed ground surface conditions.

2. STUDY SITE

The study site is the catchment of Yanase Dam, which was constructed by J-Power in 1965 in the eastern part of Shikoku Is., Southwest Japan. Characteristics of the dam and the reservoir are as follows:
Location: Kitagawa and Umaji Villages.
River: Nahari River (Managed by Kochi Prefecture).
Dam: Height 115 m, Crest length 202 m, Catchment area 100.7 km^2
Reservoir: Total volume 104.6 Mm^3, Effective volume 72.5 Mm^3, Effective drawdown 35 m.
Power station: Maximum water usage 50 m^3/s, Maximum output 36 MW.
Annual precipitation in the Yanase Dam catchment is the largest in Kochi Pref., reaches 4,000 mm, and heavy rainfall brought by typhoon occur once or several times a year (Kochi Local Meteorological Observatory, 1982).

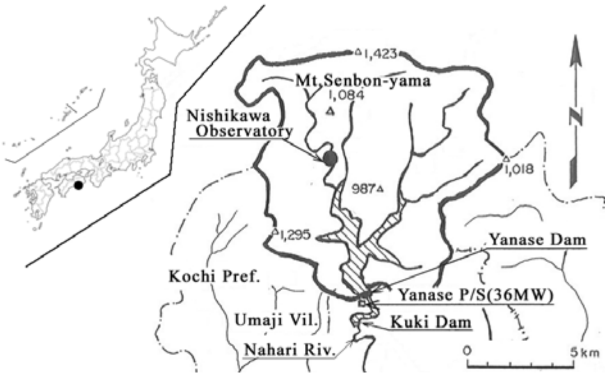

Figure 1. Catchment of Yanase Dam

Most of the catchment is composed of steep mountains covered with forest, of which slope gradient is 1:3 to 1:1, average riverbed gradient between the origin and the dam is about 1:20. As rapid and large flood occurs frequently in the catchment, a precise and real-time inflow prediction tool is desired to control the reservoir water level and spillway discharge rate in compliance with the river legislation. The river water flow in the Yanase Dam catchment is observed every 10 minutes in the two points, Nishikawa Observatory Station and Yanase Dam.

3. DISTRIBUTED RUNOFF MODEL

3.1. Modelling System

The topography of Yanase Dam catchment was modelled by the object-oriented modelling systems "OHyMoS" and "GeoHyMoS" (Takasao et al., 1995) developed and opened by Kyoto University. These systems simulate the natural topography by numerous channel segments and slope segments. In order to simulate reduction of channel storage and increase of flood propagation velocity brought by existence of the reservoir, the impounded surface was modelled by a network of channel and slope segments, of which parameters were modified so that runoff time lag may be almost zero.

3.2. Channel Segment Model

The channel network of Yanase Dam catchment was developed by selecting the channel data from National Land Numerical Information System. The channel segments (Ichikawa et al., 1998) were developed by dividing the channel network at the points such as flow observatory stations and dams, at which flow must be calculated. Width of the channel segments, *W*, was determined by measuring the width of river channels indicated on the topographic maps of 1:25,000 issued by Geospatial Information Authority of Japan.

The continuity equation (Eq.1) and motion equation (Eq.2) were applied to each channel segment. Flow rate *q* was calculated by difference method. The flow supplied from the slope segments described in 3.3 was added to the flow in the channel as lateral inflow q_L.

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}=q_L \qquad 1)$$

$$q=\left(\sqrt{i}/n\right)h^{5/3} \qquad 2)$$

where *h* is channel water depth (m), *n* is roughness coefficient of the channel bed ($m^{-1/3}s$), *x* is distance along the channel (m), *t* is time (sec) and *i* is gradient of the channel.

3.3. Slope Segment Model

The streamline network of Yanase Dam catchment was developed by processing the 50m DEM from National Land Numerical Information System. Surface area of the natural slope was distributed to the streamlines by giving width to them. A slope segment (cell) (Ichikawa et al., 1998; Tachikawa et al., 2003) was developed under each streamline by assuming soil layer of thickness *D*. Structure of a cell is described in Fig. 2. Flow rate *q* in the cell and on the cell surface is calculated by the following continuity equation (Eq.3) and motion equations (Eq.4-Eq.6).

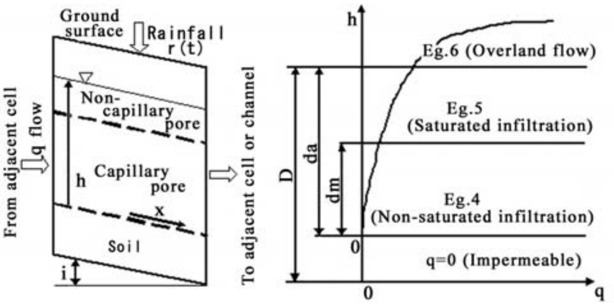

Figure 2. Model Structure of a Slope Segment

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}=r(t) \qquad 3)$$

$$q=k_m i d_m\left(h/d_m\right)^{\beta} \qquad (0\leq h\leq d_m)4)$$

$$q=k_m i d_m+k_a i\left(h-d_m\right) \qquad (d_m< h\leq d_a) \qquad 5)$$

$$q=k_m i d_m+k_a i\left(h-d_m\right)+\frac{\sqrt{i}}{n}\left(h-d_a\right)^{\frac{5}{3}} \quad (d_a< h) \quad 6)$$

where h : stored water depth in the cell (m)
i : slope gradient
r : rainfall on the cell surface (m/s)
n : roughness coefficient of the cell surface ($m^{-1/3}s$)
d_a : water depth corresponding to maximum water content in the capillary and non-capillary pores (m)
d_m : water depth corresponding to maximum water content in the capillary pore (m)
k_a : saturated hydraulic conductivity of the non-capillary soil layer (m/s)
k_m : saturated hydraulic conductivity of the capillary pore (m/s)
β : parameter indicating reduction of k_m in case the capillary pore is partially filled with water and non-saturated infiltration flow occurs ($=k_a/k_m$)

There are five parameters (n, k_a, d_a, d_m and β), to be optimized in the distributed runoff model.

4. SURVEY OF THE GROUND SURFACE ENVIRONMENT

4.1. Method and Result

Major part of the forest in Yanase Dam catchment is composed of relatively well managed plantation of

Japanese cedar and cypress. On the other hand, there are not a few lands with damaged vegetation such as clear-cut area. As the proportion of damaged vegetation to the total catchment area is expected to exert influence on runoff characteristics, the authors developed a distribution map of the land with damaged vegetation in Yanase Dam catchment by the following procedure.

4.1.1. Site visit

Some part of the lands with damaged vegetation such as bare land (land without vegetation such as degraded land), semi-bare land and communities in clear-cut area (substitution scrub on unmanaged clear-cut area) was confirmed by site visit.

4.1.2. Identification of damaged vegetation on maps

Location and range of the lands with damaged vegetation visited by the authors were identified on the satellite images (YAHOO! Map) and the forest planning maps (Aki District Forest Office, 2007) covering Yanase Dam catchment. Discrimination criteria of land with damaged vegetation were set up by color and texture of the visited lands from the satellite images, and by forestry information (woody mass accumulation per area, identification as lands without trees, etc) from the forest maps. Based on the criteria, all lands with damaged vegetation were discriminated and marked on the forest maps (Fig. 3).

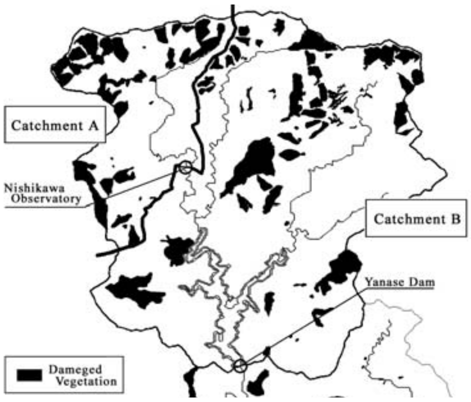

Figure 3. Distribution of the Damaged Vegetation

4.1.3. Digitization of the range of damaged vegetation

The forest map was converted into an image file on a computer. Range of the lands with damaged vegetation was digitized by tracing their boundaries by AutoCAD. Area of each land with damaged vegetation was calculated and summed up for the catchment of Nishikawa observatory station (therafter "Catchment A") and the remaining catchment obtained by excluding Catchment A from Yanase Dam catchment (thereafter "Catchment B"). Area and proportion of the land with damaged vegetation in Catchment A and B are shown in Table 1. Values in Table 1 do not contain surface area of Yanase Reservoir.

Table 1. Proportion of Land with Damaged Vegetation

Sub-catchment	Catchment area	Area of damaged vegetation	Proportion of damaged vegetation
Catchment A	22.8 km^2	4.83 km^2	21.1 %
Catchment B	75.7 km^2	9.33 km^2	12.3 %

4.2. Runoff Characteristics Expected from the Survey

As shown in Table 1, proportion of land with damaged vegetation in Catchment A is as about twice as in Catchment B. As it is generally recognized that water holding capacity is smaller and overland flow occurs easily in land with damaged vegetation, runoff parameters (n, d_a and d_m) are assumed to be smaller in Catchment A than in B. Therefore, these parameters were assumed to be smaller in Catchment A than in B during procedure of manual calibration of the parameters.

5. MODEL PARAMETER CALIBRATION

5.1. Manual Calibration

5.1.1. Survey of preceding studies

The major part of Yanase Dam catchment is covered with forest. Though there are a few flat grounds used for urban district and log stockyard, their area is negligible. Therefore, all the catchment was modelled as forest. Before calibrating the parameters, the authors surveyed the preceding papers based on the same distributed runoff model, to know the values of the five parameters applied to forest. Detected upper and lower bounds of each parameter are shown in Table 2.

5.1.2. Calibration considering actual ground surface conditions

1) One parameter set for the whole catchment

The five parameters were optimized for hydrographs of inflow to Yanase Reservoir. Only one common parameter set was allocated to all slope segments in Yanase Dam catchment. The initial parameter set was determined considering the values shown in Table 2. Simulations of the hydrographs were repeated by changing the parameters little by little, while monitoring the value of objective function. The simulated hydrographs are those of 12 large flood events (Table 3) occurred in Yanase Dam catchment since 2004, of which peak flow exceeded 300 m^3/sec.

The rainfall data used for calibration are the distributed rainfall intensity data, of which grid point interval is 1km and time interval is 10 minutes, observed by the synthetic radar system of Japan Meteorological Agency. These

Table 2. Parameters Applied to Forest in Preceding Studies

Parameter	Lower bound	Upper bound	Notes
n	0.3	0.6	mode is 0.6
d_a	0.1	0.55	mode is 0.2-0.4
d_m	0.1	0.45	mode is 0.1-0.2
k_a	0.01	0.108	mode is 0.01
β	4	9	mode is 4 and 8

Table 3. Flood Events Used for Parameters Calibration

Event No.	Cause of flood	Simulated period		Max. inflow (m^3/s)
		Start	End	
8	typhoon	2004/06/19	2004/06/22	628
9	typhoon	2004/07/30	2004/08/02	789
11	typhoon	2004/08/29	2004/09/01	839
12	front	2004/09/11	2004/09/14	495
14	typhoon	2004/10/19	2004/10/22	835
16	typhoon	2005/09/05	2005/09/08	1,167
17	low	2006/04/10	2006/04/13	373
19	low	2006/06/14	2006/06/17	345
20	typhoon	2006/08/17	2006/08/20	408
22	typhoon	2007/07/13	2007/07/16	839
23	typhoon	2007/08/02	2007/08/05	325
26	typhoon	2009/08/08	2009/08/11	873

data were modified before input to the distributed runoff model, based on the ground rainfall data observed by J-Power in its seven rain gauges located in the Nahari River basin. Computation time interval of simulation is 10 minutes. Suitability of the parameter set was evaluated by comparison of the observed and simulated hydrographs based on the following three objective functions.

a. Correlation coefficient r: the nearer 1, the better

$$r = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2 \sum_{i=1}^{N}(y_i - \bar{y})^2}} \qquad 7)$$

b. Regression coefficient b: the nearer 1, the better

$$b = \sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y}) \Big/ \sum_{i=1}^{N}(x_i - \bar{x})^2 \qquad 8)$$

c. Error ratio E: the nearer 0, the better

$$E = (1/N)\sum_{i=1}^{N}\left((y_i - x_i)/y_i\right)^2 \qquad 9)$$

where x_i : time series of simulated inflow (m^3/s)
$\bar{x}$: average of x_i (m^3/s)
y_i : time series of observed inflow (m^3/s)
$\bar{y}$: average of y_i (m^3/s)
i : computation time step (1 to N)

Using the above-mentioned three objective functions, each one most suitable parameter set was determined for each of the 12 flood events. Among these 12 parameter sets, the parameter set for Event No.22 (Typhoon No.4 in July 2007) gave the best values of the three objective functions. Another 11 events were simulated again using the parameter set for Event No.22. As the result showed generally good values of the objective functions, the parameter set for Event No.22 was selected as the common suitable parameter set for simulation of hydrographs of Yanase Dam inflow. The parameters of this parameter set are shown in the row "One parameter set" of Table 4.

2) Two parameter sets for two sub-catchments

The hydrograph of Event No.22 observed in Nishikawa Observatory was simulated using the one parameter set determined in 1). As illustrated in Fig. 4, the simulated peak flow is apparently smaller than the observed one. This suggests that discharge from Catchment A is apt to increase more rapidly and sharply than that from Catchment B because proportion of lands with damaged vegetation is larger in Catchment A than in B. Considering this difference of actual ground conditions, two different parameter sets were allocated to Catchment A and B, so that the values of n, d_a and d_m may be smaller in Catchment A than in B. The manually optimized parameter sets for Catchment A and B are shown in the row "Two parameter sets" in Table 4. As illustrated in Fig. 5, both of the two hydrographs were simulated well by the two parameter sets.

3) Simulation of all events using two parameter sets

All of the 12 flood events were simulated using the two parameter sets shown in Table 4, and the values of the three objective functions were calculated for the 12 pairs of optimized hydrographs of the flow in Nishikawa Observatory and Yanase Dam. The average values of three objective functions in case one parameter set is allocated to whole Yanase Dam catchment and in case two parameter sets are allocated to Catchment A and B are shown in Table 5.

As shown in Table 5, hydrographs of inflow to Yanase Reservoir were better simulated in case one parameter set was allocated than in case two parameter sets were allocated. However, the difference is very small (0.01 in the values) for the three objective functions. Total performance of the runoff model including simulation of the hydrographs in Nishikawa Observatory is apparently better in case two parameter sets are allocated.

Performance of the runoff model was improved by allocating two different parameter sets to two sub-catchments. The values of parameters suggest that resistance to overland flow and water holding capacity are smaller in Catchment A than in B. This results coincides with the fact that proportion of lands with damaged vegetation is larger in Catchment A than in B.

Table 4. Model Parameters Optimized by Manual Calibration

Allocation of parameter sets		Values of parameters				
		n	d_a	d_m	k_a	β
One parameter set		0.60	0.45	0.45	0.01	4
Two parameter sets	Nishikawa	0.55	0.38	0.38	0.01	4
	Yanase Dam	0.60	0.48	0.48	0.01	4

Table 5. Average Values of Objective Functions for the Optimized Hydrographs of 12 Flood Events

Hydrographs	Correlation coefficient		Regression coefficient		Error ratio	
	one set	two sets	one set	two sets	one set	two sets
Nishikawa	0.57	0.68	0.55	0.76	0.74	0.72
Yanase Dam	0.90	0.89	0.89	0.88	0.10	0.11

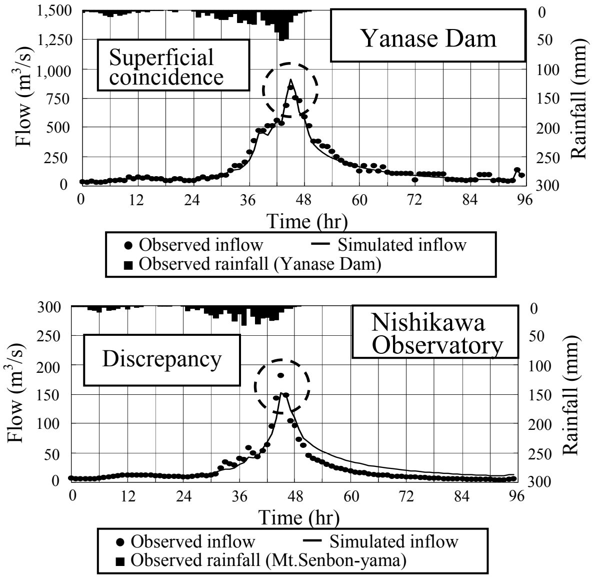

Figure 4. Manual Simulation of Two Hydrographs of Event No.22 Based on One Parameter Set

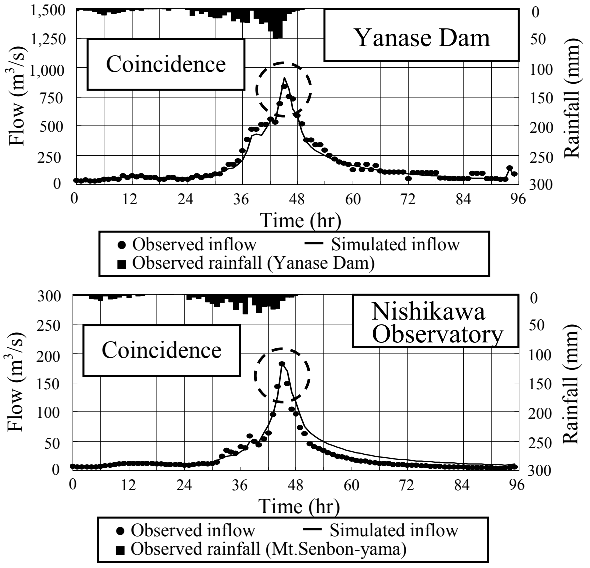

Figure 5. Manual Simulation of Two Hydrographs of Event No.22 Based on Two Parameter Sets

5.2. Automatic Calibration

5.2.1 Application of SCE-UA algorithm

The difficulty accompanying manual calibration of model parameters is that it depends on the subjective assessment of the modeller and is very time-consuming. In order to reach the condition of Fig. 5 from that of Fig. 4, the authors spent 2 weeks to repeat 10 stages of trial and error. In spite of this large manpower, the possibility of existence of more suitable solution can not be denied. In case of a model of larger basin in which more number of flow observatories exist, manual calibration is not practical. From this consideration, the authors decided to conduct automatic calibration. The authors introduced a global optimization algorithm entitled Shuffled Complex Evolution developed at the University of Arizona (SCE-UA). The SCE-UA algorithm is a single-objective optimization method designed to handle high-parameter dimensionality encountered in calibration of a nonlinear hydrological models (Duan et al., 1992), and is widely used to calibrate various hydrologic models.

In order to confirm the performance of SCE-UA algorithm, the authors simulated the hydrographs of inflow to Yanase Reservoir in the flood events in Table 3. To simplify model operation, one common parameter set was allocated to Catchment A and B. Initial values of the five parameters are the values in the row "Yanase Dam" in Table 4. To keep objectiveness of analysis, variation ranges of the five parameters were set wide as shown in Table 6. Nash-Sutcliffe Coefficient (NSC), which is most frequently used for parameter calibration of hydrologic models, was adopted as the objective function. NSC is a function defined by Eq. 10, in which meanings of the variables *x*, *y* and *i* are same as in Eq. 7 to Eq. 9. The smaller the value of NSC, the better regarded the simulation is fit to the observation.

$$NSC = \sum_{i=1}^{N}\left(y_i - x_i\right)^2 \Big/ \sum_{i=1}^{N}\left(y_i - \bar{y}\right)^2 \qquad 10)$$

Each event was simulated for 500 times, to determine the parameter set giving the minimum NSC value. Computation time for each event was roughly same as the simulated period (3 to 4 days) shown in Table 3.

5.2.2. Result of analysis and point at issue

The results of parameter optimization for the 12 events are summarized in Table 7. The minimum of 500 NSC values for each event was as small as 0.0173 to 0.170. The value of correlation coefficient accompanying the minimum NSC value was as large as 0.933 to 0.991. Therefore the hydrographs of all events were well simulated. Optimized values of the five parameters did not exceed their upper and lower bounds. However, the values themselves were distinctly different for every event, and some of them were contradictory to the values commonly accepted in the field of hydrology. For example, the minimum value 0.101 and the maximum value 0.890 of roughness coefficient *n* are too small or too large as resistance to overland flow on an actual slope of forest.

As an individual example, Fig. 6 shows the hydrograph of inflow to Yanase Reservoir in Event No.22 optimized by SCE-UA algorithm, i.e. the hydrograph corresponding to the minimum NSC value obtained by the 453th among the 500 times of simulations. Comparing with Fig.4, Fig.6 shows better coincidence between the simulated and observed hydrographs. However as shown in Table 8, the values of parameters are unnatural.

These results suggest that SCE-UA algorithm, which simply searches minimum value of the objective function without considering physical meaning of the parameters, may present a superficial optimum solution around

Table 6. Initial Values and Value Variation Ranges of the Model Parameters for SCE-UA Optimization

Parameter	Initial values	Variation ranges	
		Min.	Max.
n	0.6	0.1	0.9
d_a - d_m	0	0.0001	0.3
d_m	0.48	0.0001	0.7
k_a	0.01	0.0001	0.1
β	4	1	100

Table 7. Result of Automatic Calibration of the Model Parameters Based on SCE-UA Algorithm

Parameters and objective functions	Optimized values		
	Minimum	Mean	Maximum
NSC	0.0173	0.0737	0.170
Correlation coefficient	0.933	0.968	0.991
n	0.101	0.479	0.890
d_a	0.713	0.809	0.918
d_m	0.602	0.664	0.696
k_a	0.000152	0.00883	0.0423
β	6.82	13.0	22.1

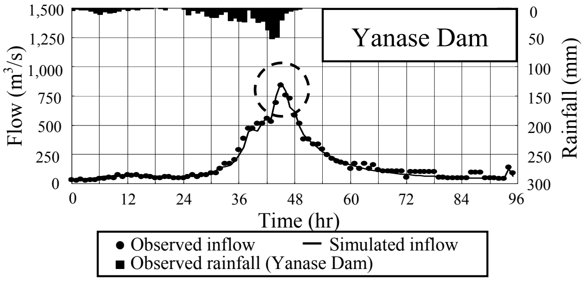

Figure 6. Automatic Simulation of Yanase Dam Inflow Hydrograph of Event No.22 Based on One Parameter Set

Table 8. Model Parameters Optimized for Event No.22 by Manual and Automatic Calibration

Calibration (one parameter set)	C. c. (*)	Values of parameters				
		n	d_a	d_m	k_a	β
Manual	0.89	0.60	0.45	0.45	0.01	4
Automatic	0.991	0.353	0.828	0.643	0.00841	11.0

*: Correlation coefficient

hydrologically impossible parameter values. It seems important to pay attention not only to the value of objective function but also to the values of model parameters when SCE-UA algorithm is applied to calibration of hydrologic models. It also seems important to appropriately restrict the variation range of the model parameters before running SCE-UA algorithm. The authors are now preparing an objective and effective procedure to select the hydrologically most plausible parameter set from the raw output of SCE-UA algorithm.

6. CONCLUSION

1) Considering the proportion of lands with damaged vegetation, two different parameter sets of the distributed hydrologic model were applied to the two parts of Yanase Dam catchment. The result of model calibration made it clear that the observed hydrographs are better simulated than in case one common parameter set is applied to the whole catchment.

2) In order to increase efficiency of parameter calibration, automatic calibration system based on SCE-UA algorithm was introduced. It made clear that this system can reduce the time for optimization of hydrographs from about 2 weeks in manual calibration to 3 to 4 days. By adding a procedure to select hydrologically plausible parameter set from its raw output, SCE-UA algorithm is expected to drastically improve efficiency and objectiveness of calibration of the hydrologic model.

3) In principle, the more the model segments and the parameter sets allocated to them are fractionized considering the actual ground surface conditions, the better the observed hydrographs are simulated. However, as any hydrologic model can not simulate the actual phenomena completely due to limit of its analytical supposition, there is a certain limit of fractionalization. The authors intend to pursuit the best balance of model fractionalization and accuracy of simulation from the viewpoint of benefit to management of actual dams.

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