Evaluation of water retention capacity and flood control function of the forest catchment

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Abstract:
This research quantitatively evaluates the water retention capacity and flood control function of the forest catchments by using hydrological data of the large flood events which happened after the serious droughts. The objective sites are the Oodo Dam and the Sameura Dam catchments in Japan. The kinematic wave model, which considers saturated and unsaturated subsurface soil zones, is used for the rainfall-runoff analysis. The result shows that possible storage volume of the Oodo Dam catchment is 162.26 MCM in 2005, while that of Samerua is 102.83 MCM in 2005 and 102.64 MCM in 2007. Flood control function of the Oodo Dam catchment is 173 mm in water depth in 2005, while the Sameura Dam catchment 114 mm in 2005 and 126 mm in 2007. This indicates that the Oodo Dam catchment has more than twice as big water capacity as its capacity (78.4 mm), while the Sameura Dam catchment has about one-fifth of its storage capacity (693 mm).

Keywords: Forest, Green dam, Flood control, Grid-cell distributed runoff model

Introduction

The Japanese Archipelago is covered by mountainous forest in great part (67%) of its land surface compared to its area. Forests are generally believed to have water retention function known as 'green dam', which can store water in the soil layers and mitigate floods. Most of the headwater zones of the Japanese rivers are in the mountainous areas covered by forests. In recent years, new dam construction is often criticized severely because of the raising awareness of environmental risks. The criticisms are based on the 'green dam' function. Although widely known qualitatively, this function is not evaluated quantitatively except the arguments done by Kosugi (2004) and Takara (2004ab). Quantitative evaluation of the flood mitigation capacity of 'green dam' is crucial to the discussion of disaster mitigation and environment protection, especially nowadays for disaster mitigation and conservation of environment are equally stressed as fundamental factors to achieve sustainable development in the Rio+20 Conference (U.N. Genaral Assembly, 2012).

Kosugi used a tank model, which is one of the lumped models, while Takara used a distributed runoff model with the hypothetical precipitation. Considering these previous quantitative studies, this research is to evaluate water retention capacity and flood control function of forests in the Oodo Dam and the Sameura Dam catchments in Japan; these catchments are covered by forest more than 85% of their surfaces.

Case study sites and events

As can be seen in Figure 1, this paper selected two dam catchments in Shikoku Island of Japan as case study sites. The Oodo Dam is located in the upper stream of the Niyodo River, whose catchment area is 688.9 km^2 and its total storage capacity is 66 MCM (million m^3); the effective storage capacity of the dam is 52 MCM. The Sameura Dam is a multi-purpose reservoir located in the upper area of the Yoshino River. The Sameura Dam's catchment is 417 km^2 and the total storage capacity is 316 MCM (effective storage capacity is 289 MCM). These catchments are ideal to assess the effect of forests because most parts of the both catchments are covered by forest (89% in the Oodo Dam, 86% in the Sameura Dam).

This research deals with the following cases:

(a) The Oodo Dam restricted 30% of water intake from August 11th in 2005, and as a result, storage capacity had decreased to 22.7%. After that, storage capacity had recovered up to 327% of the capacity on September 4th by the precipitation brought by Typhoon No. 14 in 2005;

(b) The Sameura Dam had started water intake restriction from June in 2005. Storage capacity for water utilization had dropped to 0% in September 4th; however, it had recovered to 100% by September 7th because of the precipitation induced by Typhoon No. 14 in 2005 (651.4 mm); and

(c) The Sameura Dam also restricted water intake in May 2007. The water storage had decreased to 23.5% on July 3rd; however, the storage recovered by a series of successive precipitation (718.8 mm) and became 100% on July 15th.

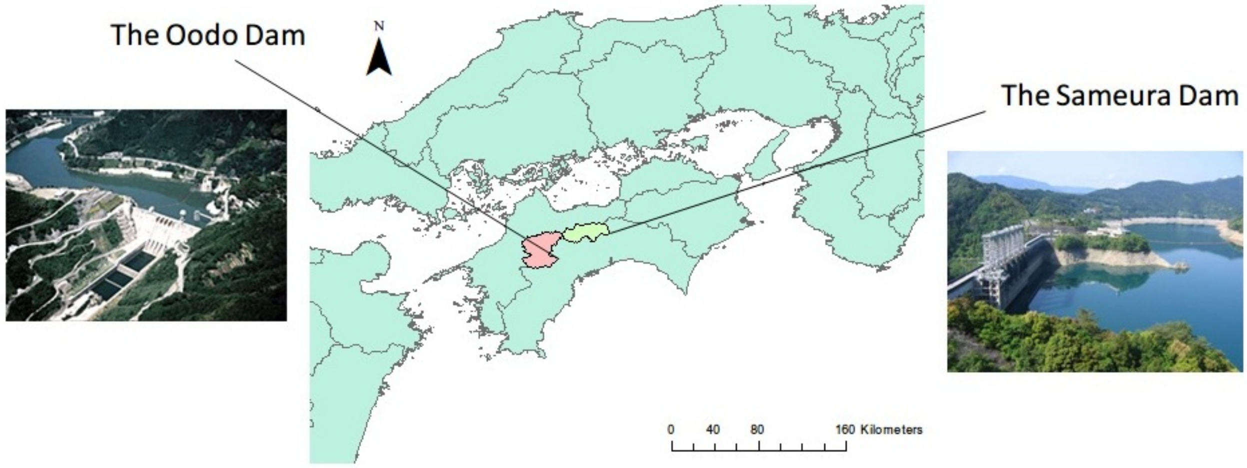

Figure 1. The location and pictures of the Oodo Dam (Oodo Dam official Website, 2012) and the Sameura Dam (Japan Water Agency Ikeda Dam Control Head Office, 2007)

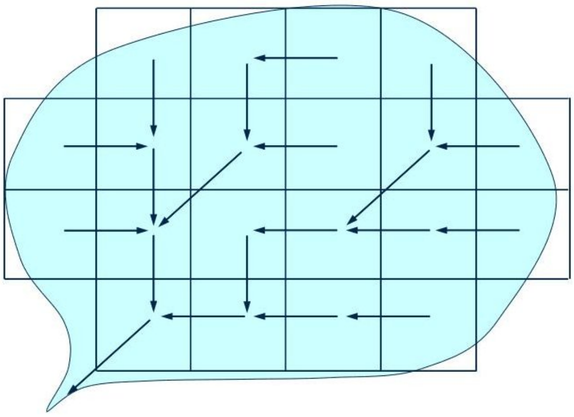

Figure 2. The concept of the cell distributed model (Takara et al., 2004b)

Analysis of water retention capacity and flood control function

This chapter describes the rainfall-runoff model used for analysis of water retention capacity and flood control function.

Summary of the distributed runoff model[1]

The concept of the distributed runoff model used in this research is shown in Figure 2. In this model, the catchment is covered by square grid-cells and each precipitation is considered to flow in the steepest direction, which is deviated from the elevation. Precipitations at each grid-cell are obtained from the nearest rain gauges. Runoff analysis is based on the kinematic wave model.

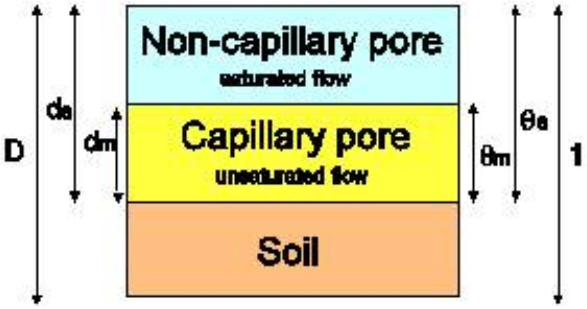

Figure 3. The subsurface soil structure of the saturated and the unsaturated zones (Tachikawa et al., 2004)

When the subsurface system is not considered, the kinematic wave model can be formulated as follows.

Continuous equation:

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

where h is water depth, q is water flow and r is precipitation at time t and location x on the slope (or grid-cell).

If the subsurface mechanism is not considered,

$$\begin{aligned} q &= f(h) \\ &= \alpha h^m \end{aligned} \qquad (2)$$

$$\alpha = \sqrt{i}/n, m = 5/3$$

where n is roughness coefficient and i is gradient.

In this research, as to consider mountain slope covered by the forest, soil structure of each cell is considered to be composed of saturated and unsaturated zones as shown in Figure 3 (Tachikawa et al., 2004). *Q-h* relation equation based on this model can be described as follows:

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[1] The model has been developed by Kojima et al. (1998) at the Disaster Prevention Research Institute in Kyoto University. It has been applied to many simulation studies such as a runoff simulation in Japan (Kojima et al., 1998) and sediment runoff simulations in Japan (Nagatani et al., 2008) and in Indonesia (Sayama & Takara, 2003).

$$q(h) = \begin{cases} v_m d_m (\frac{h}{d_m})^{\beta} & 0 \le h < d_m \\ v_m d_m + v_a(h - d_m) & d_m \le h < d_a \\ v_m d_m + v_a(h - d_m) + \alpha(h - d_a)^m & d_a \le h \end{cases} \quad (3)$$

where v_m is water velocity, d_m is the height of unsaturated zone, d_a is the height of saturated zone.

Application of the model

The grid size used in this research is 250 m and roughness coefficients reflect the different land use type at each grid-cell.

Runoff model parameters are decided by the trial and error method. Simulation performance is checked by the Nash-Sutcliff efficiency coefficient. Using this runoff model, we analyzed water retention capacity and flood control function. Evapotranspiration and percolation of water into the rock layers are not considered in this research.

Equations for water retention capacity and flood control function

In order to evaluate flood control function and water retention function, each cell is divided into N sub-areas. The average water depth at each sub-area, which is derived from the runoff simulation ($\bar{h}$), is multiplied by the area of the sub-area to calculate water retention capacity at each sub-area. The sum of water retention capacity in the sub-areas is total water retention capacity in the catchment as shown in the following equations:

$$S = \sum_{i=1}^{M} \sum_{j=1}^{N} \overline{h_{i,j}} \frac{d^2}{N} \quad (4)$$

where S is water retention capacity at the catchment, M is the total number of grid-cells, $\overline{h_{i,j}}$ is the average water depth in sub-area no. j in grid-cell no. i and d is the grid size (250 m).

Flood control function is calculated by subtracting initial water volume, which can be considered in steady state before the event, from water storage volume at each cell.

Results and findings

Oodo Dam in 2005

A runoff simulation conducted in the Oodo Dam catchment is shown in Figure 4 and parameters obtained from this simulation are shown in Table 1.

The maximum dam inflow during the calculation period was 4,550 m^3/s and the maximum dam outflow was 3,225 m^3/s, while the maximum planned dam outflow was 3,800 m^3/s. The maximum storage volume during this period was 42.51 MCM.

Figure 5 shows water storage of the saturated zone, the unsaturated zone and the whole catchment at the Oodo Dam catchment in 2005. Water retention volume maximized up to 162.26 MCM at 18:00 on September 6th, and then the value has stabilized. This result indicates that the surface soil became saturated at this point and precipitation after this point flowed as surface flows. The maximum flood control function is 173 mm in water depth at this point. The storage capacity of the Oodo Dam is 78.4 mm; hence the flood control function of the catchment is as twice as the Oodo Dam has.

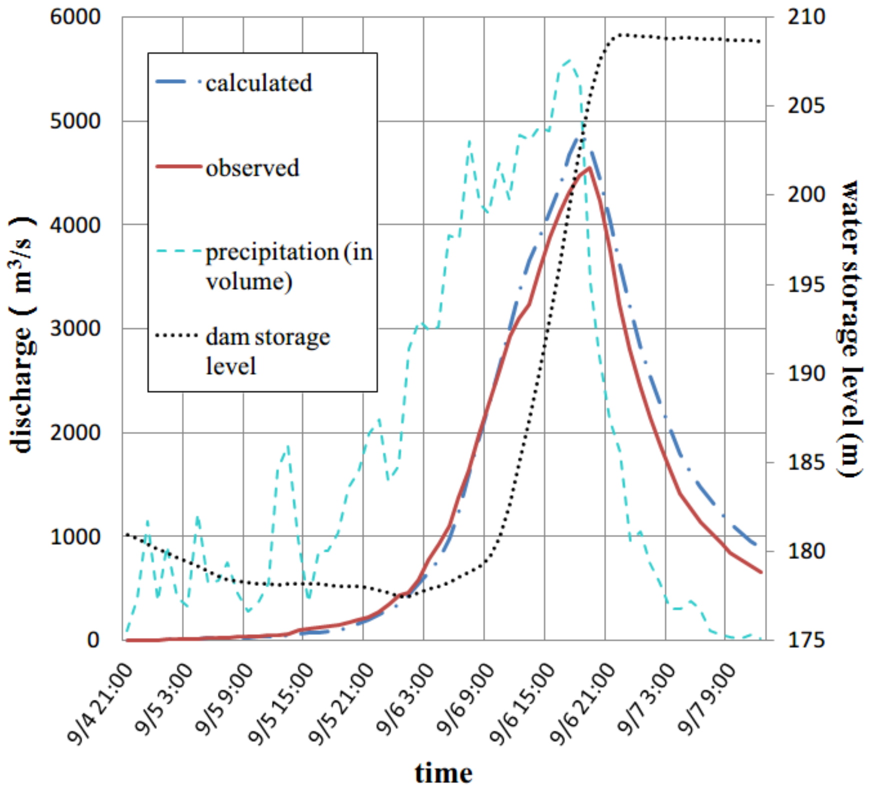

Figure 4. Runoff simulation result in the Oodo Dam catchment in 2005 (based on the model parameters calibrated as in Table 1)

Table 1. Parameters in the Oodo Dam catchment in 2005

Manning coefficient ($m^{-1/3}/s$)	Land use type	Value
Np	Paddy field	0.05
Nfi	Field	0.1
No	Orchard	0.1
Nfo	Forest	0.4
Nw	Wasteland	0.3
Nu	Urban area	0.1
Nwa	Water area	0.8
NRv	River	0.01
Soil parameter		
TOUSUIMS	*Ka* (m/s)	0.02
ASOU	*D* (mm)	1000
GAMMAS	θa	0.275
GAMMAC	θm	0.125
BETAC	β	8

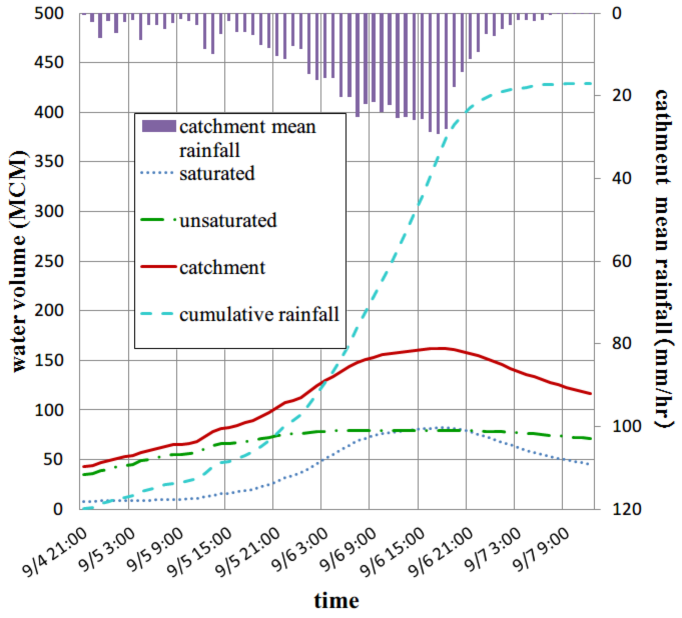

Figure 5. Water storage of the saturated zone, the unsaturated zone and the whole catchment at the Oodo Dam catchment in 2005 (based on the same simulation in Figure 4)

Sameura Dam in 2005

Figure 6 shows runoff simulation in the Sameura Dam catchment in 2005, and parameters determined by this simulation are shown in Table 2. The maximum dam inflow during this period was 5,405 m^3/s and the dam outflow was almost none. The maximum dam storage volume was 257.81 MCM at 9:00 on September 7th.

Figure 7 shows water storage of the saturated zone, the unsaturated zone and the whole catchment at the Sameura Dam catchment. The maximum water storage volume at the catchment was 102.83 MCM and flood control function was 114 mm in water depth at 19:00 on September 6th.

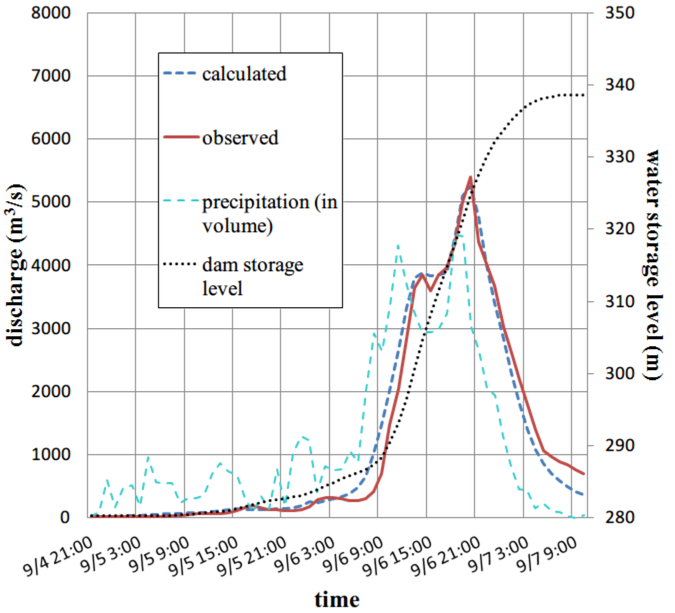

Figure 6. Runoff simulation result in the Sameura Dam catchment in 2005 (based on the model parameters calibrated as in Table 2)

Table 2. Parameters in the Sameura Dam catchment in 2005

Manning coefficient ($m^{-1/3}/s$)	Land use type	Value
Np	Paddy field	0.05
Nfi	Field	0.1
No	Orchard	0.1
Nfo	Forest	0.2
Nw	Wasteland	0.2
Nu	Urban area	0.1
Nwa	Water land	0.8
NRv	River	0.002
Soil parameter		
TOUSUIMS	Ka (m/s)	0.004
ASOU	D (mm)	1000
GAMMAS	θa	0.255
GAMMAC	θm	0.105
BETAC	β	8

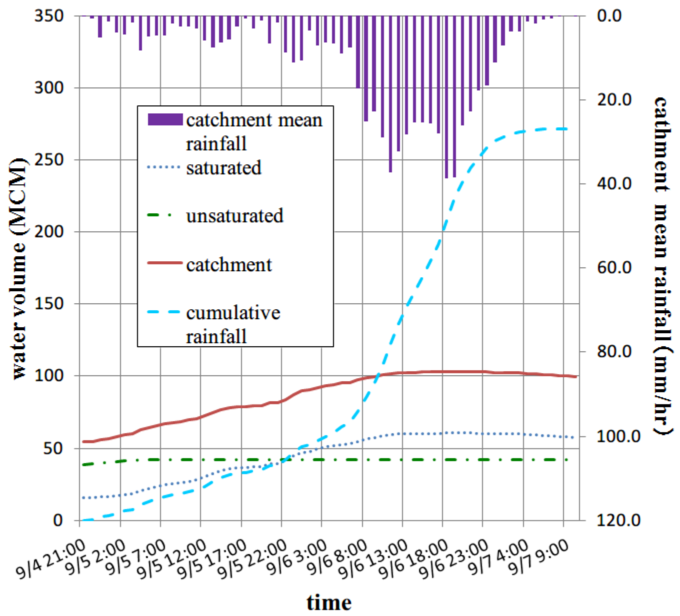

Figure 7. Water storage of the saturated zone, the unsaturated zone and the whole catchment at the Sameura Dam catchment in 2005 (based on the same simulation in Figure 6)

Sameura Dam in 2007

Figure 8 shows runoff simulation results in the Sameura Dam catchment in 2007, and parameters decided by this simulation are the same as parameters used for the Sameura Dam catchment in 2005.

The maximum dam inflow was 3,265 m^3/s, while dam outflow was almost none except on the 15th. The maximum dam storage volume was 234.33 MCM.

Figure 9 shows water storage of the saturated zone, the unsaturated zone and the whole catchment in the Sameura Dam catchment. The maximum water retention volume during the period was 102.64 MCM and the flood control function was 126 mm in water depth at 21:00 on September 14th. The storage capacity of the Sameura Dam is 693 mm; hence, the flood control function of the catchment is one-fifth of the Sameura Dam's effective storage capacity.

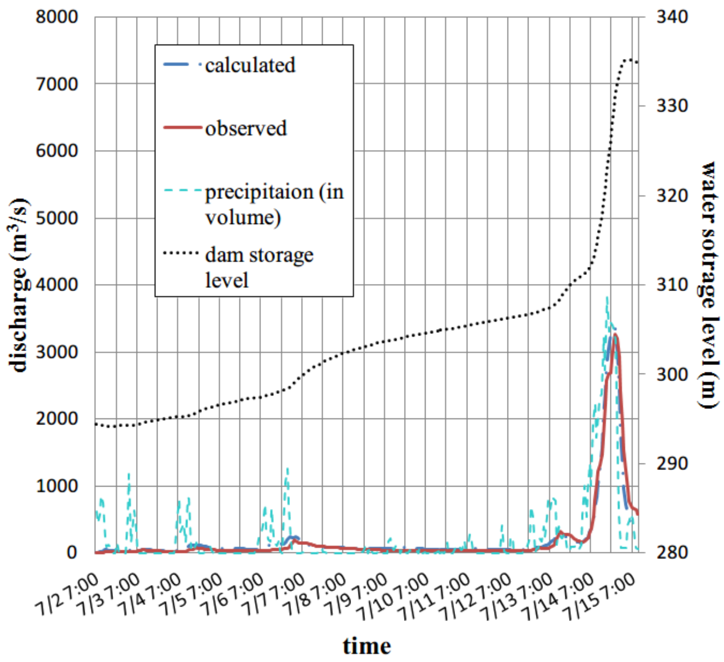

Figure 8. Runoff simulation result in the Sameura Dam catchment in 2007 (based on the model parameters calibrated as in Table 2).

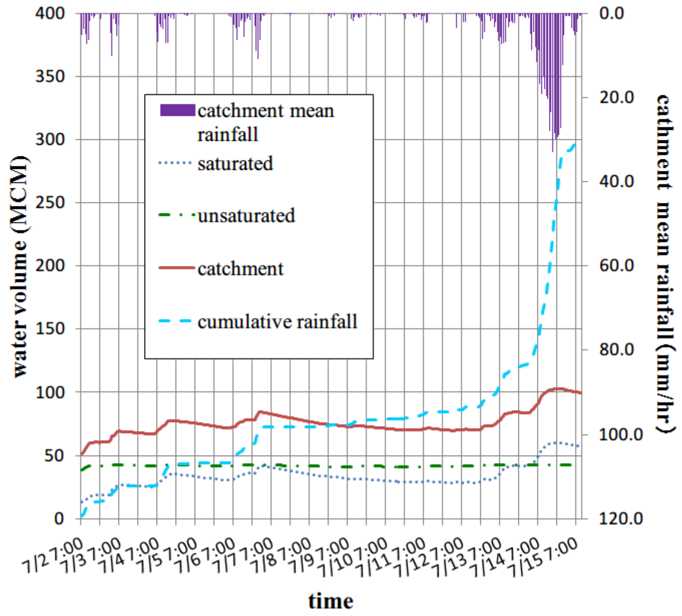

Figure 9. Water storage of the saturated zone, the unsaturated zone and the whole catchment at the Sameura Dam catchment in 2007 (based on the same simulation in Figure 8).

Table 3. Values at Oodo dam and Sameura dam catchment during the study events

Dam catchment Year	Oodo 2005	Sameura 2005	Sameura 2007
Total rainfall (mm)	622.7	651.4	718.8
Max of catchment mean rainfall (m^3/s)	5587.74	4482.75	3822.5
Max dam inflow (m^3/s)	4,550	5,405	3,265
Max dam outflow (m^3/s)	3225.1	775.6	3822.5
Max of storage capacity at the catchment (MCM = 10^6 m^3)	162.26	102.83	102.64
Flood control function of catchment (mm)	173	114	126
Cumulative rainfall (mm)	544.2	536.5	678.8
Dam storage volume (mm)	45.9	363.0	500.0
Cumulative outflow (mm)	204.3	2.0	19.7
Max of dam storage volume (MCM = 10^6 m^3)	42.51	257.81	234.33
Effective dam storage volume (mm)	78.4	693.0	693.0

Conclusions

This research has shown that the cell distributed runoff model can be used to analyze the water retention capacity and the flood control function in forest catchments by considering the subsurface soil structure of saturated and unsaturated zones, and runoff at the different land use type. By studying the case where the soil was very dry because of serious droughts, the maximum storage volume and the flood control function in the catchments can be evaluated.

Values in the Oodo and Sameura Dam catchments during the study events are shown in Table 3. The water storage volume at the Oodo Dam catchment is 162.26 MCM and the flood control function is 173 mm, while the Samura Dam is 102.83 MCM in 2005 and 102.64 MCM in 2007, and the flood control function is 114mm in 2005 and 126mm in 2007 in water depth.

This research indicates that it is of importance to assess the forest function quantitatively for disaster prevention and environmental protection. The results will provide important findings to achieve sustainable water management compatible with flood management. Our future research is to improve the accuracy of the runoff simulation results by considering the evapotranspiration mechanism and soil characteristics and spatial distribution in the forests.

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