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The Impact of Changing Storage Area on Flood Magnitude and Occurrence

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Abstract: This study focuses on the impact of combined catchment and storage upon flood occurrences and flood peaks. A significant factor that plays an important role of the combined catchment and storage is the ratio of contributing catchment area to storage area (A_C/A_S) where the impact significantly shows increasing frequency of storage overflow and flood peaks with the increasing of A_C/A_S. Some case studies examined in this work, i.e. Way Pegadungan (Lampung, Sumatra) and Nagara River (South Kalimantan) catchments show similar behavior. Swamps located on the sides of downstream of Way Pegadungan as well as Nagara River act as storages during flood events. The dyke which was planned to be built increases the ratio of A_C/A_S significantly as storage area reduced considerably. This has an impact on flood peaks which can increase considerably. The improved understanding of these process controls will be useful in assisting the management of such catchments, particularly to assist in flood prevention and mitigation.

Keywords: Storage, catchment, flood peaks.

Introduction

Lakes and swamps form an important part of tropical water resources. They contribute significantly to the water balance acting as storage in the basin. Swamps occupy much larger tropical areas than lakes. Swamps are considered as standing water series in which the water motion is not that of a continuous flow in a definite direction, although a certain amount of water flow may occur as internal currents in the vicinity of the inlets and outlets [1]. Lakes are regarded as inland bodies of standing water. Swamps are described as lowlands flooded in the rainy season and usually watery at all times. The presence of storages such as lakes and swamps in the basin greatly reduces the total runoff, introduces intermittency to the overall catchment runoff response, due to the effect of these stores attenuating or quite often terminating runoff. Smoothed values of the runoff depend on the percentage of storages in the basin and on the annual rainfall.

Storages, especially swamps, are often located near a river. The location of a storage is very crucial toward the determination of the dominant sources of streamflow reaching the storages and also the catchment outlet.

In addition to the relative location of the storages within a catchment, contributing areas to the storages also was found to influence storage-overflow behaviour as well as the overall catchment response. For example, lakes have been found to be efficient in smoothing the hydrographs of incoming catchment runoff responses only when they comprised more than 5% of the catchment area [2, 3].

The present study was motivated by general observations drawn from previous studies [2,3,4], but specifically by the flooding problems experienced in Rantau Jaya Village, located in Way Pegadungan catchment, a sub-catchment of Way Seputih in Lampung Province, Sumatera. Natural swamps exist throughout the Way Pegadungan as well as Way Seputih catchments. Way Pegadungan catchment have experienced severe flood events, causing overflow into the nearby village, Rantau Jaya. The downstream part of Way Pegadungan river is swamp areas which include Rawa Betik and Tanjung Kramat. Rantau Jaya village is located in the downstream of Rawa Betik. This village experiences flooding every year, with flood duration can be two to three months which inundate some part of the village located on the side of the river. Due to this annual flooding problems, people who live in that area ask the government to build dyke.

In addition to that, this study has also been motivated by flooding problem in the area nearby Nagara River, South Kalimantan. Swamp areas along the river have acted as flood plain. The problem arises since there was a plan a few years ago to change the land use for plantation. To prevent

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the plantation from flooding coming from the Nagara River, there were scenarios to built dyke at one side of the river or at both sides. Nowadays the plan has been implemented.

This paper consists of two main parts of analysis. The first part is sensitivity analysis upon landscape controls on the catchment toward the occurrence and the peak of floods. The analysis involves utilizing rainfall model for data generation and developing a conceptual rainfall-runoff model. The first part of the paper present the results of a sensitivity analysis that had the objective of exploring and exposing the critical process controls of flood frequencies in a catchment-storage system, in this way providing guidance toward developing an appropriate monitoring scheme to predict frequency of occurrence of such catastrophic floods in the future, and preventing them from ever happening again, or mitigating their effects. The second part of the paper will look at the case studies, Way Pegadungan and Nagara River. Utilizing available data, hydrology and hydraulic data, some analysis will be done to present the results of hydraulic modeling with regards to the effect of changing the area of storages on flood peaks.

Flood Frequency and Flood Occurrences; Sensitivity Analysis

The flood frequency curve, typically estimated from observed flood records and widely used in flood estimation practice, is the culmination of complex interactions between climatic inputs (rainfall intensities, evaporation demand) and those landscape properties that have a bearing on the rainfall to runoff to flood peak transformation, presented within a stochastic framework [4, 5, 6, 7, 8]. While the approach adopted in part of this study is general enough, climate conditions and catchment (and storages) characteristics typical of Nagara River and Way Pegadungan catchments (where storages such as swamp areas exist along the river) will be used to parameterize the adopted conceptual models.

For the sensitivity analysis, a model which can simulate rainfall and responding runoff for very long period needs to be developed, in order to construct a long period flood frequency and to figure out the frequency of storage overflow. In order to do this, it needs a rainfall model which can generate as long period as it needs [9, 10]. Variables on the rainfall model are determined based on the analysis of the rainfall data from the study area. Rainfall intensity, duration and interstorm period are based on rainfall data analysis from the study area. Average annual rainfall in study area is 2300 mm/year. The rainfall runoff model will use a bucket model which has three catchment-lake/swamps thresholds, i.e. the catchment field capacity storage governing subsurface stormflow, total storage capacity governing catchment surface runoff, and lake/swamp storage capacity governing lake/swamp overflow.

Methodology

The water balance equation for the catchment bucket is:

$$\frac{dS}{dt} = i(t) - Q_{se}(t) - Q_{ss}(t) - E_{bs}(t) - E_{veg}(t) \tag{1}$$

where S is catchment storage (mm), i is rainfall (mm/hr), Q_{se} is surface runoff (mm/hr), Q_{ss} is subsurface runoff (mm/hr), E_{bs} is bare soil evaporation (mm/hr), E_{veg} is transpiration (mm/hr) and t is time in hour. Transpiration (E_{veg}) is a function of the fraction of vegetation covering the catchment, M, potential evaporation, E_p, and storage at field capacity (S_{fc}). Bare soil evaporation (E_{bs}) is a function of potential evaporation and the fraction of the catchment with no vegetation as shown in Equations 2 and 3.

$$E_{veg} = \begin{cases} M E_p & S(t) \ge S_{fc} \\ M E_p \left(\frac{S(t)}{S_{fc}} \right) & S(t) < S_{fc} \end{cases} \tag{2}$$

$$E_{bs} = \begin{cases} E_p(1-M) & S(t) \ge S_b \\ E_p(1-M)\left(\frac{S(t)}{S_b} \right) & S(t) < S_b \end{cases} \tag{3}$$

Subsurface flow (Q_{ss}) occurs when the soil moisture storage in the bucket exceeds the field capacity threshold and is therefore a function of the dynamic storage, $S(t)$, as shown in Equation 4. The nonlinear storage-discharge relationship for subsurface flow is represented by two coefficients a and b, which are derived from recession curve.

$$Q_{ss} = \begin{cases} \left(\frac{S(t) - S_{fc}}{a} \right)^{\frac{1}{b}} & S_{fc} < S(t) < S_b \\ \left(\frac{S_b - S_{fc}}{a} \right)^{\frac{1}{b}} & S(t) > S_b \end{cases} \tag{4}$$

Surface runoff (Q_{se}) occurs when the soil is fully saturated, which occurs when the soil moisture storage $S(t)$ exceeds the bucket capacity (Equation 5).

$$Q_{se} = S(t) - S_b \quad \text{if} \quad S(t) > S_b \tag{5}$$

The water balance equation for the storage (lake/swamp) bucket is given by:

$$\frac{dS_S}{dt} = i(t) + \frac{A_C}{A_S} Q_{in}(t) - 0.7 E_p(t) - Q_{ses}(t) \tag{6}$$

where S_S is lake/swamp storage, A_C and A_S are catchment and storage (lake/swamp) area respectively, Q_{in} is inflow from the contributing catchment area,

$$Q_{in}(t) = Q_{ss}(t) + Q_{se}(t) \quad (7)$$

and Q_{ses} is outflow from the storage (lake/swamp).

$$Q_{ses}(t) = S_s(t) - S_{bs} \text{ if } S_s(t) > S_{bs} \quad (8)$$

where S_{bs} is lake/swamp storage capacity. The values of parameters used in the simulation are presented in Table 1.

Results of Sensitivity Analysis

The ratio of contributing catchment area to storage area (A_C/A_S) significantly impacts the one-dimensional rate of inflow into the storage, and therefore the incidence of storage-overflow. Figure 1 shows the relative per-storm frequency of storage-overflow for a range of sensitivity experiments involving systematic alteration of landscape parameter values. The frequency of storage-overflow events is quantified by the ratio of the number of storage-overflow triggering storms to the total number of storms. Figure 1 presents the frequency of storage-overflows as generated using average rainfall intensity of 2300 mm/year which represents the average annual rainfall in the study area. Small values of A_C/A_S mean that storage overflow is contributed more by direct rainfall falling in the storage. As the value of A_C/A_S increases, catchment contribution supplements direct rainfall, and the frequency of storage overflow increases significantly until it reaches high value of A_C/A_S and then the increase of A_C/A_S will not increase frequency of storage overflow significantly.

Table 1. Rainfall-runoff Model Parameters

Parameter	Value	Units
a	70	$mm^{0.5}hr^{0.5}$
b	0.5	
S_b	150	mm
S_{fc}	45	mm
M	0.6	
S_{bl}	1500	mm
E_p	1700	mm/year

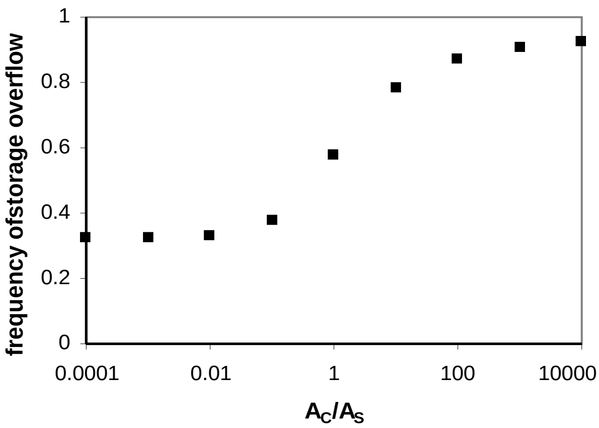


Figure 1. Frequency of Storage Overflow

Runoff generation and flooding are non-linear, threshold-driven processes. In a contributing catchment of a catchment-storage system, runoff which can be produced includes saturation excess runoff and subsurface storm flow. The existence of storages such as lakes or swamps in a catchment-storage system introduces additional runoff, storage overflow, in which storage overflow occurs when the storage capacity is exceeded. Figure 2 presents the results of an examination of the impact of landscape control upon both the frequency and magnitude of runoff response expressed in terms of the flood frequency curve. Note that the total area of the landscape, $A_C + A_S$, is the same for all simulations reported here. It can be seen that the flood frequency simulated using A_C/A_S = 100 has higher values for every return periods compared with that simulated using A_C/A_S = 5. It means that the smaller the storage area or the larger the contributing catchment area, the larger the floods peaks that occur.

Hydraulic and Hydrology Analysis on Case Studies

Way Pegadungan

To see the impact of A_C/A_S on the flood peaks, some case studies have been investigated. One of the case studies is Way Pegadungan catchment. The methods involved in the analysis include hydrology and hydraulic analysis. Hydrology analysis for Way Pegadungan used Synthetic Unit Hydrograph GAMA I [11]. Some parameters used in the calculation of synthetic unit hydrograph are shown in Table 2.

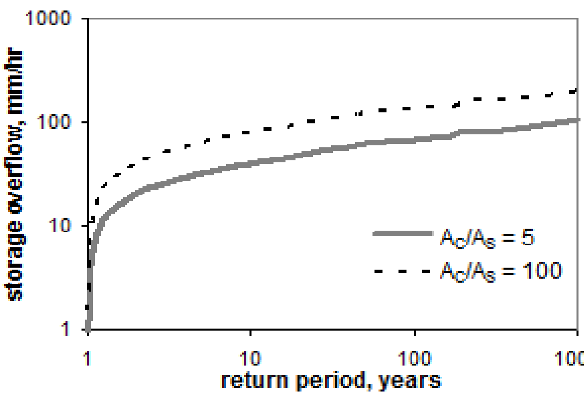


Figure 2. Flood Frequency Curve of Storage Overflow

Tabel 2. Some Parameters Describing the Catchment of Way Pegadungan

Parameter	Value
Catchment area	1200,58 km^2
River length	36,06 km
River slope	0,0167%
Number of first order branch	8
Number of all order branches	48
Length of first order branch	71,67 km
Length of all order branches	91,11 km

Hydraulic analysis used HEC-RAS software [12], which assumes that the flow is non-uniform one dimensional and steady flow. Another widely used software for hydraulic analysis is Duflow [13], a computer program for one dimensional hydraulic modeling of surface water, which has also been used for flood modeling and mitigation [14, 15]. The result of simulation using HEC-RAS for condition without dyke (existing condition) and with dyke is presented in Figure 3.

The results presented in Figure 3 used 25 years return period of river discharge as it is shown in the legend as Q-25yr. Furthermore the legend shows EG Q-25yr, WS Q-25yr and Crit Q-25yr which represents Energy Grade, Water Surface and Critical Depth using design discharge 25 years return period respectively, and Bank Sta which represents the main channel bank station. The peak discharge is 1200 m³/sec. Water surface elevations at the station observed shows the difference between the results of without and with dyke on the sides of the river. Although it is obvious that the impact of dyke is an increase of water level in the channel, the extent of water increase remains an important question to be examined. From the hydraulic simulations using HEC-RAS [12] it is found that water surface elevations without dyke is 2.99 m (Figure 3a) and with dyke is 3.99 m (Figure 3b). Therefore the difference of water surface elevations with and without dyke is 1 m.

Relating this finding with our concern regarding the ratio of contributing catchment area to storage area, it shows that the ratio of contributing area to storage area has a significant effect in flood peaks. On the existing condition (without dyke) with wide flood plain due to swampy area on the side of the river, the ratio of contributing catchment area to storage area is about 30. Using dyke means reducing storage area, and for those simulations the ratio of contributing catchment area to storage area is about 250.

Nagara River Catchment

The length of Nagara River is 155 km and the catchment area is 7801.48 km². Based on the computation using 2 day rainfall module (i.e. maximum total two day rainfall from available rainfall data), it is found that the rainfall module was 164 mm. Discharge is computed using Rational method and the value is 1750 m³/sec [16]. The computed discharge is further used in hydraulic

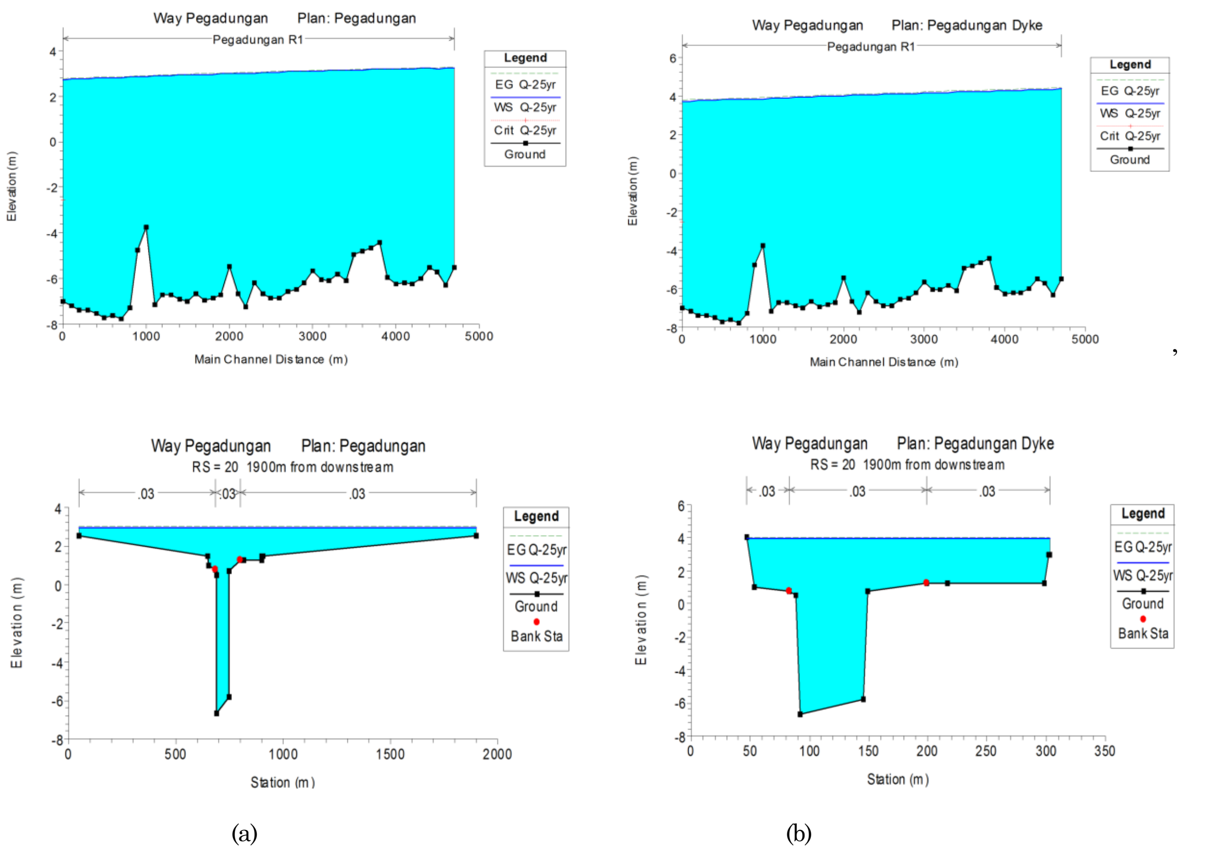


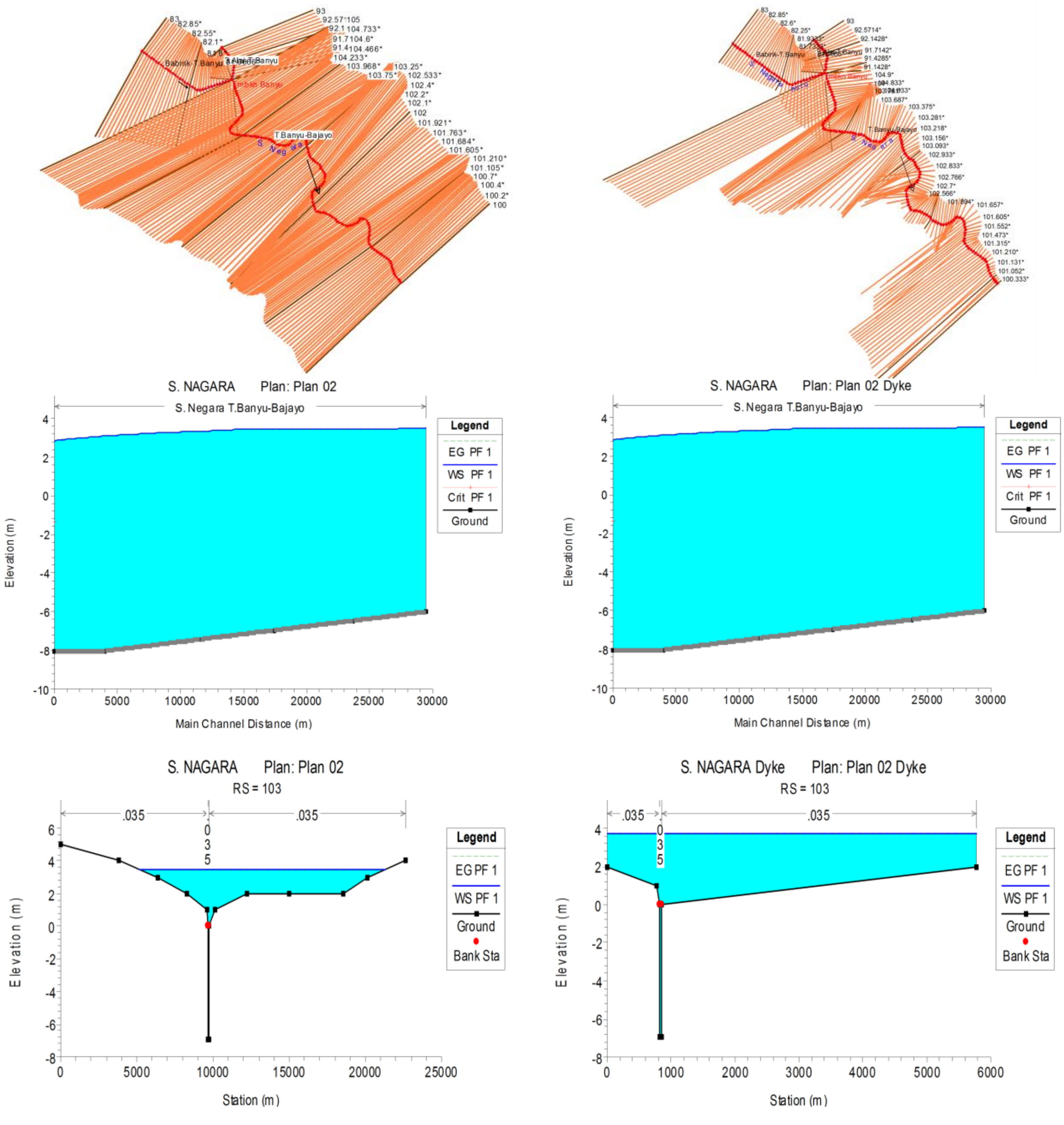
Figure 3. Water Surface for Long Profiles (top figures) and Cross Sections (bottom figures) in the Simulation at Existing Condition or without Dyke (a) and with Dyke (b)

computation. Simulation using HEC-RAS [12] shows that the discharge value is represented by PF 1 as it is shown in the legends of Figure 4 (EG PF 1, WS PF 1 and Crit PF1).

When flooding happened, flood plain was inundated. As the area is flat, water moves to swamp area near the river which can reach few kilometers. In modelling using HEC-RAS [12] during flooding the swamp area became extension of flood plain. This can be seen in Figure 4 that river geometry from the top shows that flood plain is significantly wide in condition without dyke. Figure 4 also shows that along the river, it is divided into more than 100 cross sections. The arrow displays flow direction.

Simulation on the condition with and without dyke on the sides of the river shows the difference between those results. From the hydraulic simulations using HEC-RAS [12] it is found that water surface elevations without dyke is 3.49 m (Figure 4a) and with dyke is 3.79 m (Figure 4b). The difference of water surface elevations with and without dyke is 0.3 m.

This study again shows that the change of storage area has an impact on flood peaks. In the existing



(a) (b)

Figure 4. River Geometries (top figures), Water Surface for Long Profiles (middle figures) and Cross Sections (bottom figures) in the Simulation at Existing Condition or without Dyke (a) and with Dyke (b)

condition (without dyke) with significantly wide flood plain due to swamp area on the sides of the river, the ratio of contributing catchment area to storage area is about four. When the dyke is considered to protect the area near the river, the ratio of contributing catchment area to storage area increases for nearly four times.

Building a dyke will protect the corresponding area on the sides of the river from flooding. In those two case studies, people who live in the area with annual flooding problem as well as the plantation will be protected from flooding. However, building a dyke may create a new problem. Water level in the river will increase and propagate so that it may cause flooding in another area elsewhere which has no dyke protection.

Conclusion

1. This study shows that building a dyke on the sides of a river will decrease the storage area and increase the ratio of A_C/A_S. Consequently water level in the river will increase. The extent of water increase in the river is affected by the change of A_C/A_S ratio. Despite protecting the corresponding area from flooding, the increase of water level in the river may cause flooding elsewhere.
2. This study highlights the importance of the ratio of A_C/A_S. When ratio of A_C/A_S is small, then direct rainfall on the storage (lake/swamp) is the dominant external input. However, their probability of triggering flood will be enhanced if ratio of A_C/A_S is larger, since there is increased chance for the storage capacity deficit to be exceeded by a combination of direct rainfall on the storage and runoff contribution from the upstream catchment area. This clearly points to the importance of A_C/A_S as a critical parameter governing the frequency and magnitude of storage overflow.
3. The improved understanding of the process control on catchment-storage landscape will be useful toward the estimation of flood and in assisting the management of the combined catchment-storage system for Nagara River and Way Pegadungan catchments and other similar system in the same region and regions elsewhere which contain swamps and/or lakes.

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