AN ANALYSIS OF STORM-INDUCED LANDSLIDES CONSIDERING THE RAINWATER STORAGE IN CATCHMENTS BY A HYDROLOGIC MODEL

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ABSTRACT**:** From June to September in 2004, a series of typhoon accompanying with heavy storms caused extensive flooding, deaths, and property damage in Japan. Those typhoon storms also triggered more than 160 shallow landslides in the forest of Ehime prefecture. The effective management of the hazard requires an understanding of the rainfall and soil moisture conditions those results in landslides. Therefore a conceptual and lumped hydrologic model was applied for the analysis of hydrologic conditions in the affected forest catchments. Through the model, hydrologic conditions such as rainfall intensity, rainwater storage and soil moisture in 2004 were compared with other 19 years (1985~2003), furthermore the relationship between landslide occurrence and hydrologic condition were assessed. The results indicate that the soil moisture and excess rainfall storage combined with rainfall intensity and its duration are very important for the occurrence of landslide in the forest.

KEYWORDS**:** storm induced landslide, up-layer storage, soil moisture, hydrologic process

1. INTRODUCTION

Globally, landslides cause billions of dollars in damage and thousands of deaths and injuries each year. In 2004, a series of typhoon with heavy rainfall have lashed Japan Island and they caused many flood and landslide disasters across the country. Those typhoon events of June to September 2004 triggered more than 160 landslides in the forest catchments in Ehime prefecture, Japan. Most of the slides were shallow in nature.

Shallow landslides usually occur during the heavy rainfall (Campbell, 1975). According to him, shallow storm-induced landslides require three conditions: (1) a mantle of colluvial soil, (2) a steep slope, and (3) soil moisture equal to or greater than the liquid limit of the colluvial soil. The rapid infiltration of precipitation, causing soil saturation and a temporary rise of pore-water pressure, is generally accepted to be the cause of most shallow landslides during storm events (Wieczorek, 1996). Quantitative information on soil moisture before and during a rainfall event is important to forecast the time and location of shallow landslides (Crosta and Frattini, 2003). However, these information are difficult to be obtained, while only rainfall intensity and accumulated rainfall are available for prediction of landslide. So in this research, a conceptual hydrologic model was applied for the analysis of rain-water storage and soil moisture in heavy storms which caused landslides in the forests and the relationships between them with landslide occurrences were discussed.

2. HYDROLOGIC MODEL TO EVALUATE RAINWATER STORAGE IN A CATCHMENT

2.1 Concept of the model

The model structure is shown in Fig.1. This model

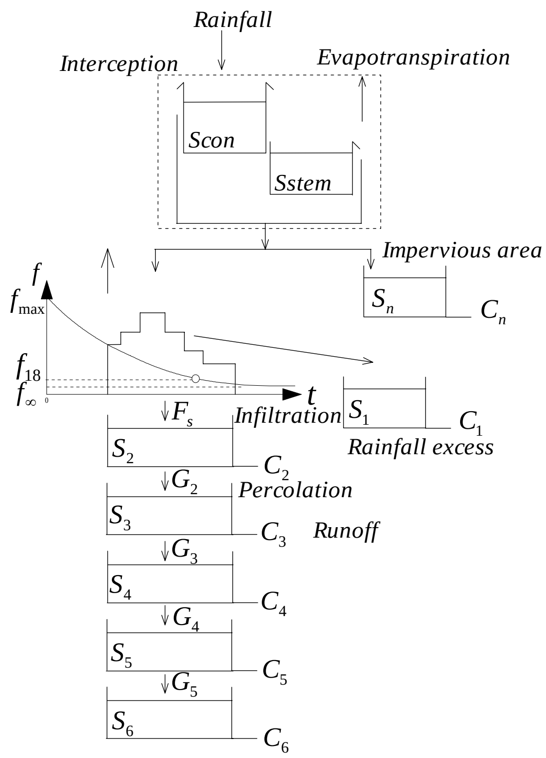

Fig.1. Schematic of model structure

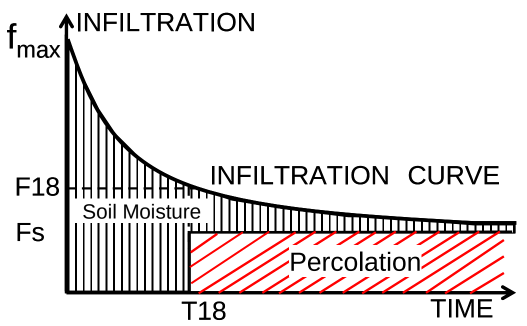

Fig.2. Infiltration curve used in the hydrologic model

which includes the infiltration curve was proposed to analyze the hydrologic processes in a catchment by TAKESHITA, et al (2001). It also includes the interception sub-model by the canopy of the trees, evaportanspiration and many kinds of runoff. This model is constructed of a series of vertical reservoirs, which represent the interception, surface flow, subsurface flow, and base flow. In Fig.1, S_n, S_1~S_6 is storage in the each reservoir, respectively. The outflow from each outlet is also influenced by the characteristics of the outlet, which further are called as the parameters of the model to be determined. In the model, Horton's infiltration theory was used to divide actual rainfall into excess rainfall and infiltrated water into the soil. S_1 represents storage of excess rainfall. The concept of the Horton's infiltration is represented by the infiltration curve (Fig.2). From the figure, it can be seen that when infiltration rate is less than gravity drainage pF1.8 (in the figure it was represented by F18) condition, the percolation which is equal to the final infiltration rate will be occurred.

And upper layer soil moisture(SM) in Fig.2 can be calculated by following:

1) $SM < SM_{18}$

$$SM = \int_0^{TT} \left\{ FS + \left(F_{\max} - FS\right) e^{-Bt} \right\} dt$$

$$= FS \cdot TT + \left(-\frac{1}{B}\right)\left(F_{\max} - FS\right)\left[e^{-Bt}\right]_0^{TT}$$

$$= FS \cdot TT + \frac{F_{\max} - F00}{B}$$

2) $SM \geqq SM_{18}$

$$SM = SM_{18} + \int_{T18}^{TT} \left\{ FS + \left(F_{\max} - FS\right) e^{-Bt} - FS \right\} dt$$

$$= SM_{18} + \int_{T18}^{TT} \left(F_{\max} - FS\right) e^{-Bt} dt$$

$$= SM_{18} - \frac{\left(F_{\max} - FS\right) e^{BTT}}{B} +$$

$$\frac{\left(F_{\max} - FS\right) e^{B\,T18}}{B} - \frac{FS}{B} + \frac{FS}{B}$$

$$= SM_{18} + \frac{F18 - F00}{B}$$

Where, SM_{18} is amount of soil moisture under condition of gravity drainage pF1.8. And F00 is the infiltration rate at time of TT.

All of model parameters were identified by a numerical optimization method.

2.2 Application and performance of the model

For checking the performance of model in runoff prediction, the model was applied to a experimental catchment which is located in a mountain of OZU city, Ehime prefecture, Japan. The longitude of the catchment is 132°37` E and the latitude is 33°28`N. The topography of the catchment is shown in Fig.3. The total area of the catchment is 21.0 ha. It is located within the Hijikawa River watershed, and it characterized by sinuous narrow valleys and steep mountains. The averaged elevation is approximately 360 meters, the stream density is 69m/ha, and the average slope is 27°. Most of the catchment are covered by Japanese cypress, cedar and broad leaf trees. The surface geology of the catchment is the mixture of sandy rock and clay slate. According to the soil survey, the saturated hydraulic conductivity of the surface soil is about 10^{-2}-10^{-3} cm/s (Takase, 1988). In late-June to September, 2004, this forest catchment suffered from typhoons with heavy storms, and landslides were caused.

In Fig.4, examples for the comparison of measured and calculated discharge in different years are shown. The year of 1994 is a low-flow year with annual rainfall of 1,012mm and we had some heavy rainfall by typhoons in 2004. From those

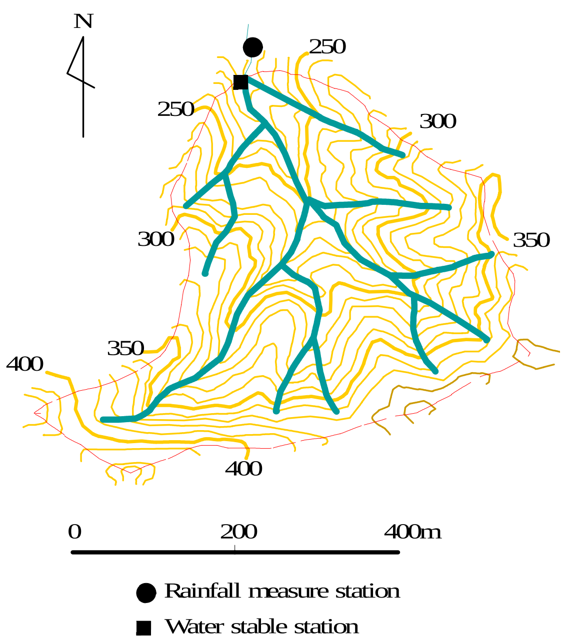

Fig.3 Catchment location and gauging stations

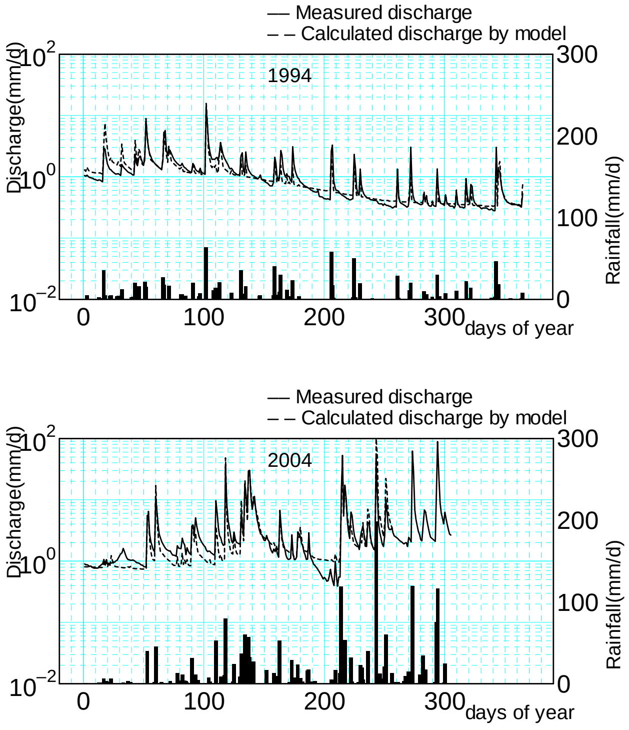

Fig.4 Comparison hydrograph of measured and calculated discharge in different years

hydrographs, it can be seen that the result shows acceptable agreement between the measured and calculated discharge. Average relative daily errors between them in all the years were less than 30%. Furthermore, we could obtain the soil water content as output through the model. Fig.5 shows the changes of upper layer soil moisture(SM) in each year. The soil moisture was changing due to the influence of evapotranspiration and rainfall. The changing was small in winter with high water content while big in summer and it reached to saturated condition during the heavy rainfall.

From the results, it is considered that the model has capacity to represent rainfall-runoff properties and hydrologic process well; hence it can be used in this study for the analysis of relationship among soil moisture conditions, rainfall characters and occurrence of landslide in the forest experimental catchment.

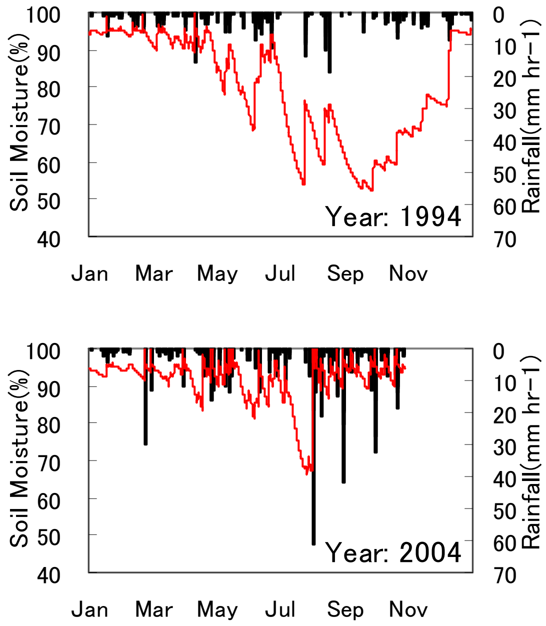

Fig.5 Changing of soil moisture in different years

3. HYDROLOGIC ANALYSIS AND DISCUSSION

3.1 Analyses of hydrologic conditions

To provide forecasts and warnings about the hazard associated with shallow landslide, accurate identification of hydrologic conditions which include not only rainfall but also soil moisture conditions is necessary. Therefore, the hydrologic conditions in the forest catchment were investigated. In Table 1, observed maximum daily and hourly rainfall (Rd_{max}, Rh_{max}) of 1985~2004 were shown. Also maximum hourly discharge (Q_{peak}) and upper layer soil moisture(SM) with excess rainfall storage (S_1) and storage ($S_2 \sim S_6$) in the lower layers were calculated by using the model in each year.

From the table, it can be found that the extremely heavy and successive storms occurred in 2004. Maximum daily and hourly rainfall, peak discharge, the sum of upper layer soil moisture(SM) and excess rainfall storage (S_1) in 2004 show the biggest values among all years. This might be considered as the reason why heavy landslides occurred in the forest area in 2004.

3.2 Statistical Analysis

In order to compare the hydrologic conditions of those years, a detailed analysis has been carried out.

Table1. Comparison of hydrologic properties in different years

Year	Rd_{max}(mm/d)	Rh_{max}(mm/hr)	Q_{peak}(mm/hr)	SM～$S_{1(mm)}$	SM～$S_{2(mm)}$	SM～$S_{3(mm)}$	SM～$S_{6(mm)}$
1985	79.5	20.5	3.31	336.4	351.9	397.4	753.4
1986	94.0	40.0	6.54	355.4	374.2	394.0	768.5
1987	111.0	32.0	5.11	355.8	379.4	396.0	751.4
1988	132.5	41.0	7.73	364.8	377.7	385.3	747.8
1989	117.5	31.5	8.98	371.2	390.7	404.8	796.8
1990	99.5	29.5	6.27	355.1	372.0	382.2	772.8
1991	70.0	33.0	3.94	340.5	354.6	377.7	768.8
1992	115.5	23.5	2.80	333.7	340.4	350.6	742.4
1993	160.0	40.0	10.38	382.3	401.6	442.4	799.2
1994	64.0	19.0	1.97	328.7	334.7	336.7	690.3
1995	171.0	27.0	9.77	375.4	410.4	423.1	775.0
1996	119.0	27.0	3.76	339.5	355.8	365.7	679.6
1997	159.5	40.0	6.93	360.0	366.0	368.1	714.1
1998	99.5	32.0	4.97	344.7	375.0	388.0	721.4
1999	76.5	30.0	4.34	343.2	361.7	369.8	724.2
2000	99.0	21.5	5.68	352.1	362.3	372.3	705.7
2001	69.0	25.0	3.85	338.5	356.7	370.4	705.1
2002	56.0	13.5	0.57	316.4	330.5	338.1	689.3
2003	79.3	28.0	5.66	351.7	356.2	370.3	762.7
2004	198.5	61.0	14.55	399.0	410.5	414.4	750.0

Rdmax: Maximum daily rainfall; Rhmax: Maximum hourly rainfall

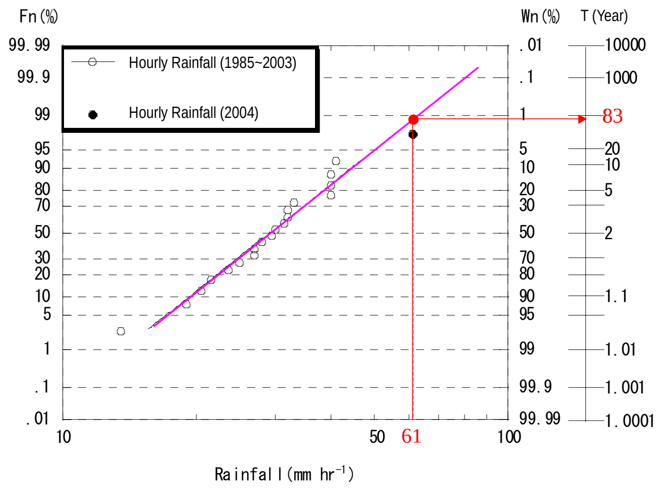

Fig.6 Return period of maximum hourly rainfall in 2004

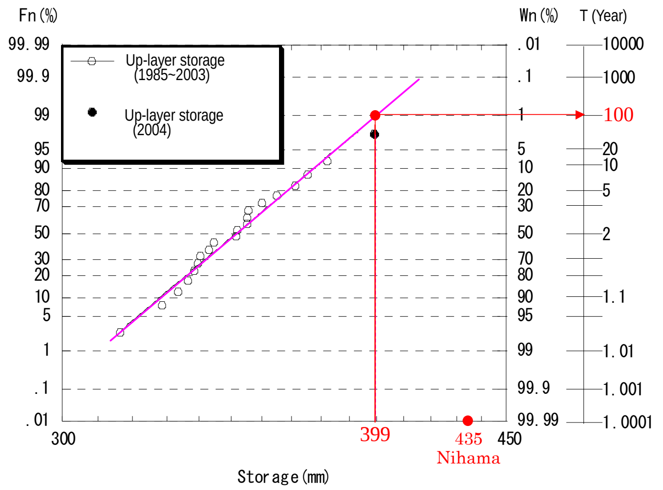

Fig.7 Return period of maximum up-layer storage in 2004

The statistical properties of maximum hourly rainfall and up-layer storage which means the sum of SM and S_1 events were evaluated by Hasen Plot method and the result are shown in Fig.6 and Fig.7.

$$W_n = \frac{2n-1}{2N} \times 100$$

$$F_n = \left(1 - \frac{2n-1}{2N}\right) \times 100$$

$$T = \frac{100}{W_n}$$

W_n : Exceedence probability; F_n : 1- W_n Non-exceedence probability; T : Return period; N : Total number of events.

The regression line of lognormal distribution was obtained as shown in figures. From the regressive relations, it is found that the maximum hourly rainfall occurred in 2004 with a return period of 83 years and the period of up-layer storage in 2004 is corresponding to 100 years. It can be supposed that the unusual hydrologic phenomenon may be the reason to produce heavy storm disasters which include landslides in 2004. This analysis indicates that soil moisture storage may have a very important effect on occurrence of landslide as well as rainfall. For getting more information to understand the hydrologic conditions that lead to shallow landslide initiation, connections of landslide occurrence to storm properties will be necessary to be analyzed in each landslide event.

3.3 Detail analysis of each storm in the catchment

In 2004, 2 heavy landslides occurred in our forest catchment by two typhoons on August 30 and September 29. To consider the phenomena of these storm-induced landslide occurrences, hydrologic

Table2. The hydrological properties in the catchment during typhoon events

DATE	STORM EVENT	Rdmax (mm/d)	Rhmax (mm/hr)	$DT_{1.8\text{-}S}$ (hr)	$(SM+S_1)max$ (mm)	Raccum (mm)
2004/8/1	TYPHOON 10	126.5	59.5	8	339.1	110.5
2004/8/30	TYPHOON 16	220.5	39.5	18	394.3	120
2004/9/7	TYPHOON 18	59.5	10	13	314.2	30
2004/9/29	TYPHOON 21	128.5	28.5	20	355.7	98

$DT_{1.8\text{-}S}$: Duration time in which soil moisture is bigger than pF1.8 condition (which include saturated condition)

Raccum: Accumulated rainfall before maximum rainfall which does not include max rainfall

Table 3. Relationship between hydrologic properties and frequency of landslide in Ehime prefecture

DATE	STORM EVENT	LANDSLIDE EVENT	SM+S1)MAX (mm	DAILY RAINFALL (mm/d)
2004/6/27	STORM	6	327	18
2004/7/31	TYPHOON 10	8	333	91
2004/8/17	TYPHOON 15	14	362	189
2004/8/30	TYPHOON 16	49	393	214
2004/9/7	TYPHOON 18	8	346	83
2004/9/29	TYPHOON 21	75	435	299

conditions during these two landslides events were analyzed in detail and compared with other heavy storms. The hydrologic properties which include rainfall and soil moisture conditions of each storm have been investigated and they are shown in Table 2. Judging from rainfall properties, it might be expected that typhoon 10 which have the highest hourly rainfall intensity was very dangerous for inducing of landslide. However, in this storm, the duration time ($DT_{1.8\text{-}S}$), in which upper layer soil moisture was bigger than gravity drainage pF1.8 condition and saturated state which can represent the wet condition of soil and has effect on soil loosing, was only 8 hours; also the up-layer storage ($SM+ S_1$) which reflects the effects of cohesion and pore-water pressure of this storm was smaller. It means the soil still had strong capacity to resist to the slope failure. This might be the reason why this heavy storm has not caused landslide disaster in our

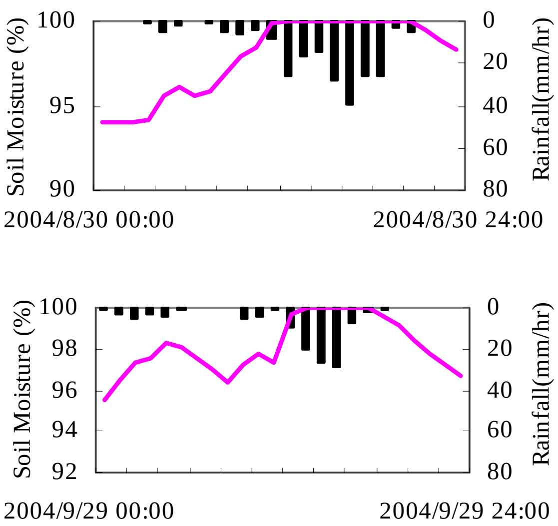

Fig. 8 Saturation of soil moisture in the typhoon event

catchment. In the case of September 7, duration time of $DT_{1.8\text{-}S}$ was 13 hours, as well the rainfall intensity and up-layer storage was the smallest, so that landslide has not produced. In August 30 and September 29, there were heavy rainfalls and wet condition of soil ($DT_{1.8\text{-}S}$) continued for long time as shown in Fig.8. Furthermore, maximum of up-layer storage($SM+S_1$) of these two storms were bigger than other storms. That may be the reason why heavy landslide occurred in our catchment during these days.

3.4 Landslide analysis in Ehime prefecture

In 2004, Ehime prefecture has suffered greatly from a series of landslide during the typhoon events. Most of disasters were occurred in Nihama city, there was serious heavy rainfall and the city has been seriously damaged. Therefore, rainfall data in Nihama were applied to estimate the hydrologic phenomena during the storm events in 2004 by our model. Through it the correlation tendency between frequencies of shallow landslide and hydrologic properties can be examined.

The relationships among the maximum up-layer storage ($SM+S_1$) which was calculated by the model, observed maximum daily rainfall and total number of landslide in Ehime prefecture during each storm event are shown in Table 3. In the table, the greatest values of up-layer storage and daily rainfall are found in the event of typhoon 21 on September 29th and it is known that the up-layer storage, 435mm, is greater than the maximum value in Table 2, 394.3mm. It is considered that this extremely great storage might induce the numerous landslides. Furthermore, the high correlation between the number of landslide and the storage can be found in the table. So, it can be concluded that the concept of our analysis will be available to evaluate the possibility of landslide occurrence, if the more detail information about the type of soil and vegetation or distribution rainfall are collected in each districts.

6. CONCLUSION

In this research, a hydrologic model that included the infiltration curve was proposed to evaluate hydrologic processes which include soil moisture and water storage in a watershed. The relationship between the hydrologic conditions and landslide occurrence were analyzed on the basis of hydrologic data available. As the result of application to an experimental catchment, time distribution of infiltration, soil moisture and water storage as well as discharge could be understood. Comparison of hydrologic conditions of storms in different years shows the unusual presence in 2004, which include the highest value of daily and hourly rainfall, peak discharge and upper layer soil moisture with excess rainfall storage. It was thought to be reason of heavy flood disasters including landslide which occurred in 2004. In our forest catchment, the analysis was focused on two serious landslide disasters and the correlation between landslide occurrence and hydrologic conditions were investigated. The result shows that rainfall intensity and the level of up-layer storage which reflect cohesion and pore-water pressure are very significant factors on occurrence of the landslide disaster. This study has proved that in the condition of high antecedent soil moisture, when soil moisture reaches the gravity drainage condition and saturates, the heavy storm with long duration have high chance to induce shallow landslide. The hydrologic model which was used in this study was able to represent hydrologic phenomena reasonably. And it can be used for estimation of discharge, soil moisture content and water storage in our catchment. The concept of this model is available to be applied in other area, if the inherent parameters can be obtained for the area. The model can be expected to provide important information on soil moisture behavior for forecasting and preventing landslide disaster in the filed.

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