Assessment of soil moisture dynamics and storm-induced landslides hazard in forest landscapes

YI WANG[1] , KEIJI TAKASE[2], SRIKANTHA HERATH[1]

[1]Environment and Sustainable Development Programme, United Nations University (UNU Centre), 5-53-70, Jingumae, Shibuya-ku, Tokyo 150-8925, Japan, ywang@hq.unu.edu

[2]Faculty of Agriculture, Ehime University, Matsuyama 790-8566, Japan

ABSTRACT: This study aims to provide insights in the linkages between soil moisture dynamics and landslides occurrence. A hydrologic model was developed for assessing storm-induced landslides in forest landscapes. For model validation, it was applied in a forest catchment in Japan, which was affected by typhoons in 2004. Through the model, hydrologic conditions such as rainfall intensity, rainwater storage and soil moisture in 2004 were obtained and compared with other 19 years (1985~2003). The relationship between landslide occurrence and hydrologic phenomena were then assessed. Results indicated that soil moisture, excess rainfall storage combined with rainfall intensity, and its duration were the key elements for landslides occurrence. It was able to represent hydrologic phenomena reasonably and used for assessment of discharge, soil moisture, and water storage. The concept of this model can be applied in other areas and is expected to provide important information on soil moisture behavior for forecasting and preventing landslide disasters.

Keywords: landslide; soil moisture dynamics; forest landscape

1. INTRODUCTION

In 2004, a series of typhoon accompanying with heavy rainfall have lashed the Japan Islands and caused many floods and landslide disasters across the country. Those typhoon events from June to September in 2004 have triggered more than 160 landslides in the forest of Ehime Prefecture, Japan. Most of the slides were shallow landslides in nature. Shallow landslides usually occur during the heavy rainfall (Campbell, 1975). Normally, rainwater storage is considered as a very important indicator to the landslide occurrence, water saturation in the field is a significant factor that allows the force of gravity to overcome the resistance of earth material to landslide movement (Grozier, 1999). The rapid infiltration of precipitation, causing soil saturation and a temporary rise of pore-water pressure, is generally accepted to be the cause of

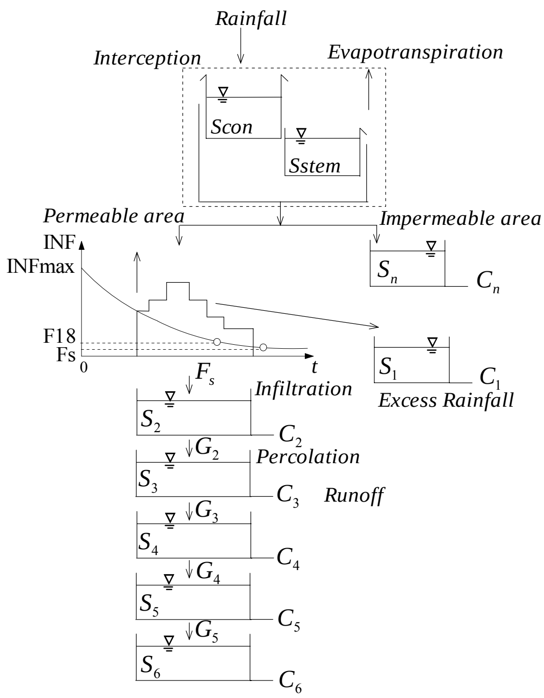

Fig. 1 Schematic structure of the hydrologic model in this study

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, 2003,1998) and floods (Glade, 2000). However, surface soil moisture content is highly variable in both space and time; for many regions, soil moisture conditions, such as rainfall infiltration and soil water percolation, are not available (Wieczorek and Glade, 2005; Wieczoroek, 1996). Hence, in this research, a conceptual hydrologic model was applied for the analysis of rainwater storage and soil moisture behavior in heavy storms, which caused landslides in a forest catchment. The relationships between them and landslide occurrences were then discussed.

2. HYDROLOGIC MODEL TO EVALUATE RAINWATER STORAGE

The concept of the proposed model in this study is shown in **Fig. 1**. This model, which includes infiltration curve, was proposed to analyze the hydrologic processes in a catchment by Takeshita (Takeshita, *et al.*, 2001. Takeshita and Takase, 2003). It is constructed by a series of reservoirs to represent hydrologic processes in a forest catchment. It includes the interception by the canopy of trees, evapotranspiration, infiltration, percolation, and surface flow in both permeable and impermeable areas, subsurface and base flow in different soil layers. In **Fig. 1**, S_{con}, S_{stem}, S_n, S_1~S_6 are storage in each reservoir, respectively. In the model, Horton's infiltration theory was used to divide actual rainfall into excess rainfall and infiltration water. S_1 represents storage of excess rainfall. The Horton's infiltration equation is represented as follows

$$INF(t) = F_S + (INF\max - F_S)\exp(-B \cdot t) \quad (1)$$

Where, *INF (t)* is the infiltration rate at time *t*, F_s is the final infiltration rate, *INFmax* is the maximum rate and corresponds to the infiltration rate when surface soil layer is perfectly dried.

In this research, the occurrences of storm-induced landslide in an experiment forest catchment were analyzed by the proposed hydrologic model. The catchment is located in a mountain of OZU city, Ehime Prefecture, Japan. The total area of the catchment is 21.0 ha, the surface geology of the catchment is the mixture of sandy rock and clay slate (Takase, 1988, 2000). From late-June to September of 2004, this forest catchment suffered from landslides caused by typhoons accompanying with heavy storms. In this study, therefore, long-term hydrologic properties in this catchment were investigated by comparing with the hydrologic condition in 2004, to identify the role of hydrologic conditions for landslide initiation.

3. HYDROLOGIC ANALYSIS AND DISCUSSION

3.1 Analysis of hydrologic properties in the catchment

To manage the hazard associated with shallow landslides, accurate identification of hydrologic properties including not only rainfall but also soil moisture conditions that triggered slope failure is needed for landslides' forecasts and warnings. Therefore, the hydrologic properties in our experimental forest catchment were investigated. Observed maximum daily and hourly rainfall (Rd_{max}, Rh_{max}) of 1985~2004 were shown to compare the difference of rainfall characteristics of 2004 with other years in Table 1. In addition, maximum hourly discharge (Q_{peak}) and upper layer soil moisture(SM) with excess rainfall storage (S_1) and storage in the lower layers ($S_2 \sim S_6$) were calculated in each year by using the proposed hydrologic model. It was found from the table that an extremely heavy and sustained storm occurred in 2004. Maximum daily and hourly rainfall, peak discharge, sum of upper layer soil moisture (SM) and excess rainfall storage (S_1) in 2004 show the highest values among all years. This might be considered as the reason that flood disaster occurred in the forest area in 2004.

3.2 Statistical Analysis

In order to compare the hydrologic properties, a detailed analysis has been carried out in those years. The statistical properties of maximum hourly rainfall, up-layer storage that means the sum of SM, and S_1 events were evaluated by the Hasen Plot method. The regression line of logarithm distribution was obtained as shown in **Fig. 2** and **Fig. 3**.

Table 1 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	220.5	61.0	19.41	399.0	410.5	414.4	750.0

Rd_{max}: Maximum daily rainfall; Rh_{max}: Maximum hourly rainfall

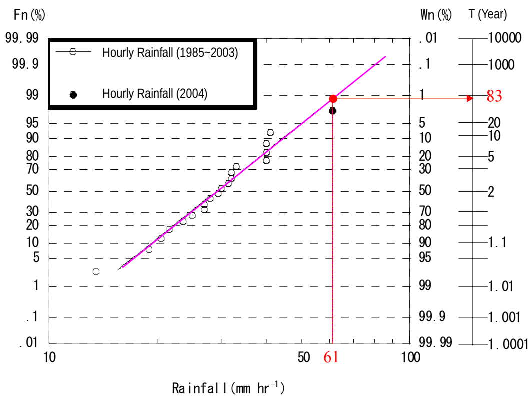

Fig. 2 Return period of maximum hourly rainfall in 2004

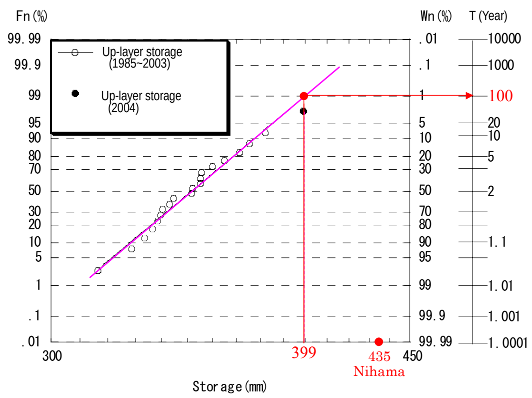

Fig. 3 Return period of maximum up-layer storage in 2004

From the regressive relation, it is clear that the maximum hourly rainfall occurred in 2004 corresponds to a return period of 83 years and the up-layer storage in 2004 corresponds to a return period of 100 years. It can be supposed that the unusual hydrologic phenomenon may be the reason to produce heavy storm disasters that included landslides in 2004.

3.3 Detailed analysis of each storm in the catchment

In 2004, two heavy shallow landslides occurred in the forest catchment by two typhoons

Table 2 The hydrological properties in the catchment during typhoon events

DATE	STORM EVENT	Rd_{max} (mm/d)	Rh_{max} (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

Rd_{max}, Rh_{max}: Maximum daily and hourly rainfall

$(SM+S_1)_{max}$: Maximum of up-layer storage

$DT_{1.8\text{-}S}$: 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

on August 30 and September 29. To consider the phenomena of these storm-induced landslide occurrences, hydrologic conditions during these two landslide events were analyzed in detail and compared with other heavy storms. The hydrologic properties of each storm which include rainfall characters were recorded and soil moisture conditions were estimated by using the model as 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 landslides. However, in this storm, the duration time ($DT_{1.8\text{-}S}$), in which the upper layer's soil moisture was bigger than both that in gravity drainage pF1.8 condition and saturated condition, which can represent the wet condition of soil and has effect on soil loosing, was only 8 hours. Moreover, the value of maximum up-layer storage ($SM+S_1$), which reflects the effects of cohesion and pore-water pressure of this storm, was smaller. This might be the reason why this heavy storm has not caused landslide disaster in our 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 among all storms, so that landslide was not produced. On August 30 and September 29 when serious landslide occurred, there were heavy rainfalls, upper layer of the soil remained partly saturated and reach the saturated state which continued

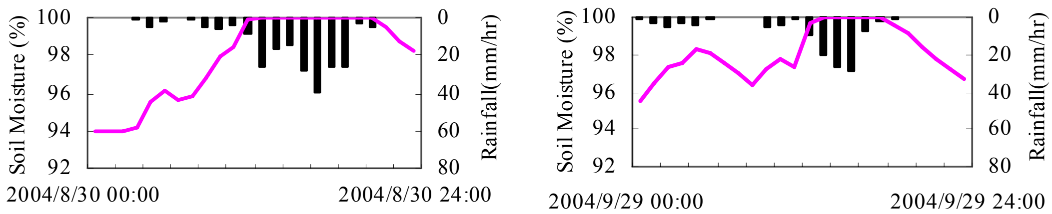

Fig. 4 Saturation of soil moisture in typhoon events

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

DATE	STORM EVENT	LANDSLIDE EVENT	$(SM+S_1)_{max}$ (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

Table 4. Relationship between hydrologic properties and frequency of landslides in Ehime prefecture in different year (1993~2004)

	Frequency				
Year	R≥10	R≥30	S1>0,SM18≥0	S1>0,SM≥SM18,R≥10	Forest Disaster
1993	40	2	613	16	81
1994	8	0	26	1	2
1995	23	0	212	10	22
1996	14	0	134	5	12
1997	20	1	298	7	33
1998	25	2	285	7	56
1999	18	1	358	10	73
2000	18	0	278	7	31
2001	23	0	190	4	52
2002	5	0	0	0	2
2003	21	0	235	5	3
2004	39	3	421	18	160

for a long time as shown in **Fig. 4**. 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 landslides during the typhoon events. It has caused a lot of death of peoples and serious economic damage. Most of disasters were occurred in Nihama city. There was serious heavy rainfall in this city and it 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 was examined.

Relationships among the calculated maximum up-layer storage ($SM+S_1$) by the model, observed maximum daily rainfall, and total number of landslides 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. It is considered that this extremely great storage might induce the numerous landslides. Moreover, the high correlation between landslides' quantity and the soil water storage was found in the table. Furthermore, according to the data from Ehime prefecture disaster report, forest landslide disasters of the prefecture and the frequency of rainfall intensity which was bigger than 10mm and 30mm in different year can be obtained (**Table 4**). In addition, it shows the model calculated frequency of upper layer soil moisture(SM) was bigger than SM_{18}, which means the amount of soil moisture under condition of gravity drainage pF1.8 of each year. From the **Table 4**, the high correlation between landslides frequency and soil water storage combined with rainfall intensity can be found.

4. CONCLUSION

A hydrologic model including the infiltration curve was proposed to evaluate hydrologic processes which include soil moisture and rainwater storage in a watershed in this study. Based on available hydrologic data, the relationship between the hydrologic conditions and landslide occurrence were analyzed. As the result of its application to an experimental catchment, time distribution of infiltration, soil moisture, water storage as well as discharge could be understood. Comparison of hydrologic conditions of storms in different years showed the unusual presence in 2004, which included 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 that occurred in 2004. Furthermore, the detailed analysis was focused on two serious landslide disasters in the catchment, the correlation between landslide occurrence and hydrologic conditions were investigated. Result shows that rainfall intensity and the level of up-layer storage, which reflects the cohesion and pore-water pressure, are the critical factors to trigger a landslide disaster. We conclude 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 can induce shallow landslide. The proposed hydrologic model in this study was able to represent hydrologic phenomena reasonably. In addition, it can be used for the estimation of discharge, soil moisture content, and water storage in forest catchment. The concept of this model is available to be applied in other areas if the inherent parameters can be obtained for the areas. The model can be expected to provide important information on soil moisture behavior for forecasting and preventing landslide disaster in the forest landscapes.

REFERENCES:

Campbell RH, 1975. Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, Southern California. U.S. Geological Survey Professional Paper 851, 1-20.

Crosta G, 1998. Regionalization of rainfall thresholds: an aid to landslide hazard evaluation. Environ. Geol. 35 (2-3), 131-145.

Crosta GB, Frattini P, 2003. Distributed modeling of shallow landslides triggered by intense rainfall, Nat. Haz. Earth Sys. Sci., 3, 81-93.

Crozier MJ, 1999. Prediction of rainfall-triggered landslides: A test of the antecedent water status model. Earth Surface Processes and Landforms 24, p825-833.

Glade T, 2000. Modeling landslide: triggering rainfall thresholds at a range of complexities. Thelford, T. Proc. Of the 8th Int. Symp. On Landslides held in Cardiff on 26-30 June 2000, Landslides in Research, Theory and Practice, vol.2, pp. 633-640.

Takase K, 1988. Water cycle changes of catchment after land reclamation-Cases of Shikoku Coast and Catchments in Ozu, Ehime Prefecture-, Doctoral Thesis, 102p.

Takase K, 2000. Properties of Hydrologic Cycle in Catchments in Different Land Use and Runoff Analysis by a lumped Parameter Model. Proceeding of Korea Society of Hydrology and Water Resource, 48-56.

Takeshita S, Takase K, Ihara K, 2001. Development of Long-Term Runoff Model including Infiltration Sub-model, Trans of JSIDRE, 212: 71-77. (in Japanese with English summary).

Takeshita S, Takase K, 2003. Development of a Long-Term Runoff Model including Evapotranspiration Sub-model，J.Jpan Soc.Hydrol.& Water Resour., 16-1: 23-32, (in Japanese with English summary).

Wieczorek GF, 1996. Landslide triggering mechanisms, A.K. Turner and R.L. Schuster, op.cit, 76-90.

Wieczoreck GF, Glade T, 2005. Climatic factors influencing occurrence of debris flows. M. Jakob and O. Hungr (eds), Debris-flow Hazards and Related Phenomena.