

Peak Discharge and Hydrograph Assessments Induced by Heavy Rainfall Events Using Tank Model

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Abstract. Tank Model is a kind of simulation of rainfall movement in soil horizon. With the runoff and piping rate, the peak discharge could be effectively calculated. Having 17 rain gauge stations in 13 debris flow events during 1996-2010 as the studied cases, the peak discharge at 12 control points along Chenyulan River is simulated. Furthermore, the data in Neimaopu discharge station is established parameters of Tank Model to estimate the peak discharge in Shenmu Village. By comparing with the parameters of Shueili Station and Japanese Granite, the mean error of the parameter in this study is 51.0%, which is better than those of Japanese Granite 189% and Shueili discharge stations 251%. The parameter in this study appears the highest in allowance analysis, showing that it is more suitable for simulating the peak discharge than the other two. In spite that the percentage of the three parameters is still low, Shenmu Village could be ignored as it locates in the sub-basin of Chenyulan River with few factors. The parameters of Tank Model are applied to transform average rainfall into hydrograph so as to solve the problem of no discharge records when analysing the areas with various debris flow simulation programs.

1 Introduction

Rainfall and peak discharge are the factors causing sediment disasters in slopeland. Since the Unit Hydrograph for simulating effective rainfall and hydrograph was proposed [1-2], it has been largely studied by researchers. In addition to effective rainfall causing direct runoff, the rainfall mobile mechanism of rainfall infiltrating to soil horizon and further effusing as runoff becomes the blind spot for effective rainfall and hydrograph. Not until the rainfall moving in soil with a four-layer tank was simulated [3], the proposed Tank Model became one of the major methods to simulate rainfall and peak discharge in hydrology. With a three-layer tank and eleven parameters, the study [4] calculated hydrograph by dividing sub-basin, analysed the relations between the rainfall and runoff in the watersheds of Kohira, Minamihatajiki, Tsukigase, Mino, and Kiyohorobashi, established five Tank Model parameters for the five watersheds, and confirmed four parameters of Tank Model from the geological distribution in the watersheds (see Table 1). Up to then, Japanese researchers followed such a framework for further studies. In 1990, Japan Meteorological Agency Forecast applied Automated Meteorological Data Acquisition System (AMEDAS) and 80% detectivity to national verification and found the difference between simulation and actual measurement merely several percentage [5] when utilizing the parameters of granite and other geology. As a consequence, the parameter of granite was utilized for forecast.

Although Tank Model has been used for years in Japan, it is still under research and promotion in Taiwan. The previous study [6] estimated the effective rainfall and direct runoff of rainfall events with soil water index Φ infiltration and further simulated the rainfall runoff in sub-watersheds with the built-in kinematic-wave based geomorphic IUH model, triangular Unit Hydrograph, linear reservoir model, dimensionless hydrograph method, and Tank Model. A hydrologic process-based rainfall-runoff model was also established for the earth surface and subsurface [7-10]. The subsurface runoff model is structured with two in-line Tank Models to simulate interflow and groundwater flow; the total is the runoff. Another research [11] increased vegetation covering and established rainfall-runoff model with a five-layer tank. Nonetheless, most researchers still focused on direct runoff and effusion from soil horizon caused by water after rainfall; the total runoff was not discussed the water concentrating on channel flow. According to Chingualiaochiao, Chinshan, Xinanchiao, Shueili, and Tukuchiao discharge stations, the parameter of Tank Model was established by applying the Least Square Method [12]. Based on the research framework of this research, the peak discharge simulation is preceded in this study.

The researchers [13] proposed that Tank Model is a conceptual model which simulates the moving behaviour of water in the soil layers including runoff, infiltration and percolation, because the sum of rainfall depth as “depth of rainfall retention in soil layer” in three tank of tank model. Therefore, they referred to as a “soil water

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index (SWI),” which as the national criteria of disaster preparedness phase in Japan. Besides, Tank Model is also employed to simulate groundwater [14-16], and many optimization methods [17-19] are proposed to raise the

accuracy of this model. Therefore, the Tank Model is still one of the commonly used models to estimate the relationship of rainfall and runoff.

Table 1. Parameters of Tank Model in Japan and Taiwan.

Area	L_1	L_2	L_3	L_4	a_1	a_2	a_3	a_4	b_1	b_2	b_3
Japan, Ishihara (1979)											
Granite	15	60	15	15	0.10	0.15	0.05	0.01	0.12	0.05	0.01
Volcanic rocks	30-40	60-75	15	15	0.10	0.15	0.05	0.01	0.12	0.08	0.01
Paleozoic	30	75	5	15	0.10	0.15	0.05	0.01	0.12	0.04	0.01
Quaternary	15	40	5	15	0.10	0.15	0.05	0.01	0.12	0.04	0.01
Taiwan, Chen (2011)											
Chingualiaochiao	15	30	5	5	0.15	0.3	0.03	0.02	0.15	0.03	0.02
Chinshan	20	75	20	20	0.05	0.2	0.05	0.01	0.40	0.20	0.05
Xinanchiao	10	30	15	15	0.10	0.4	0.10	0.01	0.10	0.05	0.05
Shueili	15	60	15	15	0.10	0.2	0.10	0.05	0.10	0.05	0.01
Tukuchiao	5	30	15	15	0.10	0.2	0.10	0.01	0.10	0.05	0.01
Suggested parameters in this study											
Chenyulan River	30	100	100	100	0.1	0.2	0.02	0.01	0.3	0.02	0.01

Equation	$R_1=(H_1-L_1)\times a_1$	L_1 : First tank Layer 1 discharge depth	b_2 : Second tank infiltration rate
	$R_2=(H_1-L_2)\times a_2$	L_2 : First tank Layer 2 discharge depth	b_3 : Third tank infiltration rate
	$R_3=(H_2-L_3)\times a_3$	L_3 : Second tank discharge depth	R_1 : First tank Layer 1 discharge
	$R_4=(H_3-L_4)\times a_4$	L_4 : Third tank discharge depth	R_2 : First tank Layer 2 discharge
	$F_1=H_1\times b_1$	a_1 : First tank Layer 1 discharge rate	R_3 : Second tank discharge
	$F_2=H_2\times b_2$	a_2 : First tank Layer 2 discharge rate	R_4 : Third tank discharge
	$F_3=H_3\times b_3$	a_3 : Second tank discharge rate	H_1 : First tank depth
		a_4 : Third tank discharge rate	H_2 : Second tank depth
		b_1 : First tank infiltration rate	H_3 : Third tank depth

$a_1\sim a_4$ & $b_1\sim b_3$
unit: no unit

$L_1\sim L_4, R_1\sim R_4$ & $H_1\sim H_4$
unit: mm (millimeter)

2 Materials and methods

2.1 Research area

Chenyulan River watershed in Nantou County is one of the areas with the most debris flow in Taiwan, where sixteen debris flows appeared in Shenmu Village during 1996-2010. Neimaopu discharge station is the only one still working in Chenyulan River watershed; however, it is far away from Shenmu Village that the peak discharge is hard to estimate. Taking the thirteen debris flow events during 1996-2010 as the cases, the peak discharge at twelve control spots along Chenyulan River is simulated. Data of Neimaopu discharge stations are established the parameter of Tank Model for estimating the peak discharge of Shenmu Village. The thirteen debris flow events occurred in Shenmu Village, located along Huosa River and Chushuei River, the upstream of Chenyulan River, is simulated the discharge.

2.2 Research method

The hourly precipitation around rain gauge stations is first collected for calculating the average hourly precipitation. With Kriging method in ArcGIS is utilized for analyses in order to draw the hourly discharge distribution.

Chenyulan River watershed is divided into thirty sub-basins, which are numbered as Figure 1. According to these sub-basins in Figure 1, the main tributary control spots, depending on the afflux, are set twelve, from A to L, where the control spot I and Neimaopu discharge station are overlapped.

Table 2. Debris flow events in Shenmu Village.

No.	Event	Date
1	Typhon Herb	1996/08/0 1
2	Heavy Rainfall	1999/05/2 8
3	Typhon Toraji	2001/07/3 0
4	Typhon Mindulle	2004/07/0 2

5	Typhon Haitang	2005/07/19
6	Typhon Matsa	2005/08/04
7	Typhon Talim	2005/09/01
8	Heavy Rainfall	2006/06/09
9	Heavy Rainfall	2007/08/13
10	Typhon Sepat	2007/08/18
11	Typhon Krosa	2007/10/06
12	Typhon Kalmaegi	2008/07/18
13	Typhon Morakot	2009/08/08

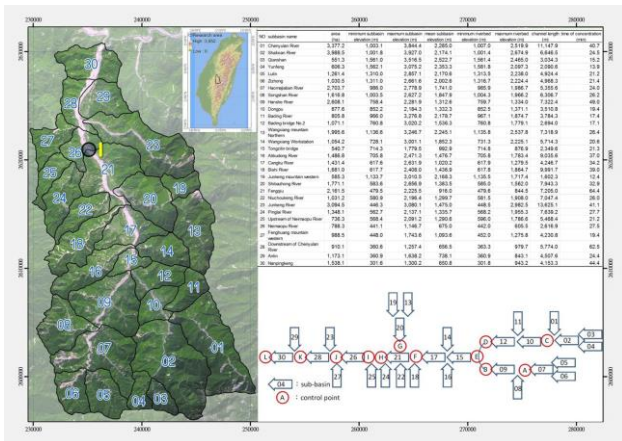


Figure 1. Distribution of sub-basin in the upstream and discharge balance of Chenyulan River watershed.

The discharge of each control spot is calculated by summing up the discharge of each sub-basin during the time of concentration at the control spots. The time of concentration (t_c) is the sum of inflow time of slope (t_1) and the outflow time of channel (t_2). The equations for the time of concentration at each sub-basin are shown as follows [20].

$$t_c = t_1 + t_2 \quad (1)$$

$$t_1 = L_1/v \quad (2)$$

$$t_2 = L_2/W \quad (3)$$

$$W = 72(H/L_2)^{0.6} \quad (4)$$

where, t_c is the time of concentration (hr), t_1 the inflow time of slope (hr), t_2 the outflow time of channel (hr), L_1 spreading length (m), L_2 the length of

river channel (km), v the overland flow velocity (0.3-0.6 m/sec in general), W the channel velocity (km/hr), and H the elevation difference of river channel (m).

The difference in the time of concentration between each control spot and each sub-basin is regarded as the time difference between the peak discharges of each sub-basin to each control spot. The peak discharge of each sub-basin to the control spot is summed every hour to establish the hydrograph of each control spot.

Allowance analysis aims to understand the closeness between the simulated parameter of Tank Model to the observed value in discharge stations. The structure of allowance analysis shows (1) the important information in deducting the observed error from the simulated parameter, (2) certain limitation on accuracy being acceptable as the model cannot be perfect, and (3) the accuracy of the parameter being definable to understand the limitation of the model.

3 Results and discussions

3.1. Peak discharge simulation results

From the discharge simulation results, the average hourly precipitation and the peak discharge of the thirty sub-basin are shown as Figure 2.

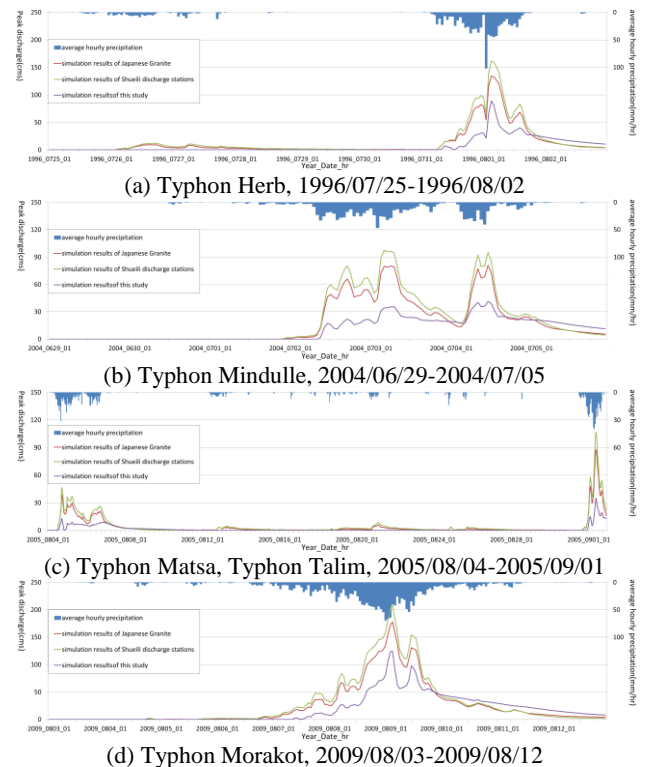
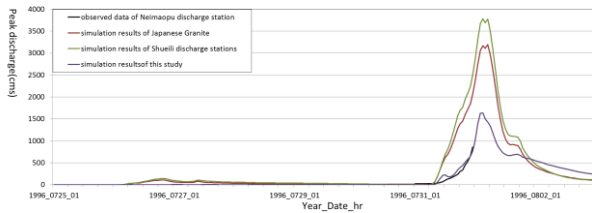


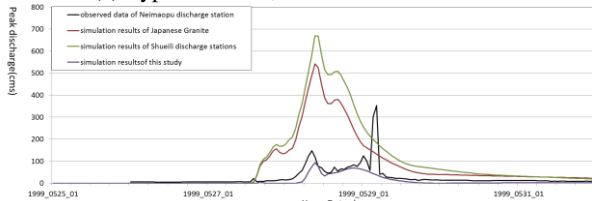
Figure 2. Average hourly precipitation and simulated peak discharge of Lulin sub-basin in Shenmu Village.

The hydrographs simulated by the parameters of Japanese Granite and Shueili discharge station appear

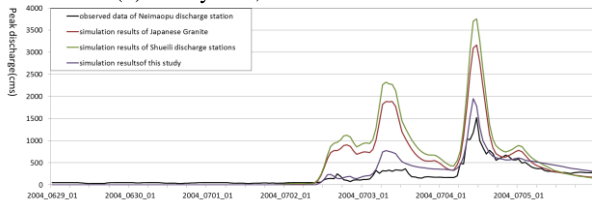
large difference with the observed value of Neimaopu discharge station using the data of Typhoon Mindulle as the training sample. With the parameters to simulate the hydrograph at the control spot *I* in the thirteen hydrologic events, they are further compared with the observed values of Neimaopu discharge station, Figure 3. The discharge simulated by the parameters of Japanese granite and Shueili discharge station is obviously doubled the observed discharge of Neimaopu discharge station.



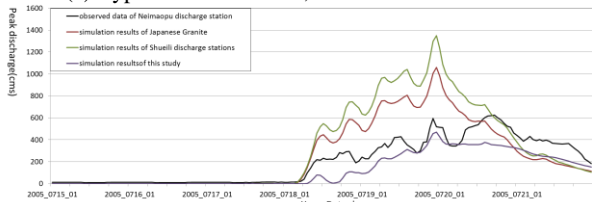
(a) Typhon HERB, 1996/ 07/25~1996/08/02



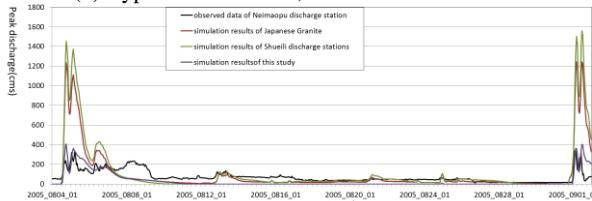
(b) Heavy rain, 1999/05/25~1999/05/31



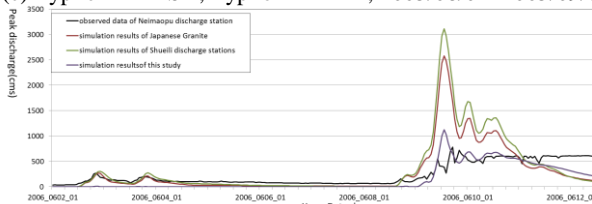
(c) Typhon MINDULLE, 2004/06/29~2004/07/05



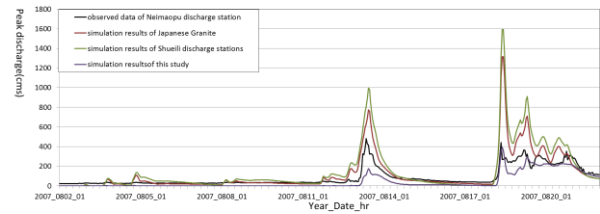
(d) Typhon HAITANG, 2005/07/15~2005/07/21



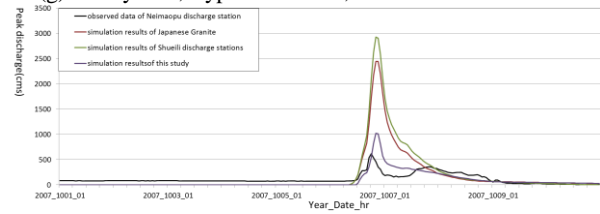
(e) Typhon MATSA, Typhon TALIM, 2005/08/04~2005/09/01



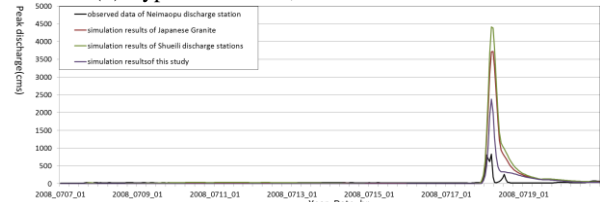
(f) Heavy rain, 2006/06/02~2006/06/12



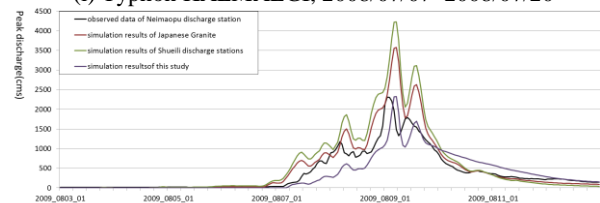
(g) Heavy rain, Typhon SEPAT, 2007/08/02~2007/08/21



(h) Typhon KROSA, 2007/10/01~2007/10/10



(i) Typhon KALMAEGI, 2008/07/07~2008/07/20



(j) Typhon MORAKOT, 2009/08/03~2009/08/12

Figure 3. Hydrograph at the control spot *I* and Neimaopu discharge station.

3.2 Comparison of simulated discharges and observed values

According to the peak discharge of each hydrologic event, the largest error appears on the mean error of the parameter of Shueili Station 251%, and followed by it of the parameter of Japanese granite 189%. The mean error of the parameter 51.0% in this study is favourable.

From Figure 4(a), the linear relationship between the measured discharge (x) and the simulated discharge (y) appears $y = ax$, where both the measured discharge and the simulated discharge should be equal. For this reason, when variable a approaches 1, the parameter simulation is better. The parameter in this study receives $a = 0.8542$, close to 1, and $R^2 = 0.71$; the parameter of Japanese Granite acquires $a = 1.4648$ and $R^2 = 0.60$; and, the parameter of Shueili Station obtains $a = 1.759$ and $R^2 = 0.59$, presenting that the parameter in this study is more suitable for this area.

Finally, the allowance of the three parameters are analyzed, Figure 4(b), where the parameter in this study appears the highest allowance percentage, that it is more suitable for simulating the peak discharge in this area. When the allowance percentage is set lower than 50%, the percentage of the parameter of Shueili

Station is higher than it of the parameter of Japanese granite; however, it shows the opposite situation when the allowance percentage is higher than 50%. In fact, the percentage could reach up to 80% when the allowance is set 40%. The three parameters therefore present low percentage, as Neimaopu discharge station is located in the downstream that the factors in discharge contain rainfall distribution, discharge of each sub-basin, afflux time, and the velocity and discharge at each section. Tank Model cannot overcome such problems, that other theories and models are required. Nevertheless, Shenmu Village is located at the sub-basin of upstream Chenyulan River, the factors are few so that they are ignored. The parameter of Tank Model is utilized for transforming average rainfall into hydrograph so as to solve the problem of no discharge when simulating various debris flows.

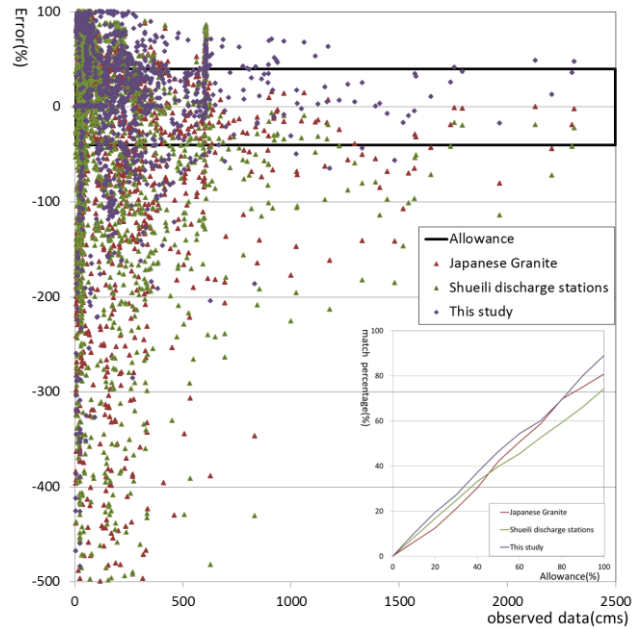
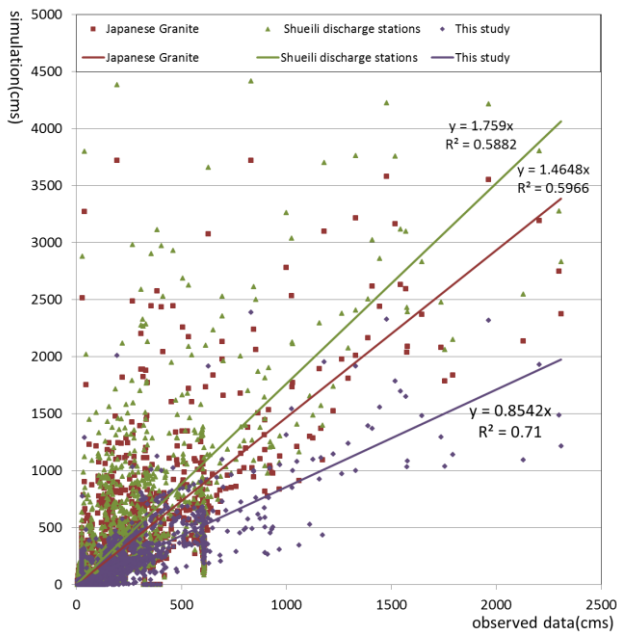


Figure 4. Comparison and allowance analysis of simulated and observed data.

4 Conclusions

Thirteen debris flow events around seventeen rain gauge stations within 1996-2010 are regarded as the cases for simulating the peak discharge at twelve control spots along Chenyulan River. The data in Neimaopu discharge station are established the parameter of Tank Model to estimate the peak discharge in Shenmu Village. The parameters of Shueili Station and Japanese Granite are further compared that the mean errors of the discharge simulated by the parameters achieve 251% and 189%, respectively. The mean error of the parameter in this study 51.0% is favourable, showing the simulated hydrograph is close to the measured discharge in Neimaopu Station. Shenmu Village locates at the sub-basin on the upstream Chenyulan River that the few factors could be neglected. The parameter of Tank Model therefore could be applied to transforming average rainfall into hydrograph to solve the problem of no discharge when simulating various debris flows.

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