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Research Paper

Event-based Soil Erosion Estimation in a Tropical Watershed

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Abstract: OpenLISEM, a hydrological modelling tool developed for small to medium-sized watersheds for temperate climates, was used to determine its applicability in simulating discharge and soil erosion during high rainfall events in a large tropical watershed in the Philippines. Based on the simulation results of a thunderstorm (TS) event, the openLISEM model can satisfactorily estimate the resulting discharge and soil erosion given that certain parameters are adjusted to suit the different conditions of the study area. However, simulation of a series of overlapping storm events spanning several days, which is characteristic of tropical regions, proved to be difficult to model. It was deemed that for long rain events, certain parameters related to infiltration and soil detachment change through time. A separate module for varying the watershed's hydraulic conductivity as the simulation evolves was developed and was proved helpful in bringing the model results closer to the observed values. Further development of other openLISEM modules is ongoing; their main purpose is to incorporate the effects of extreme hydrologic processes that come into play during long duration, high rainfall events.

Keywords: hydrology; LISEM; soil erosion; event-based modelling; tropical watershed; erosion modelling; Philippines

Introduction

Soil erosion is a severe problem especially in the tropical regions where high intensity, long duration rain events typically occur every year. In the Philippines, soil erosion has been recognised as one of the major environmental problems particularly in agriculture (Olabisi, 2012). According to the Forest Management Bureau (unpublished, 1998), it was estimated that 71 to 84 million tons of soil are eroded from agricultural lands every year in the country. Aside from the deterioration of land fertility and productivity, soil erosion could cause problems in terms of water quality, health and sanitation to downstream areas (Billota and Brazier, 2008). Deposition of these eroded sediments, on the other hand, presents problems to reservoirs and waterways which will eventually lead to more frequent flooding.

Numerical models have been developed for soil erosion that vary in terms of spatial and temporal scales as well as in computational approach. Two of the most widely used models are the Water Erosion Prediction Project (WEPP) and the Revised Universal Soil Loss Equation (RUSLE), both developed by the US Department of Agriculture and have been applied extensively in the tropical region (Schmitt, 2009; Bareng 2010). The two models require daily precipitation data to compute for annual soil loss. However, in tropical conditions, bulk of soil loss in watersheds occurs during extreme rain events which typically last for only about half an hour to several hours. There is therefore a need to account for soil erosion at an individual event scale rather than as an accumulated amount annually.

OpenLISEM model

The openLISEM model is the open source version of the Limburg Soil Erosion Model (LISEM) which is a physically-based, spatial hydrological model developed in the Netherlands. It is an event-based model that can simulate runoff, sediment erosion and shallow floods in rural and urban catchments (Baartman, 2012). Since it is event-based, it cannot be used for long-term estimation of discharge and sediment erosion in the basin. It is, however, capable of doing simulations for knowing the effects of detailed land use changes or conservation measures during storm events as well as for disaster risk management (Jetten, 2002).

Many studies have been made on the calibration and validation of the openLISEM model in many countries in Europe including the Netherlands (De Roo et al., 1996; De Roo and Jetten, 1999), France (Rahimy, 2012), Spain (Baartman et al., 2012; Baartman et al., 2013), Belgium (Jetten et al., 2003; Takken et al., 2005) and Norway (Kvaerno and Stolte, 2012). The LISEM model has also been tested in some parts of Africa (De Roo and Jetten, 1999; Hessel et al., 2006) and also in China (Hessel et al., 2003; Hessel, 2005). However, the openLISEM model has not been tested extensively in simulating soil erosion in a tropical setting like the Philippines where around 3,000 mm of rain falls annually. Also, in most studies in the literature, the LISEM model has only been used for relatively short duration storm events and has not been used for periods of extreme rain events that can last for several days such as during the southwest monsoon.

In this study, the openLISEM is used to estimate the discharge and the amount of sediment eroded from the Upper Marikina River Basin during short-duration (i.e. thunderstorms) and long duration rainfall events (i.e. typhoon-enhanced southwest monsoon). The capability of the openLISEM model in simulating soil erosion in a tropical country will be tested, as well as its capability of simulating longer intense rainfall events in a relatively larger catchment.

Study Area: Upper Marikina River Basin

The Upper Marikina River Basin is a 300-square kilometre watershed located in the southern end of the island of Luzon and is adjacent to the urban areas of northern Metro Manila particularly the city of Marikina (Figure 1). Starting in mid-May to the end of October, the Upper Marikina River Basin is frequented with thunderstorms and precipitation coming from the Southwest monsoon and tropical cyclones. From 1912 to 1991, records show that the Upper Marikina River had an annual average discharge of 18.3 cubic meters per second (Nicer, 2004).

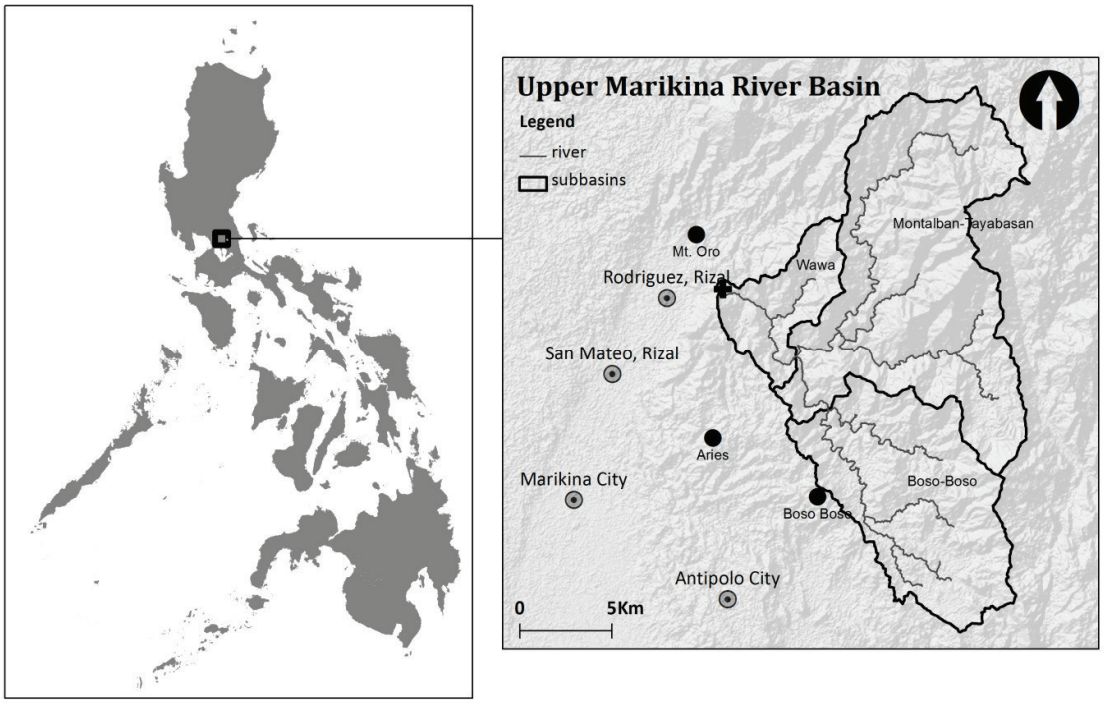


Figure 1. Location and configuration of the Upper Marikina River Basin (cross = location of discharge and sediment measurements, black circles = automatic weather stations used in the study)

Materials and Methods

Input Data

The openLISEM model requires a considerable amount of input data (Jetten, 2002). The major input data required are rainfall data, plant and soil characteristics, and a digital elevation model (DEM). Ten-minute rainfall data were obtained from the three nearest automatic weather stations (AWS) of the Department of Science and Technology (DOST). Plant and soil characteristics were obtained from values in the literature using landcover and soil maps obtained from the National Mapping and Resource Information Authority (NAMRIA) and the Bureau of Soils and Water Management (BSWM), respectively (Figure 2). The DEM that was used in this study was generated from the ASTER Global Digital Elevation Model Version 2. The DEM has a 30-m spatial resolution and 20-m vertical resolution. Conversion of all input data into the format that can be read by the openLISEM and the generation of other maps needed by the openLISEM were done in PCRaster, an open source GIS software by the University of Utrecht, Netherlands.

Field Data

During the high rainfall months of July and August 2013, water discharge was manually measured using a USGS price type AA Model 1210 current meter. River discharge was impossible to measure during the high discharge levels of the southwest monsoon event. To estimate this, water level data from an automatic water level sensor (Montalban Water Level (MWL)) 8 km downstream from the outlet point was included to serve as a visual guide for discharge. Note, however, that a lag time of a few hours between the MWL and the outlet point of the study should be expected.

Suspended sediment samples were obtained and were subjected to TSS analysis to determine the sediment concentrations during the event. These parameters were measured before, during and after rainfall events that meet the following criteria: 1)

greater than 2.4 mm/hr rain rate at some stage during the event, 2) less than 300 min time between recorded rainfall, i.e. if there was no additional rainfall for over five hours, the event is considered to have ended, 3) event must have greater than 5 mm total rainfall and greater than 30 min total duration (modified from the rainfall analysis done by Baartman et al., 2012). Two events were modelled: a local thunderstorm (TS) and a typhoon-enhanced southwest monsoon (TSWM) event which is an extreme rainfall event that spanned from August 18-23, 2013 (Heistermann et al., 2013). All rainfall events used in the study were classified using the event index (EVI) developed by Baartman et al. (2012).

$$EVI = \frac{P_{max} x P_{tot}}{T}$$

where P_{max} is the maximum intensity during the rainfall event, P_{tot} is the total rainfall depth of the event and T is the duration of the event.

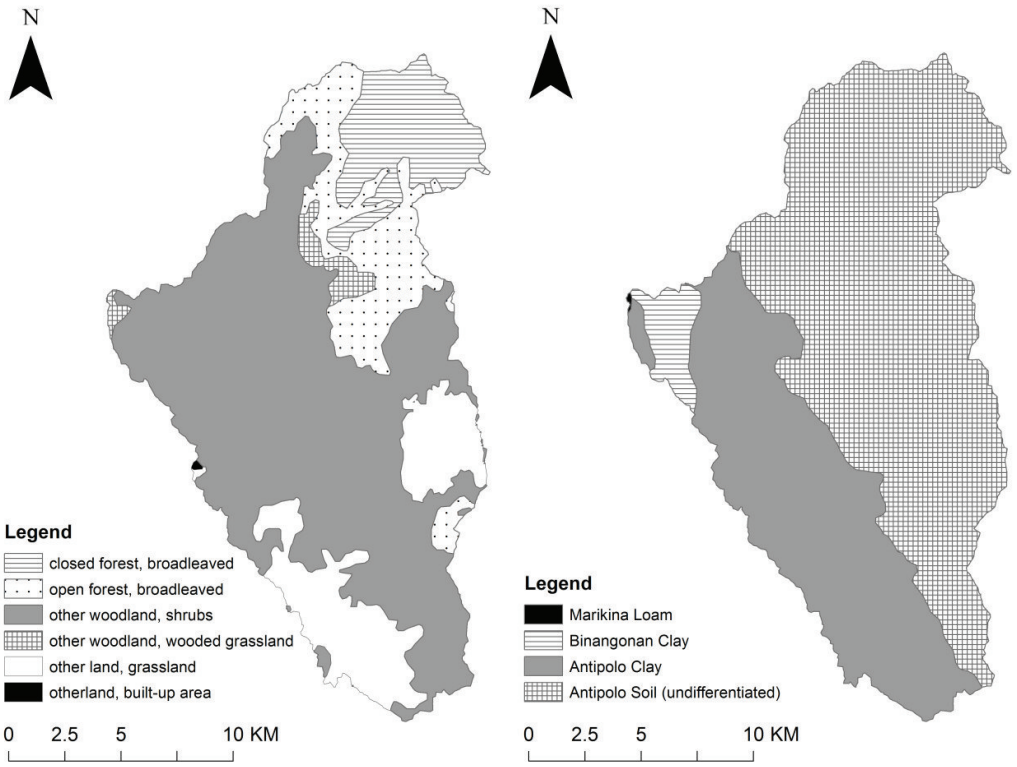


Figure 2. Landcover and Soil Maps

Model Simulation

The openLISEM model (version 1.79) was run with 30 m grid size and a time step length of 15 seconds. The infiltration model used is the 1-layer Green & Ampt infiltration equation. For this catchment, a channel network was defined using the DEM to represent the permanent streams. Since the openLISEM model is an event-based model, one limitation is that it only models direct runoff and that baseflow is not included in its calculations. In this study, baseflow was assumed to be constant regardless of discharge. Table 1 lists some of the important parameters used by the openLISEM and the corresponding literature values for each of the specific soil texture and landcover classification of the study basin. The model was run using values inside the range of these published literature values for each parameter particularly for saturated hydraulic conductivity (ksat). On the other hand, manning's n values in the model started at the maximum values and were optimized using multiplication factors which apply equally throughout the catchment. Cohesion values were also optimized using multiplication factors starting at 20 kPA (cohesive strength for soft clay soils; Bowles, 1996 p. 165)

Ksat module: Varying Ksat values

In the previous studies using openLISEM, it was observed that a single set of parameters is not sufficient to model rainfall events with different characteristics. This was further illustrated in the study made by Baartman et al. (2012) where they classified rainfall events depending on specific characteristics such as maximum rainfall intensity, total rainfall depth and duration of the event using the event index (EVI). They observed that a higher ksat value was needed for events with higher EVI. This observation was already demonstrated physically by the rainfall experiments made by Yu et al. (1997), Paige et al. (2002),

Karssenberg (2006), Leonard et al. (2006), Stone et al. (2008). In their studies, apparent infiltration rate changes depending on the intensity of the rainfall event.

In this study, a separate module was created that varies the ksat value input as openLISEM runs its simulation. In particular, the ksat module sets a multiplication factor to be used for specific time interval that is specified by the user or in the form of an equation that is a function of rainfall. This factor is then multiplied to the original ksat value as the simulation progresses (e.g. for time interval 0-50 mins the multiplication factor to be used is 1.0 and for time interval 50-200 mins the multiplication factor to be used is 3.0)

Table 1. Literature values of important parameters used in openLISEM

Soil Texture			
		Clapp and Hornberger (1978)	Chow (1988)
Clay	Ksat (mm/hr)	4.62	0.3
	Psi (cm)	40.45 (39.7)	31.63 (6.39- 156.6)
Loam	Ksat (mm/hr)	25.02	3.4
	Psi (cm)	47.8 (51.2)	8.89 (1.33- 59.38)
Land Cover (Chow, 1959)			
	Min	Normal	Max
closed forest, broad leaved	0.11	0.15	0.2
open forest, broad leaved	0.11	0.15	0.2
other woodland, shrubs	0.045	0.07	0.11
other woodland, wooded grassland	0.045	0.07	0.11
other land, grassland	0.02	0.03	0.04
other land, built-up area	0.01	0.011	0.013

Results and Discussion

Outlet Measurement

Table 2 summarizes the characteristics of the two rainfall events simulated and the actual measured discharge and sediment concentration. Figure 3 compares the simulated and the measured hydrograph and sediment concentration for the TS event which shows satisfactory congruence of the model output with the actual measurements. The same parameters used to model the TS event (Table 3) were also used to simulate the discharge and sediment concentration for the TSWM event.

Figure 4 shows the result of the simulation of the TSWM event which, as can be deduced from its rainfall pattern, is actually a series of overlapping individual events. The TSWM simulation resulted in unsatisfactory values for both discharge and soil erosion estimation. It shows that the openLISEM model significantly overestimated the discharge values compared to the actual measurements. The discharge to rainfall ratio was significantly larger (54.39%) than the one produced from the TS event (2.31%). The shape of the simulated hydrograph was also different from the hydrograph at the MWL. The hydrograph from the MWL consists of three broad overlapping discharge events: 0-3000 min, 3000-4500 min and 4500-8500 min, which correspond to the three distinguishable rainfall sub-events: 0-2000 min, 2400-4200 min, and 4400-6400 min. The hydrograph produced by the simulation, on the other hand, contains several narrow peaks at the 500-2000 min, 2500-4000 min and 4500-6500 min periods.

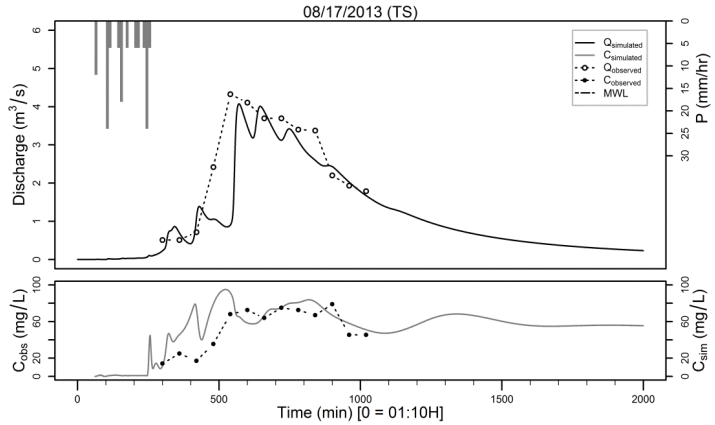


Figure 3. Simulation result of TS event. C_{sim} and C_{obs} refers to simulated and observed sediment concentration (in mg/L) while P refers to the rainfall intensity (in mm/hr).

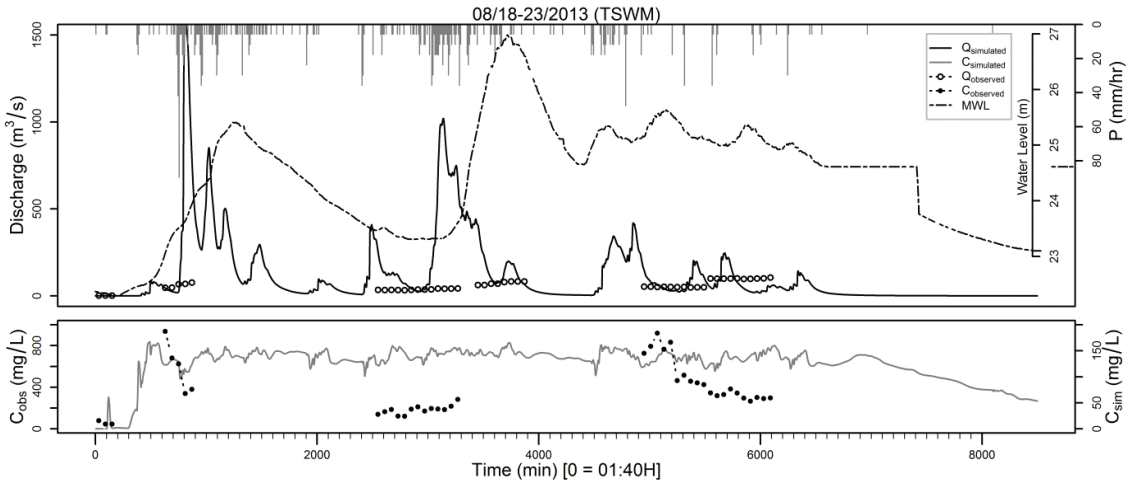


Figure 4. Simulation of TSWM using the same model parameters used in the TS event

Table 2. Event characteristics for the two selected events from the sampling period (July and August 2013).

	TS	TSWM
Date	17 Aug 2013	18-23 Aug 2013
Total Rainfall (mm)	20	373
Peak rainfall (mm/h)[a]	24	90
Total duration (min)	200	6560
Peak discharge(m^3/s)[b]	4.326	--
EVI	2.40	5.12

a Maximum average intensity over a 10-min interval
b Only the Aug 17 event has a complete discharge and concentration measurements during the whole event

Table 3. Ksat, psi, manning's n values and cohesion values used in the simulation of the TS and TSWM events

	Land Cover	Soil Texture - Clay	Soil Texture – Loam
Ksat value (mm/hr)	--	1.86	3.4
Psi (cm)	--	31.63	8.89
Manning's n multiplication factor (slopes)	0.3	--	--
Manning's n multiplication factor (channel)	0.4	--	--
Cohesion (kPa)	--	400	20

The simulated sediment concentration values, in contrast, were significantly underestimated compared to the actual measurements. Because of the unsatisfactory results for TSWM, the ksat module was developed and a new TSWM run was made. Throughout the new simulation, ksat varied from 3 to 90 mm/hr.

Table 4 compares the results of the initial TSWM with a fixed ksat and that of the TSWM with the ksat module. The difference in the results obtained is significant particularly for total discharge.

The varying ksat simulation shows a significant improvement in the shape of the hydrograph (Figure 5). Multiple narrow peaks were eliminated leaving three significant discharge peaks which were also observed in the MWL hydrograph. Discharge values were also closer to the actual measurements although still relatively overestimated. Still, the upper limit of the ksat value (90 mm/hr) is already beyond the typical ksat for clay soil and is already nearing the hydraulic conductivity values for sand material. It is perceived that besides the reported increase in hydraulic conductivity during a rainfall event, there may be other processes that contribute to the apparent high ksat value. This includes among other things the surface ponding of rainwater in temporary pools. Also during high flow events, an increased infiltration along and beyond the banks of the river which are composed of coarser sediment should be expected.

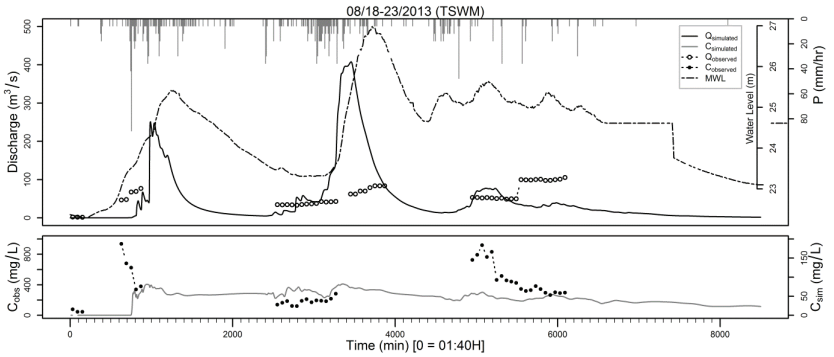


Figure 5. Simulation of TSWM using the varying ksat module

Table 4. Comparison of the TSWM simulation with and without the ksat module

	TSWM	TSWM (varying ksat)
LISEM results at time (min):	8500	8500
Total rainfall (mm):	375	375
Total discharge (m3):	59,334,223.73	23,388,233.06
Peak discharge (l/s):	1,628,686.32	407,771.41
Peak time rainfall (min):	750	750
Peak time discharge (min):	811	3457
Discharge/Rainfall (%):	54.39	21.44
Splash detachment (land) (kg):	238,067.83	881,436.53
Flow detachment (land) (kg):	12,504,138.51	4,284,827.39
Deposition (land) (kg):	(4,257,291.02)	(3,616,705.39)
Suspended Sediment (land) (kg):	2,354.62	14,715.27
Flow detachment (channels) (kg):	23,757.09	12,309.67
Deposition (channels) (kg):	(214,585.89)	(88,126.44)
Susp. Sediment (channels) (kg):	824.77	996.90
Total soil loss (kg):	8,290,907.12	1,458,029.59
Average soil loss (kg/ha):	267.057	46.964

The simulated sediment concentration values were still unsatisfactory compared to the actual measured values. The underestimation of the sediment concentration values in the TSWM simulation can be accounted in a number of ways:

1. Other major processes such as gully erosion are not yet considered in the openLISEM model. These processes could be major factors during large rainfall events.
2. The unit stream power equation by Govers (1990) used by the model for sediment transport assumes a clear water discharge and gives a finite limit on how much sediment it is able to carry (Hessel and Jetten, 2007). This also means that highly concentrated flows are not considered in the model which could occur during large events like the TSWM.
3. The way the sediment is transported in the model is largely dependent on the velocity of water which is determined by the manning's n roughness coefficient and the slope of the terrain (Govers, 1990). Due to the large differences of slope between the tributaries and the main river, large amounts of sediment are deposited immediately at these portions of the watershed.

Conclusion

While simulation of short rain events produces satisfactory results, simulation of longer duration events like the TSWM event will require further modifications in the openLISEM since more complex hydrological processes will be in effect. Incorporation of the interaction of surface water and groundwater which will affect baseflow contributions to discharge is deemed essential. Other forms of soil detachment such as gully erosion may also need to be considered in the computation of total eroded materials. Lastly, development of modules, such as the ksat module, that can vary input parameters related to infiltration and sediment transport as the simulation evolves is also important. The latter issue is currently being addressed with the ongoing development of more peripheral modules to the openLISEM. These will soon be made available to other researchers which can only contribute to the overall applicability of the openLISEM software in simulating soil erosion during extreme conditions.

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