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Application of Hydrodynamic Model for Sedimentary Management in Alishan River

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ABSTRACT

Heavy rainfall in Taiwan induces landslides in upper watersheds, results in sediment deposits on the riverbed, reduces river cross-sections, and changes the flow direction of rivers. This study numerically investigated sediment transport in the Alishan River and determined that the KINEROS 2 and CCHE1D models could accurately represent both sediment transport and morphological changes. Most of the simulated sections were similar to the measured data; thus, the results can be used as a strategic reference for sedimentary management.

KEY WORDS: CCHE1D; hydrodynamic model; sedimentary management.

INTRODUCTION

Taiwan is an island with a unique natural environment. Plate compression often affects the orogeny, including by producing steep topography and soft geological conditions. However, steep topography, frail geology, and concentrated rainfall during the wet season frequently cause slope disasters as well as landslides in the upper watersheds of Taiwan. These deposits reduce river cross-section and change flow direction as well as damage river functioning and shorten the life of hydraulic structures. The increasing sediment transport capability of the water leads to general scour in the main channel, which makes the river unstable and poses challenges to river regulation, structural efficiency, and traffic safety.

Sediment yield estimation emphasizes watershed management and disaster prevention, and has a substantial effect on the sediment volumes between the extremes of excess and deficiency in the watershed. Thus, combining sediment production and transport in watershed management is appropriate. In general, sediment yield on the slopeland includes both annual sediment yield and the sediment yield from rainfall events; however, because of the limited information on environmental conditions in the upper stream, establishing sediment monitoring equipment is difficult. Consequently, an empirical formula evaluates the sediment yield.

Several simulation models are useful for analyzing the long-term effects in a watershed scale, such as the USLE (Wischmeier and Smith, 1978), SWAT (Arnold et al., 1998) and AnnAGNPS (Bingner and Theurer, 2001) models. AGNPS (Young et al., 1987) and KINEROS (Woolhiser et al., 1990; Smith et al., 1995) are additional single rainfall event models. However, the AGNPS model only simulates the total sediment yield during a rainfall event, it cannot simulate the sediment yield and is unable to analyze riverbed changes over time. Therefore, the KINEROS model was used in this study to simulate the sediment yield from rainfall and as input data into the hydrodynamic model. Because of the lack of environmental information in the upper watershed, a one-dimensional hydrodynamic model was used in this study to simulate riverbed changes. GSTARS (Molinas and Yang, 1986), HEC-6 (U.S. Army Corps of Engineers, 1993), and CCHE1D (Wu and Vieira, 2002) are the most commonly used one-dimensional models. Of these, the CCHE1D model has been successful for predicting bed scouring and deposition on the Taan and Choshui Rivers in Taiwan; therefore, this study used the CCHE1D model to simulate riverbed changes, with the results expected to be a primary strategic reference for sedimentary management.

The upper stream of the Qingshuei River, the Alishan River, was used as the study area (Fig. 1). In August 2009, Typhoon Morakot produced sedimentation in the midstream and downstream river courses of the Alishan River. To improve the capability of stream drainage and sediment transport, the Taiwan government subsidized a project to conduct stream dredging; however, even the dredged sections of rivers are in continual danger of sedimentation during flood season.

This study numerically investigated the sediment transport in the Alishan River by using the KINEROS 2 model developed by the United States Department of Agriculture and the CCHE1D model developed by the National Center for Computational Hydroscience and Engineering. The sediment production on the slopeland, calculated by the KINEROS 2 and CCHE1D models, was designed to simulate steady and unsteady flows and sedimentation processes in dendritic channel networks. The simulated results represent the characteristics of river flow, sediment transport, and morphological changes in the Alishan River during typhoon events, and offer a critical strategic reference for sedimentary management of the Alishan River.

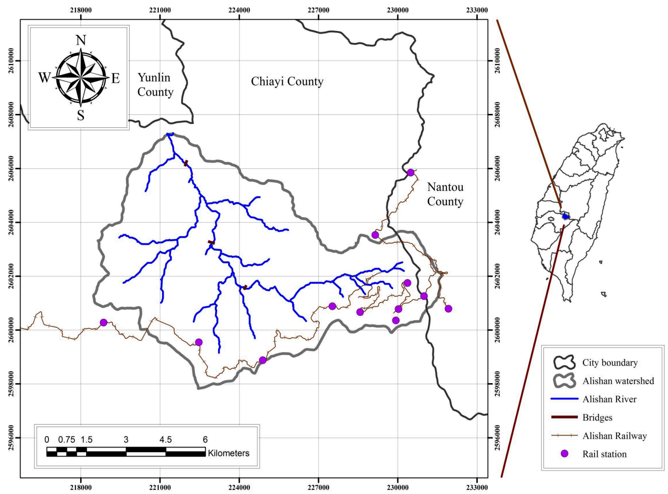

Fig. 1 Location of the study area

METHODS

Environmental information of the Alishan River is challenging to obtain because it is located at the upper watershed. The digital elevation model (DEM) measured in 2004, cross-sectional data measured in 2003 and 2009, rainfall data from 2004 to 2009, and sediment size distributions were collected for this study. DEM was used as the initial condition to calibrate the model regarding the significant typhoon events that occurred between 2004 and 2009. The KINEROS 2 and CCHE1D models estimated sediment production from the slopeland to the river and simulated sediment transport in the river, respectively. The simulated results were then compared with the cross-sectional data from 2009.

KINEROS 2

KINEROS 2 is an event-oriented, physically based model that describes the process of interception surface, runoff, and erosion, and was designed for modeling events in arid and semiarid watersheds. Finite difference methods were used to solve the overland flow, channel flow, and partial differential equations for sediment transport; subsequently, the spatial variation of rainfall, runoff, and sediment yield during the rainfall event were accommodated (Woolhiser et al., 1990; Smith et al., 1995).

CCHE1D

CCHE1D model was designed to examine steady and unsteady flow, sediment transport, and water quality in channel networks. The flow model uses the diffusive wave model or the dynamic wave model. The de Saint Venant equations (Wu and Vieira, 2002) were used for the open channel flows, whereas the four-point implicit scheme of Preissmann discretized the flow equations. The sediment transport model can predict channel morphological changes and sediment yield using a nonequilibrium approach; the actual sediment transport rates were assumed to be equal to the sediment transport capacity at every cross-section.

RESULTS and DISCUSSION

Sediment production built on the slopeland

The Alishan rainfall station (Fig. 2) is the only rainfall station within the Alishan watershed and only the DEM from 2004 and the cross-sectional data measured between 2003 and 2009 in this study area.

The long-interval data and the analysis method were used to be verified because of the limited data, eight severe typhoon events between 2005 and 2009 were combined into one rainfall event by using the Alishan rainfall station data. The eight severe typhoon events were typhoons Haitang (2005), Talim (2005), Longwang (2005), Sepat (2007), Krosa (2007), Sinlaku (2008), Jangmi (2008), and Morakot (2009); these typhoons had a total rainfall duration of 635.0 hours, with maximum rainfall of 53.3, 63.0, 24.5, 37.0, 87.5, 53.0, 64.5, and 123.0 mm/hr, respectively (Fig. 3). The distribution of the outflow (mm/hr) and total sediment (kg/s) were obtained by the KINEROS 2 model and used as inputs for the hydrodynamic model.

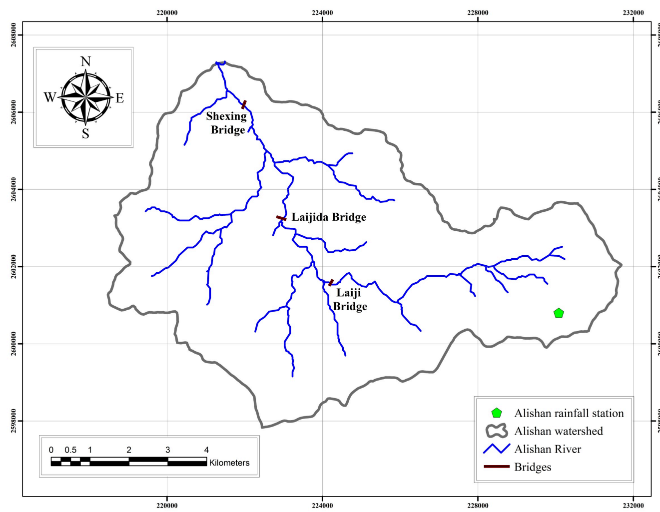

Fig. 2 Location of the Alishan rainfall station

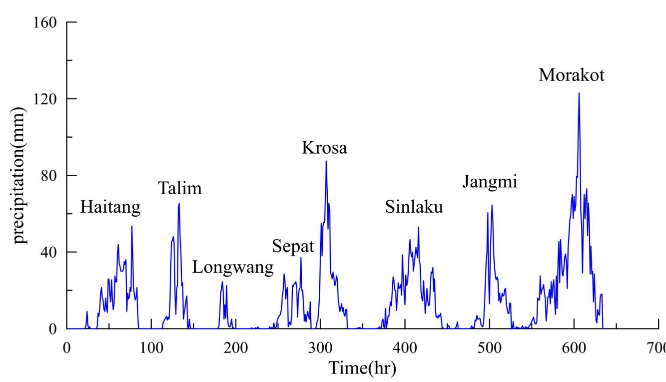

Fig. 3 Precipitation distribution of the eight typhoon events

Hydrodynamic model built in the Alishan River

The input data for the hydrodynamic model comprised river elevation, discharge hydrographs, and Manning's n values. The DEM measured in

2004 was used as the initial condition for calibrating the model, the outflow from the KINEROS 2 model was discharged hydrographs, and Manning's n values converted surface particle sizes. There were six riverbed material sampling points between the Shexing and Laiji bridges (Fig. 4). Using several empirical formulas, including the Strickler, Mayer and Peter, Einstein, Lane, and Ho Hung formulas, the surface particle sizes were transformed into Manning's n values (Table 1). Table 1 reveals that the Ho Hung formula analysis was larger than the others; however, the Manning's n value of the Ho Hung formula was negligible. The average Manning's n value from the four empirical formulas in the six riverbed material sampling points were 0.019, 0.019, 0.019, 0.020, 0.020, and 0.021. The Manning's n values for upstream of the Laiji Bridge, between Laijida Bridge, and Laiji Bridge were 0.021, 0.20, and 0.019, respectively. Because the cross-sectional data measured from the Laiji Bridge to the junction of Alishan River were from 2009, the distance for each cross-section of the CCHE1D model varied from approximately 100 meters (Alishan River to the Laiji Bridge) to approximately 350 meters (all other sampling points).

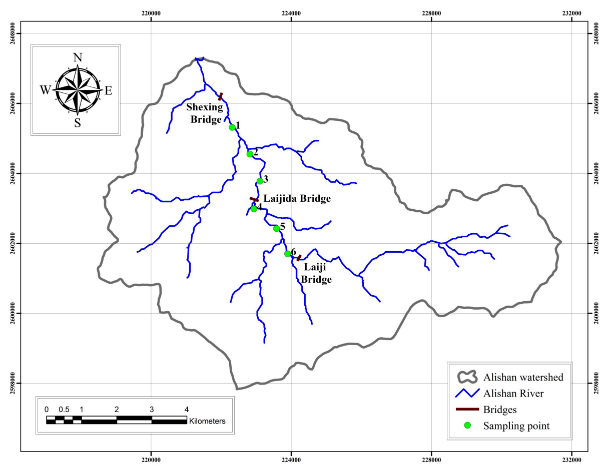

Fig. 4 Locations of the bed material sampling

Comparison between the measurement and simulation longitudinal profiles in 2009 in the Alishan River

The CCHE1D model examined the sediment transport and morphological changes. Most of the sections had similar results and were applicable to the measured data (Fig. 5). The three main protect objects within the simulation reach were the Shexing, Laijida, and Laiji bridges; a comparison of the measurement and simulation elevation in these main protect objects is presented in Table 2. The measurement elevations of the Shexing, Laijida, and Laiji Bridges were 588.45, 714.34, and 834.19 m, respectively, whereas the simulation elevations were 585.35, 717.04, and 848.64 m, respectively. Using the measurement data as criteria, the difference and percentage error of these three protect objects were −3.10 m (−0.53%), 2.70 m (0.38%), and 14.45 m (1.70%) for the Shexing, Laijida, and Laiji Bridges, respectively; this verified the applicability of the CCHE1D model for examining the Alishan River.

Discussion of the river profiles from 2003 to 2009

River profile changes in the Alishan River are depicted in Fig. 5. A comparison of the profiles from 2003, 2004, and 2009 indicated that most of the river reach began to deposit gradually, especially upstream and downstream of the Shexing and Laiji bridges. According to an investigation, the Shexing and Laiji bridges were damaged by typhoon Morakot, which was consistent with the results of this simulation. Because the cross-sectional data measured from the Laiji Bridge to the junction of Alishan River were from 2004, and the simulation data were from 2009 in the upstream of the Laiji Bridge, deposition was concluded to have occurred in this river reach.

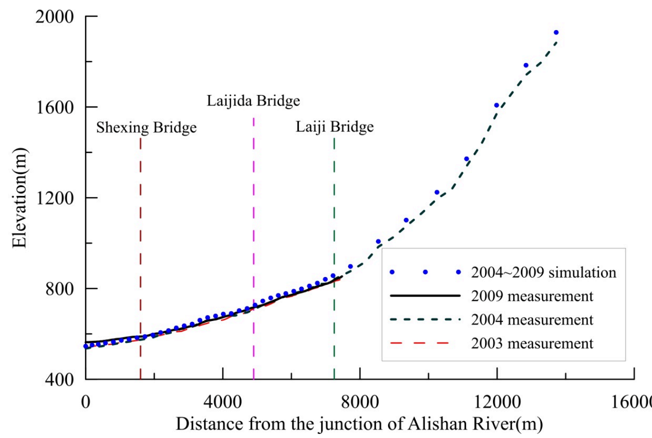

Fig. 5 Longitudinal profiles changes from 2003 to 2009 in the Alishan River

Table 2 Difference in the river profiles from 2003 to 2009 in the main protect objects (unit:m)

	Shexing Bridge	Laijida Bridge	Laiji Bridge
2009 simulation	585.35	717.04	848.64
2009 measurement	588.45	714.34	834.19
difference between the measurement and simulation in 2009	-3.10(-0.53%)	2.70(0.38%)	14.45(1.70%)
2004 measurement	574.27	699.99	827.98
2003 measurement	574.89	699.94	827.54

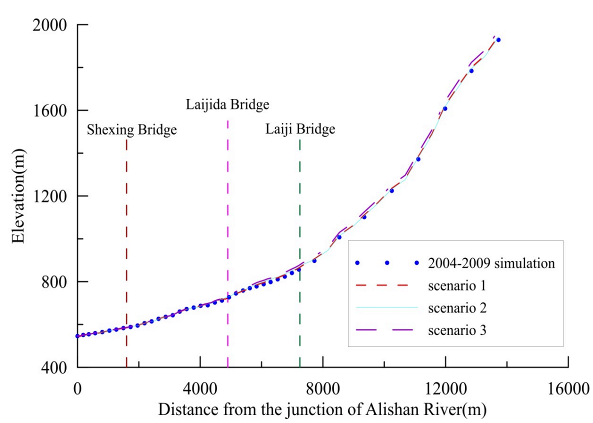

Fig. 6 Compared the morphology changes with the three different scenarios in the Alishan River

Morphological changes in three scenarios using the simulation model in the Alishan River

The simulation model accurately predicted morphological changes in the river reach. In this study, three scenarios were implemented and compared. Total rainfall in these scenarios were 85.05, 214.32, and 582.74 mm, respectively, with average rainfall intensities of 2.43, 8.93, and 32.42 mm/hr, respectively. The morphological changes, as well as the benchmark of the simulation results in these scenarios, are illustrated in Fig. 6. Notably, the river elevation in the river reach was not far from the benchmark in scenario 1. Specifically, from the Laijida Bridge to the junction of the Alishan River was almost completely scoured, except upstream and downstream near the end of the Laiji Bridge are deposited, where the maximum depths were 0.77 and 7.53 m, respectively. The results of scenario 2 were similar to those of scenario 1, with maximum depths of 2.39 and 12.24 m. The river was the deposited in scenario 3 and the maximum depth was 23.10 m at the source of the Alishan River. From this, the deposit river reach was found and the main protect objects were deposited in the three scenarios. This indicates that the Shexing, Laijida, and Laiji bridges were prominent locations for the river reach after typhoon events; however, maintaining the river elevation in the river reach is preferable. With river dredging and the monitoring of river morphological changes, disasters can be avoided.

CONCLUSION and OUTLOOK

There is a shortage of sediment-related information regarding the environmental conditions of the upper stream. This study combined two models, KINEROS 2 and CCHE1D, to calculate the sediment yield on the slopeland and the sediment transport and morphological changes in the upper river. The longitudinal profiles in measurement and simulation were similar in most sections and the deposit river reach was found. The results also present a critical strategic reference for sedimentary management on the basis of morphological elevation changes in the Alishan River. However, only the DEM from 2004 and the cross-sectional data measured between 2003 and 2009 were used in this study; future research should include a broader range of data. Additionally, long-term morphological changes can be properly evaluated if the river elevation data of Alishan River are collected regularly and more often.

ACKNOWLEDGEMENT

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Table 1 Analysis of the Manning N

Sampling point	Stickler	Meyer-Peter	Einstein	Lane	Ho Hung	Average n
	$n=d_{50}^{1/6}/25.68$	$n=d_{90}^{1/6}/26$	$n=d_{65}^{1/6}/75.75$	$n=d_{75}^{1/6}/39$	$n=d_{90}^{1/6}/16$	
1	0.020	0.017	0.017	0.020	0.041	0.019
2	0.021	0.017	0.017	0.020	0.041	0.019
3	0.021	0.018	0.017	0.021	0.042	0.019
4	0.021	0.018	0.018	0.022	0.043	0.020
5	0.021	0.019	0.018	0.022	0.046	0.020
6	0.022	0.020	0.019	0.023	0.047	0.021