Pol. J. Environ. Stud. Vol. 33, No. 2 (2024), 1347-1356
DOI: *10.15244/pjoes/170763*
ONLINE PUBLICATION DATE: 2023-11-21

Original Research

Characteristics of Bed Profiles Due to Sediment Transport in a Debris River

I Gede Tunas*, Muhammad Galib Ishak, Saparuddin Saparuddin, Rudi Herman

Graduate Program of Civil Engineering, Faculty of Engineering, Universitas Tadulako,
Jalan Soekarno-Hatta Km. 9 Palu, Central Sulawesi, 94117, Indonesia

Received: 27 December 2022
Accepted: 7 August 2023

Abstract

Sediment transport in debris rivers is a unique phenomenon of sediment transport in general. This is related to the complexity of the characteristics of the material transported and the nature of the flow that transports sediment. This work aims to predict potential bed profile changes in one of the debris rivers in Indonesia: the Sombe-Lewara River in Central Sulawesi Province. The control of debris flow in this river has been carried out simultaneously by the relevant government agencies by building sediment control structures along the river section. The study was carried out by hydraulic simulation at the intersection of the Sombe River and Lewara River using the HEC-RAS Model with two input data: average discharge and bed load gradations at both upstream boundaries. The average discharge was obtained by rainfall-runoff transformation using the HEC-HMS Model due to the limited discharge data in the study area, while the sediment gradation data was obtained from laboratory test results based on bed load sample data. Due to the limitations of the observation data, the parameter optimization is only applied to the HEC-RAS model, especially the Manning roughness coefficient by comparing the observed water level elevation with the simulated water level elevation. The results of the study indicate that the bed profile elevation in the upstream confluence of the river tends to increase and the bed profile downstream of the confluence tends to decrease. This is closely related to the transport intensity and bed slope upstream and downstream of the river confluence. The results of this study can be used as a reference for handling sedimentation in debris rivers.

Keywords: hydraulic simulation, debris flow, flood, degradation, aggradation, HEC-HMS, HEC-RAS

Introduction

The intensity of debris flow in Central Sulawesi after the 2018 Palu earthquake is increasing at this time. Besides being triggered by rainfall, landslides on unstable slopes caused by earthquake shocks can also be a cause. Slopes with high steepness, especially in the upstream catchment, are very susceptible to becoming unstable and subsequently it will become easily eroded and landslide even at low intensity rainfall. The flow with a high sediment concentration erodes the cliffs and river channels and then transforms into material deposits in the downstream section along with the decrease in the slope of the river bed [1-2].

---

*e-mail: tunasw@yahoo.com

Debris rivers generally carry high concentrations of sediment. This material can not only come from eroded slopes and landslides, it can also come from very massive river channel erosion. Debris material triggers high destructive power to the river channel and water structure in the river. In fact, often flood debris can endanger agricultural areas, settlements and other areas in the downstream segment. Debris material that settles simultaneously also has a bad impact on channel capacity [3-5].

The government has carried out control and handling of debris flow and material in the Sombe-Lewara river by controlling upstream erosion and building sediment control structures along the river channel such as sabo dams, check dams, ground sills and end sills, revetments and several other similar structures. Due to the high destructive power caused by material debris, these control structures do not function optimally. Even some of them have collapsed due to the inability to accommodate and hold debris material [6-7].

The complexity of the debris flow characteristics and the high impact of the damage require a special, careful and in-depth study due to the uncertain nature of the triggering factors. Rainfall as the main trigger is very hard to predict due to climate change, especially in tropical areas such as Indonesia [8]. Recently, in the study area, the intensity and duration of rainfall tend to increase, often the duration of the rainfall is more than 24 hours with an intensity above 100 mm/day. The characteristics of rain like this can trigger debris flow with a very large potential hazard.

Studies on debris flow and its relation to sediment transport have been carried out, especially in the Sombe-Lewara river by several researchers. Bawias investigated the impact of sand mining on the bed profile around the sediment control structure [9]. Intensive sand mining, especially upstream of sediment control structures, can cause bed degradation. Edison et al. studied the conservation strategy in the Sombe Lewara catchment to reduce the erosion rate which contributes to the sediment supply in the Sombe-Lewara river [10]. They propose recommendations for land rehabilitation and soil conservation to reduce erosion potential by 20,770 tons/year. Recent research conducted by Pratama et al. and Pratama which relates to the prediction of potential sediment transport rates in connection with sand mining activities along the river channel. The results of the study show that the sediment transport rate is indicated to be in a high category along with the increasing rainfall intensity and the potential for erosion and landslides in the upstream area [11-12].

Based on this series of studies, it indicates that the sediment transport rate in the Sombe-Lewara river increases along with the high sediment supply from the upstream catchment. Massive erosion and debris flow contributed greatly to the rate of transport. Sediment control has been carried out in a sustainable manner

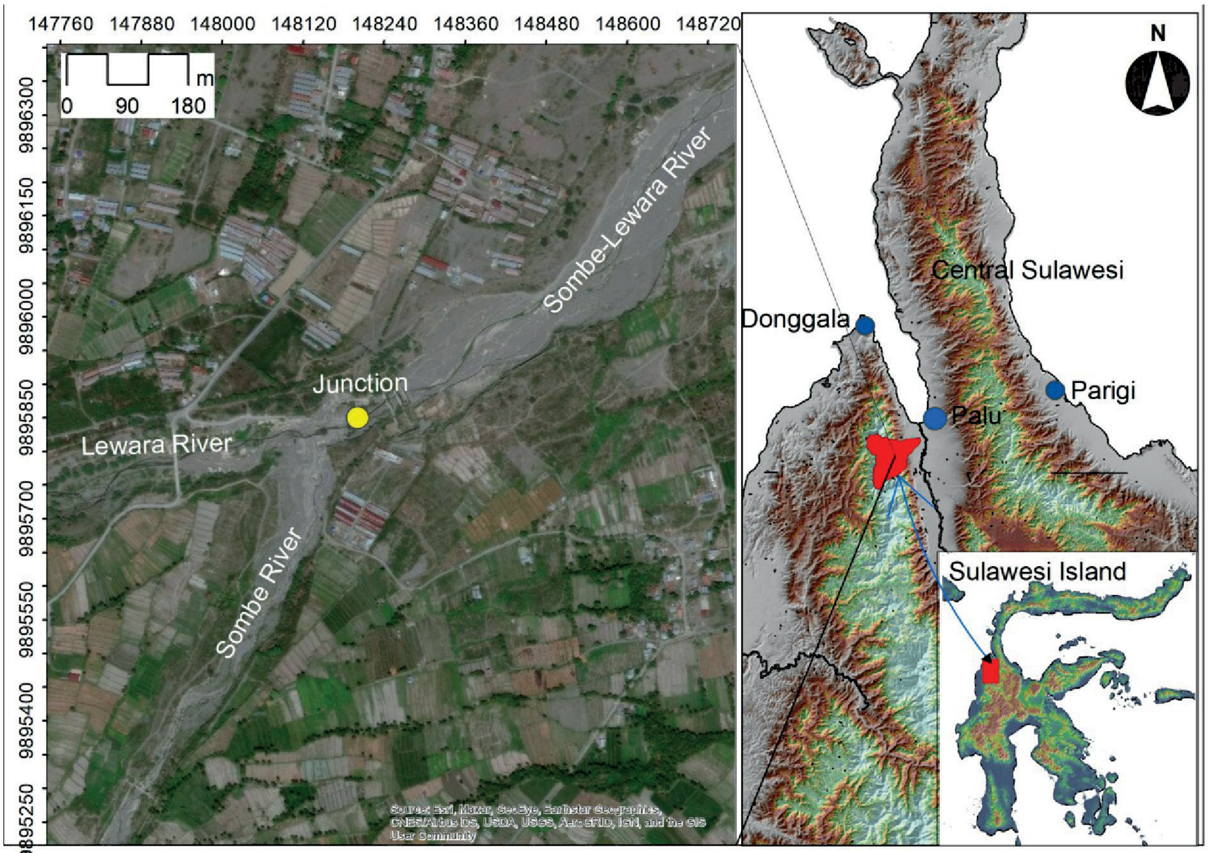


Fig. 1. Detail location of research site.

but has not shown optimal performance. Sand mining activities as a construction material have triggered the bottom degradation and instability of riverbanks.

Referring to the complexity of sediment problems in the Sombe-Lewara river, this research is very important to be performed. This study examines bed profile changes along the evaluated segment without distinguishing the presence of sediment control structures in that segment, especially at river confluence due to debris flow. The built hypothesis is that these sediment control structures have the potential to affect the stability of the bed profile. Based on the results of this study, the existence of existing sediment control structures can be reviewed and a new control concept can be proposed.

Material and Methods

Study Area

This study was carried out in one of the debris rivers in Central Sulawesi, Indonesia: the Sombe-Lewara River (Fig. 1). This river with a catchment area of approximately 84.73 km^2 is a combination of two tributaries known as the Sombe river on the right side and the Lewara river on the left side. The discharge of the Sombe River is slightly higher than the discharge of the Lewara River due to the difference in catchment area. The two sub-catchments show an elongated shape and the width of the catchment decreases gradually downstream until it reaches the junction and finally rouge in the Palu River. This river is the most downstream river on the west side of the Palu Catchment which contributes to the flow of the Palu River [11].

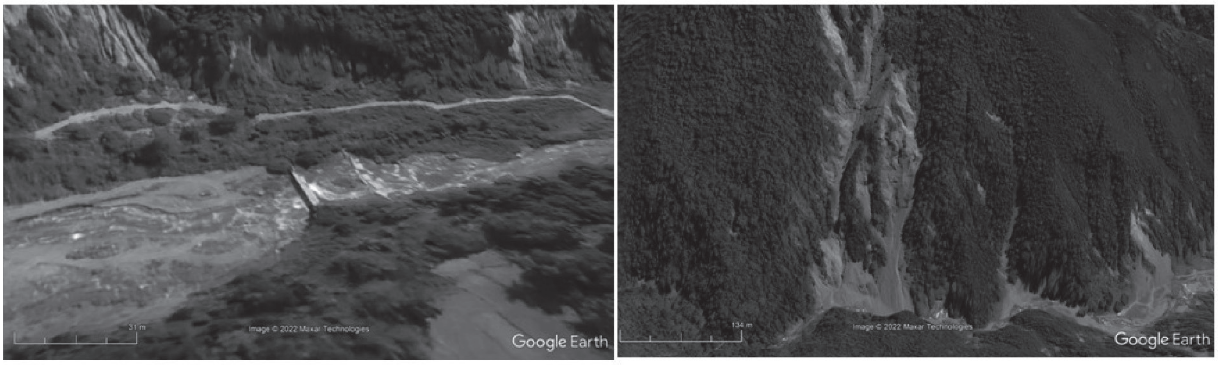
As a debris river, along the river segment from the middle to the downstream, it can be seen the bed sediment deposit with a high concentration of mud content. The intensity of sediment transport increases during the rainy season where the rainfall intensity is generally high. In addition, the 2018 Palu earthquake has the potential to trigger slope instability, especially in the upstream catchment with steep slopes (Fig. 2). Slope instability can cause erosion and landslides even though the rainfall intensity is relatively low.

Along the Sombe-Lewara river segment, at least 20 sediment control structures have been constructed. There are structures that function as sediment reservoir, sediment diversion, bed stabilizers and there are also as river bank reinforcements. Sediment deposited on the structure is mined by local communities as construction material. Material mining activities at that location have the potential to affect sediment transport characteristics and river bed stability. However, the mining activity of this material has been authorized by the local government as a way to maintain the capacity of the sediment control structure.

Data Details

The data of this research are the results of field investigations and secondary data obtained from government institutions such as the River Basin Management Board of Sulawesi III, Forestry Office of Central Sulawesi and others. Primary data in the form of measurements of discharge, water level elevation, sediment bed samples in the Sombe river, Lewara river and Sombe-Lewara river. This data is the input of the HEC-RAS model for Manning roughness calibration and sediment transport simulation. Another important primary data is the cross section of the river along 1 km upstream and 1 km downstream measured from the confluence of the two rivers. The location of the primary data measurement can be seen in Fig. 3.

Other data in this study as secondary data is daily rainfall data obtained from the Porame rainfall station for the period 2011-2020. This data is used as a transformation material to predict the average discharge due to the unavailability of discharge data. This transformation process also uses other data such as topographic data/digital elevation model (DEM), land use/land cover data and soil characteristics data. DEM data is the basic data for compiling catchment as shown in Fig. 4.



a) Lewara **b) Sombe**

Fig. 2. Landslide at Sombe and Lewara sub-catchments.

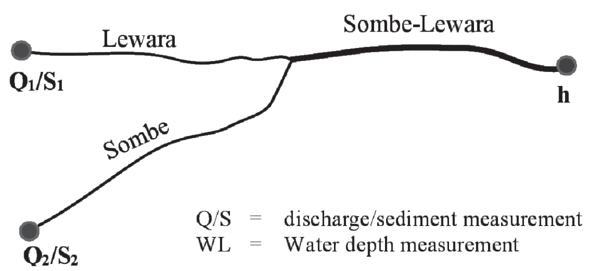


Fig. 3. Detail site of sample measurements.

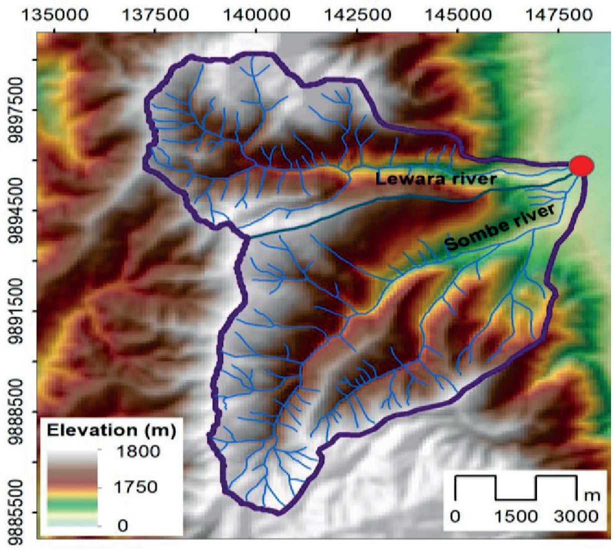


Fig. 4. Sombe-Lewara catchment.

HEC-RAS Hydrodynamic Model

HEC-RAS is a hydrodynamic program that can be applied to calculate the intensity of sediment transport in natural or artificial channels. Fluctuations in transport intensity due to changes in sediment supply from upstream areas cause changes in the bed profile. Changes in the channel bottom profile due to sediment transport are divided into 2 types: degradation and aggradation [13-14]. Degradation is a decrease in the channel bottom due to erosion of the bed channel, while aggradation is an increase in the channel bottom due to sediment deposits transported from upstream. Riverbed degradation occurs because the outgoing sediment transport is lower than the incoming sediment transport. On the other hand, riverbed degradation occurs when the outgoing sediment transport is more than the incoming sediment transport. If sediment transport occurs in a balanced way between in and out, the riverbed will be stable.

There are at least 6 sediment transport equations in the HEC-RAS Model: Ackers-White, Englund-Hansen, Laursen, Toffaleti, Yang, and Meyer-Peter Müller (MPM) equations. This study will apply the last equation considering that in various cases, the MPM equation has been indicated to be quite reliable. This equation is widely used for the calculation of river sediment transport with coarse-grained sedimentary material with a particle size between 0.4 to 29 mm and a specific gravity of 1.25, which is expressed by [15-16]:

$$\left(\frac{k_r}{k'_r}\right)^{\frac{3}{2}} \gamma RS = 0.047(\gamma_s-\gamma)d_m + \left(\frac{\gamma}{g}\right)^{\frac{1}{3}}\left(\frac{\gamma_s-\gamma}{\gamma_s}\right)^{\frac{2}{3}} g_s^{\frac{2}{3}} \quad (1)$$

$$g_s \propto 8\left\{\left(\frac{k_r}{k'_r}\right)^{\frac{3}{2}}\tau^* - 0.047\right\}^{\frac{3}{2}} \quad (2)$$

where: k_r = a roughness coefficient, k_r' = a roughness coefficient based on the grains, γ = unit weight of water (N/m^3), R = hydraulic radius (m), S = energy slope, γ_s = unit weight of sediment (N/m^3), d_m = median diameter of the particle (m), g = gravity acceleration (m^2/s), g_s = rate of unit sediment transport (weight/time/unit width), and τ' = the Shield's stress.

Methods

This research was carried out by hydrodynamic simulation using the HEC-RAS model. As stated in the previous section, the application of this model is intended to predict the bed profile changes caused by flow. Conceptually, bed profile changes can be represented by sediment transport at dominant discharge conditions. The dominant discharge as the input of this hydrodynamic model is expressed by the average discharge over a long period of time. Since discharge data is not available at the study site, this parameter can be obtained from daily rainfall data through the transformation process using the HEC-HMS model.

In addition to the average discharge as the upstream boundary, at the downstream end, normal depth boundary conditions are also set. Sediment data at both upstream boundaries are inputted as grain size gradations. The simulation is performed under quasi-unsteady flow conditions. The profile bed modeling scheme can be seen in Fig. 5.

Results and Discussion

Average Discharge and Sediment Gradation

As introduced in the previous section, the average discharge is obtained from the daily rainfall transformation for the 2011-2020 period in the two sub catchments: Sombe and Lewara. The simulation results using the HEC-HMS Model show that the daily average discharge in the two sub catchments is 1.95 m^3/s and 1.03 m^3/s, respectively. The transformed daily rainfall for 10 years is shown in Fig. 6.

Furthermore, based on the analysis of the gradation of sediment grains at the two sample investigation

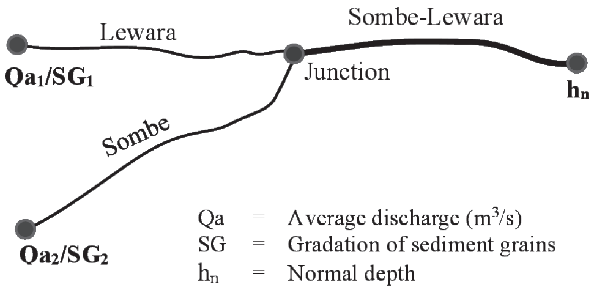


Fig. 5. Geometric schematic of the river in HEC-RAS model.

sites, the results of the sieve analysis indicated that the gradations of the two samples showed similarities at d35, d50, d60 and d90. Both samples show that the type of sediment grain belongs to the sand and coarse gravel group. The grain sizes of the two sediment samples are presented in Table 1.

Table 1. Grainsize of sediment sample.

Grainsize	Diameter (mm)	
	Sombe	Lewara
d35	0.9	0.7
d50	3.1	4.2
d60	5.1	8.2
d90	18	17

Manning Parameter

One of the important parameters in the hydraulic modeling of flow both in the channel and in the river is the roughness parameter. Physically, this parameter can be determined based on the type of bed material and river bank [17]. Channel beds with fine materials tend to trigger higher velocities than coarse materials. The basic material of river beds can be formed from fine sand, coarse sand, gravel, coarse gravel to large rocks. Flow fluctuations in the river affect the bed configuration at any time. Bed configuration becomes stable in dominant discharge conditions. This dominant discharge is a discharge that dominates over a certain period of time, for example 1 year. This discharge is generally close to the minimum discharge in the river.

Simultaneous determination of roughness coefficient can be performed with model calibration. HEC-RAS was performed with measured discharge inputs at both ends of the upstream river (Qm1 and Qm2) with normal depth as the downstream boundary condition (Fig. 7). This normal depth can be expressed by the slope of the riverbed in the downstream section of the junction. The simulated water depth is compared with the observed water depth at a predetermined point (hm). If the two water depths show a small difference, the roughness coefficient that has been set can be considered as a representative roughness coefficient.

A series of ten running models have been performed for calibration as shown in Table 2. Several rougness coefficients have been entered in the HEC-RAS Model which is referred to from the type of bed material which is dominated by sand and gravel. This is done in connection with the unavailability of optimization facilities in this model. For sand and gravel materials, the rougness coefficient ranges from 0.020 to 0.030. The average optimal roughness coefficient representing the various discharge variations was obtained at 0.0265, with the mean difference between the observation water depth and the simulated water depth being 7.6%. The calibration results of the roughness coefficient

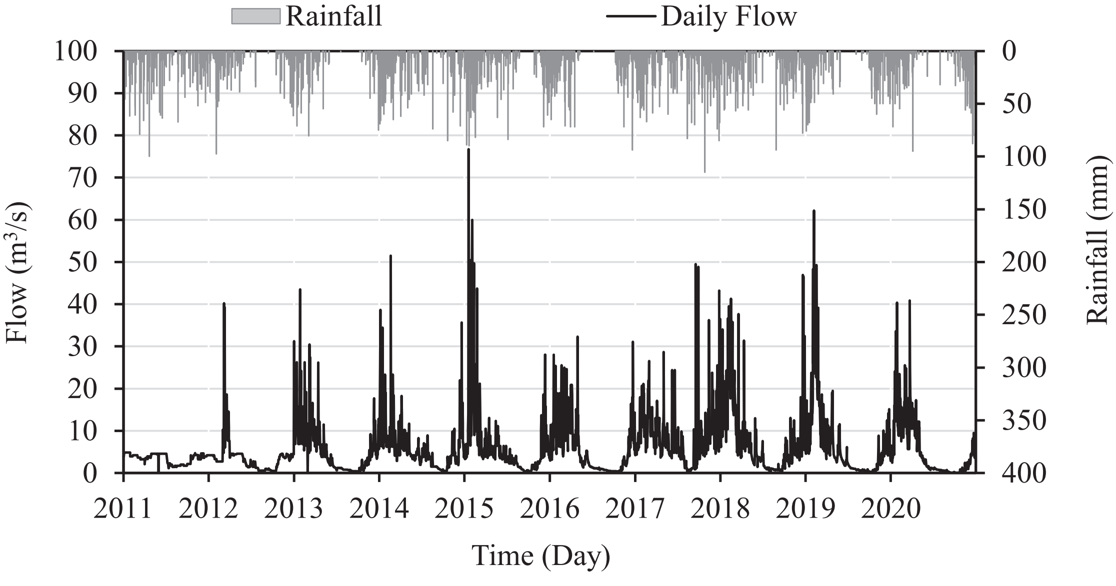


Fig. 6. Daily flow predicted using HEC-HMS for 2011-2020.

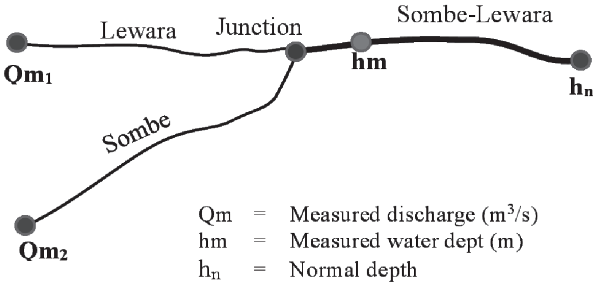


Fig. 7. Calibration scenario for roughness determination.

are indicated to be very satisfactory due to the low water depth deviation. In addition, the correlation between observed and simulated water depth is also very good (Fig. 8a). This performance is also confirmed by the high correlation between the observed discharge and the simulated water depth which is close to 1 (Fig. 8b). This shows that the roughness coefficient of 0.0265 can be applied to represent various depths with regard to sediment debris modeling.

Basically, the coefficient of roughness is a very difficult parameter to determine. This parameter is not only affected by the roughness of the bed material but also the interaction between the bed material and the flow. Friction between the stream and the river bed can increase the roughness. The roughness caused by this interaction is referred to as hydraulic roughness. This roughness is the reference in performing calibration in the HEC-RAS Model.

The important thing that can be observed in determining the roughness coefficient is the dependence between velocity and roughness coefficient. Increasing the flow velocity can increase the roughness coefficient and vice versa. Therefore, the bed roughness under stationary flow conditions is the basic roughness as a reference for determining hydraulic roughness.

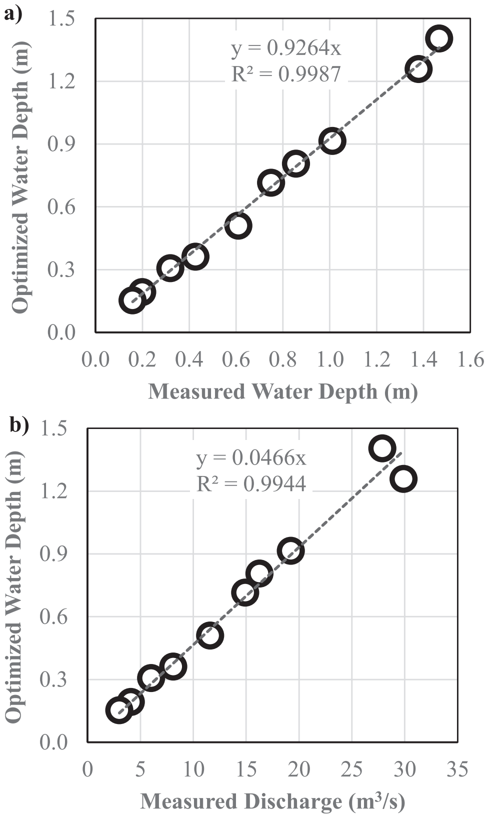


Fig. 8. Relationship between water depth/discharge and optimized water depth/discharge.

Bed Profile

Bed profile analysis is based on the HEC-RAS Model simulation with input average discharge at both upstream boundaries, selected roughness coefficient and normal depth at downstream boundary conditions. The choice of upstream boundary conditions is to

Table 2. Calibration of the roughness coefficient at different discharges.

No.	Discharge (m³/s)		Water Depth (m)		Deviation (%)	Roughness Coefficient (n)
	Lewara (Qm1)	Sombe (Qm2)	Measured (hm)	Optimized (ho)		
1	2.15	3.86	0.32	0.31	4.1	0.0235
2	9.55	20.34	1.38	1.26	8.8	0.0221
3	1.43	2.68	0.20	0.19	3.9	0.0310
4	4.41	7.20	0.61	0.51	16.4	0.0257
5	5.10	9.82	0.75	0.72	4.6	0.0303
6	5.91	10.36	0.86	0.81	5.8	0.0281
7	2.90	5.21	0.43	0.36	15.4	0.0199
8	10.44	17.45	1.47	1.40	4.3	0.0248
9	1.15	1.86	0.16	0.15	3.2	0.0276
10	6.95	12.28	1.01	0.92	9.57	0.0320
Average					7.6	0.0265

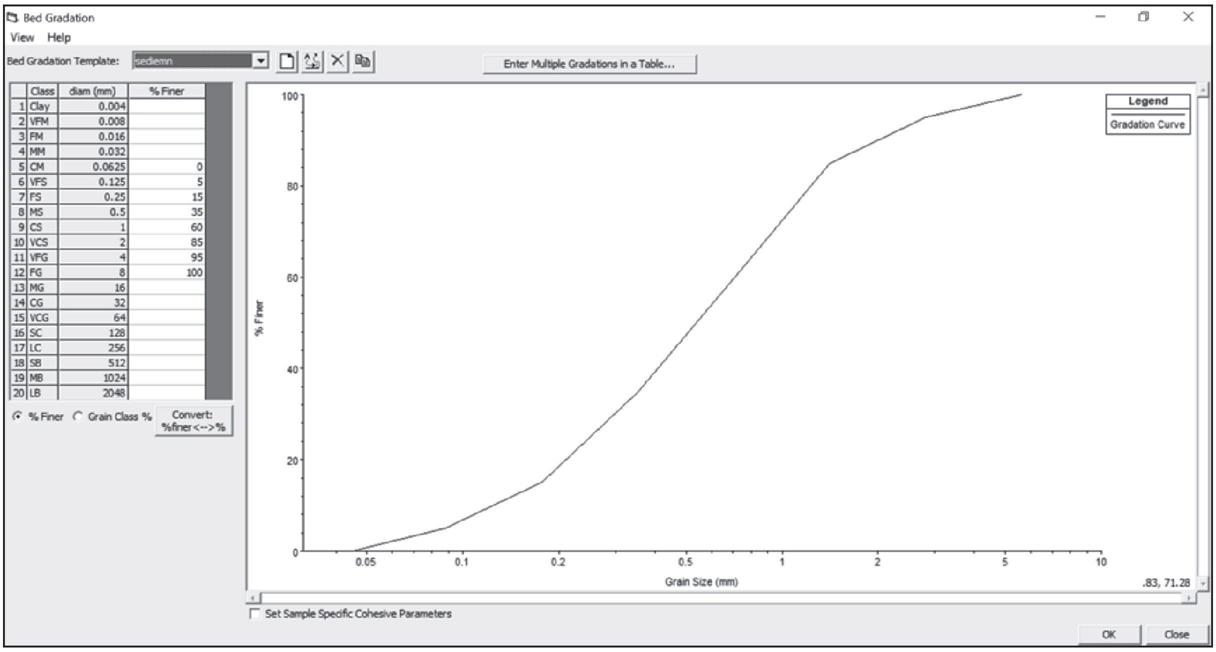
accommodate the dominant discharge as a representation of the bed profile formation in the river. As published by a number of researchers, the bed profile is formed slowly and gradually over a long time due to the interaction of discharge, transported sediment and river cross section [18-19]. At a certain time, dynamic equilibrium will be reached, where the intensity of incoming and outgoing transport is balanced which indicates a stable sediment transport. This can be met if the supply of sediment from the upstream area is constant and stable.

Debris rivers generally carry very large amounts of sediment especially during heavy rainfall. The supply of sediment originating from cliff and slope landslides triggers massive sediment transport and is subsequently deposited in rivers. On other occasions, this deposited sediment will be transported back when the frictional stress triggered by the flow exceeds the critical frictional stress of the sediment. Erosion and sedimentation in the river will fluctuate simultaneously as long as the sediment supply is available continuously from the upstream area.

The definition of sediment transport in the HEC-RAS Model is filled in by inputting the gradation of sediment grains at both ends of the upstream boundary: Sombe and Lewara. Gradation of sediment grains is expressed by the relationship between sediment diameter and % finer (Fig. 9). These two gradation curves can represent the size distribution of sediment in each of the tributaries transported and deposited along the downstream river channel. When examined in detail on the gradation curve in Fig. 9, most of the sediment grains have a coarse fraction and are dominated by gravel. This is related to the nature of the debris flow where the high flow velocity has selected the fine grains to be transported downstream first. Generally, the fine fraction settles in the river mouth where the flow velocity reaches stagnation due to backflow from the estuary. Coarse fractions are generally deposited in the upstream area according to the carrying capacity of the flow that transports them. Likewise, it will erode again along with fluctuations in flow velocity.

The hydraulic simulation of sediment transport to predict bed profile changes can be seen in Fig. 10. The total section modeled is 1420 meters long, consisting of 900 meters downstream of the junction and 520 meters each upstream of the junction. The average bed river slope is relatively uniform both upstream and downstream of the junction, with a slope of more than 1%. This indicates that the Sombe-Lewara river can be categorized as a high-sloping river. This is related to the topographic typology of rivers that empties into the Palu River located in hilly and mountainous areas.

The simulation results show that several basic profile shapes are indicated along the section under review. In general, bed elevations upstream of the junction tend to rise up to 0.30 meters, especially on the inner side of the river cross section. The deposition of sediment in this area is related to the stagnation of flow velocity from the Sombe and Lewara rivers. The streamlines of the two rivers meet at the junction and the meeting of the two streamlines causes velocity stagnation and has an impact on decreasing the carrying capacity of the flow. It has also been suggested by some researchers that flow stagnation creates transported sediment deposits [19-20]. Furthermore, downstream of the junction, scour tends to occur and the bed river has the potential to decrease due to the velocity shift from stagnation to accumulation. The increase in velocity and changes in the cross-sectional width downstream of the junction caused sediment deposition along the segment. However,



Bed Gradation Template: sediemn

	Class	diam (mm)	% Finer
1	Clay	0.004	
2	VFM	0.008	
3	FM	0.016	
4	MM	0.032	
5	CM	0.0625	0
6	VFS	0.125	5
7	FS	0.25	15
8	MS	0.5	35
9	CS	1	60
10	VCS	2	85
11	VFG	4	95
12	FG	8	100
13	MG	16	
14	CG	32	
15	VCG	64	
16	SC	128	
17	LC	256	
18	SB	512	
19	MB	1024	
20	LB	2048	

● % Finer ○ Grain Class %

Fig. 9. The input of sediment gradation at the upstream boundary.

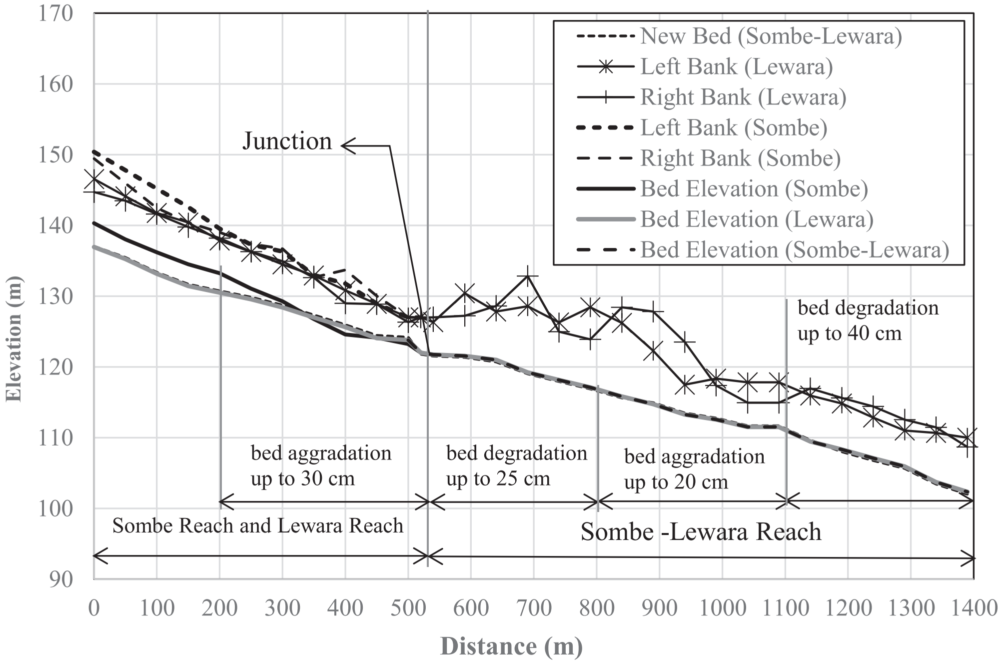


Fig. 10. Bed profile of Sombe-Lewara river.

the shape of this bed profile will continue to change dynamically during sediment and flow fluctuations.

Experimental and numerical studies that have been carried out by Ludeña et al. (2017) stated the formation of backwater in the upstream of the confluence [21]. This backwater is triggered by flow confluence in the stagnation zone. Flow velocity in this zone tends to weaken due to merging streams as also reported by Bilal et al. (2020) who studied sediment transport in river confluence [22]. Sediment grains have the potential to be deposited in this zone related to the weakening of flow due to stagnation, as also confirmed by Smith et al. (2019) which revealed deposition in the upstream and erosion in the downstream confluence [23]. Yang and Cong (2019) state that the cause of sediment deposition in the upstream of the confluence is as a result of streamline convergence at the junction along with reduced shear stress and Froud Number [24]. Therefore Gosh (2022) declared that the confluence represents locations of abrupt change of sediment transport that affect the morphology of the bed profile [25].

Studies on sediment transport in the confluence of river debris have not been widely reported in publications, especially in tropical regions such as Indonesia. Therefore, as the state of the art of this research, the most important point of this study is that the accumulation of flow in the junction affects the velocity of the debris flow. Debris material tends to be deposited upstream of the junction due to flow stagnation, although it is not very significant. If the bed slope of the river is low, the deposition intensity tends to be higher and vice versa. In addition, the concentration of debris flow also affects the rate of deposition. Meanwhile, bed aggradation at the downstream junction is not only caused by an increase in velocity after stagnation, but also as a result of changes in cross-section which can trigger an increase in flow velocity.

Changes in bed profile due to debris flow in the junction segment can be explained by scouring phenomena around the bridge pier. Stagnant flow in front of the pier causes the flow energy to drop momentarily and can cause bed material to be deposited upstream of the pier [15]. Furthermore, the downflow upstream of the pier forms a flow vortex which is known as a vortex, along with increasing turbulent intensity behind the pier. In addition to increasing the turbulence intensity downstream, the vortex also increases the shear stress from the left and right of the pier to a certain distance behind the pier. Increasing the shear stress in the bed causes scouring in a certain pattern [18]. Scouring will begin to weaken in proportion to the decrease in shear stress at a certain distance behind the pier, and then the flow will return to normal. The longitudinal profile scouring around this pier can reflect changes in bed elevation at the junction of debris river segments [19].

However, this research still has limitations in several aspects. This study has not accommodated the confluence angle which can affect the bed profile as stated by Ludeña et al. [21]. Variations in the slope of the bed on confluence have also not been performed in this modeling, where the slope of the bed can also affect velocity at the junction as reported by Yang and Cong [24]. Moreover, this study also did not represent unsteady flow conditions in the river, where the sediment transport simulation in this study was performed under steady flow conditions. Therefore all of these limitations can be improved in further research with the support of more detailed field verification.

Conclusions

The hydraulic simulation has been performed at the confluence segment of the Sombe and Lewara rivers to predict the potential bed profile changes caused by debris flow. The boundary conditions of the model are defined by average discharge at the upstream end of the segment and sediment gradation at the downstream boundary. Manning roughness calibration has been performed through parameter optimization by evaluating the difference between the observed and simulated water levels at the downstream boundary point. Manning roughness represents the material characteristics of the bed and bank which affect the flow velocity and water level along the segment. Verification of transported sediments was not carried out due to limitations of observation data. However, the reliability of the model can be represented by the calibration results of the discharge and water level.

The simulation results show that the river bed elevation at the upstream confluence is higher and at the downstream segment is lower than the initial profile conditions. The increasing of bed profile at the upstream of the junction is caused by the deposition of sediment grains along with the reduced velocity due to stagnant flow originating from the two tributaries, whereas the degradation of the bed at the downstream segment is caused by an increase in velocity due to flow accumulation after the flow stagnates at the junction. The enlargement of the turbulence flow after stagnation causes an increase in erosion energy in the vertical direction to the bottom and the horizontal direction to the bank.

The characteristics of turbulence in each segment of the river vary depending on the intensity of stagnation at the junction. The intensity of stagnation is proportional to the discharge in both tributaries which affects the rate of sediment transport before and after the junction. This phenomenon is similar to the flow characteristics around bridge piers where sediment is deposited upstream of the pier and degraded downstream of the pier. The elongated profile of the scouring around the piers can also illustrate changes in the bed profile at the river junction. In addition, the bed elevation next to the downstream junction can also fluctuate due to various factors such as changes in cross section, bed slope, hydraulic structures, back water, and others. The results of this study become a reference for sediment control due to debris flow at river confluence.

Acknowledgments

This work was funded by DIPA Pascasarjana Research Grant of Universitas Tadulako Number: 3655/UN28/KU/2022, April 11th, 2022. Authors thank the head of Pascasarjana for supporting this work.

Conflict of Interest

The authors declare no conflict of interest.

References

1. SALAMATIAN S.A., ZARRATI A.R., KARIMAEE M. Sediment transport in unsteady flow conditions. Journal of Water Sciences Research, **6** (1), 59, **2014**.
2. RALSTON D.K., STACEY M.T. Tidal and meteorological forcing of sediment transport in tributary mudflat channels. Continental Shelf Research, **27** (10-11), 1510, **2007**.
3. UNDE M.G., DHAKAL S. Sediment characteristics at river confluences: a case study of the Mula-Kas confluence, Maharashtra, India. Progress in Physical Geography: Earth and Environment, **33** (2), 208, **2009**.
4. BEST J.L. Sediment transport and bed morphology at river channel confluences. Sedimentology, **35**, 481, **1988**.
5. AZARANG F., TELVARI A.R., SEDGHI H., BAJESTAN M.S. Application of HEC-RAS model for evaluating erosion and sedimentation of Karkheh river. Ecology, Environment and Conservation Paper, **21** (4), 49, **2015**.
6. LUDEÑA G.S., CHENG Z., CONSTANTINESCU G., FRANCA M.J. Hydrodynamics of mountain-river confluences and its relationship to sediment transport. Journal of Geophysical Research: Earth Surface, **122** (4), 901, **2017**.
7. ZHANG T., FENG M., CHEN K. Hydrodynamic characteristics and channel morphodynamics at a large asymmetrical confluence with a high sediment-load main channel. Geomorphology, **356** (107066), 1, **2020**.
8. SAFAR M., ISHAK M.G., TUNAS I.G. Analysis of erosion and sediment movement at the confluence of two rivers (A case study of Tawaeli river, Central Sulawesi, Indonesia). International Journal of Design & Nature and Ecodynamics, **17** (1), 55, **2022**.
9. BAWIAS Y.A. Effect of sand mining activity on the sediment control system (a case study of Sombe-Lewara river, Donggala, Indonesia). Journal of the Civil Engineering Forum (JCEF), **21** (1), 1191, **2012**.
10. EDISON E., BISRI M., SUHARTANTO, E. Study of conservation technology to reduce erosion rates in the Sombe Lewara Sub-watershed, Central Sulawesi province. Jurnal Teknik Pengairan, **3** (2), 204, **2013** [In Indonesian].
11. PRATAMA M.I., LEGONO D., RAHARJO A.P. Analysis of sediment transport and the effect of mining activities in Sombe river, Palu city, Central Sulawesi. Jurnal Teknik Pengairan, **10** (2), 84, **2019** [In Indonesian].
12. PRATAMA M.I. Sediment transport using the Yang Method in Sombe river, Palu, Central Sulawesi. Rekonstruksi Tadulako: Civil Engineering Journal on Research and Development, **2** (1), 33, **2021** [In Indonesian].
13. MAJOR J.J. Depositional processes in large-scale debris-flow experiments. The Journal of Geology, **105** (3), 345, **1997**.
14. PAPA M., EGASHIRA S., ITOH T. Critical conditions of bed sediment entrainment due to debris flow. Natural Hazards and Earth System Sciences, **4**, 469, **2004**.
15. TANG H., MCGUIRE L.A., RENGERS F.K., KEAN J.W., STALEY D.M., Smith J.B. Evolution of debris-flow initiation mechanisms and sediment sources during a sequence of postwildfire rainstorms. Journal of Geophysical Research: Earth Surface, **124**, 1572, **2019**.

16. EGASHIRA S., ITOH T., TAKEUCHI H. Transition mechanism of debris flows over rigid bed to over erodible bed. Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, **26** (2), 169, **2001**.
17. HABIB-UR-REHMAN, CHAUDHRY M.A., NAEEM U., HASHMI H.N. Performance evaluation of 1-D numerical model HEC-RAS towards modeling sediment depositions and sediment flushing operations for the reservoirs. Environmental Monitoring and Assessment, **190** (433), 1, **2018**.
18. RIBEIRO L.M., BLANCKAERT K., ROY A.G., SCHLEISS A.J. Flow and sediment dynamics in channel confluences. Journal of Geophysical Research: Earth Surface, **117** (F01035). 1, **2012**.
19. THEULE J.I., LIÉBAULT F., LAIGLE D., LOYE A., JABOYEDOFF M. Channel scour and fill by debris flows and bedload transport. Geomorphology, **243**, 92, **2015**.
20. MUGADE U.R., SAPKAL J.B. Influence of aggradation and degradation on river channels: a review. International Journal of Engineering and Technical Research (IJETR), **3** (6), 209, **2015**.
21. LUDEÑA S.G., CHENG Z., CONSTANTINESCU G., FRANCA M.J. Hydrodynamics of mountain-river confluences and its relationship to sediment transport. Journal of Geophysical Research: Earth Surface, **122**, 901, **201**7.
22. BILAL A., XIE Q, ZHAI Y. Flow, sediment, and morphodynamics of river confluence in tidal and non-tidal environments. Journal of Marine Science and Engineering, **8**, 591, **2020**.
23. SMITH G.H.S., NICHOLAS A.P., BEST J.L. BULL J.M., DIXON S.J., GOODBRED S., SARKER M.H., VARDY M.E. The sedimentology of river confluences. Sedimentology, **66**, 391, **2019**.
24. YANG H., CONG P. Confluence dynamics in a modelled large sand-bed braided river. Water, **11**, 1829, **2019**.
25. GHOSH K.G. Sediment transport at the river confluences: few observations from a sub-tropical plateau fringe river of eastern India. Geology, Ecology and Landscapes, **6** (2), 75, **2022**.