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Sediment transport modelling at river confluence using HEC-RAS2D

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ABSTRACT

Sediment deposition is a serious issue in river channels, especially at river confluences. Massive sediment deposition triggered by flow stagnation causes changes in riverbed cross-section and morphology. The capacity of the river cross-section decreases along with the increase in sediment deposition in the area. This paper aims to simulate sediment transport at the confluence of the Palu and Sombe-Lewara Rivers, one of the rivers with sedimentation issues in Central Sulawesi, Indonesia. The simulation is performed with the HEC-RAS2D model to predict sediment transport rates and bed morphology changes due to flooding. Supporting data for this model are discharge data transformed from rainfall data with a return period of 50 years, DEM data generated from field measurement data, and sediment grain gradation data obtained from sieve analysis of field sediment samples. The formation of mesh/grid as the basis for numerical modeling is performed on the RAS Mapper module based on DEM data of the study area. The DEM resolution is a reference in determining the mesh/grid distance which will ultimately affect the accuracy of predictions of water level, sediment transport and bed morphology changes. Calibration has also been done by assessing observed and simulated water levels and obtaining the optimal Manning roughness coefficient of 0.037. The results of the study indicate that the flow velocity is distributed in the transverse direction at the river confluence. The velocity increases on the left and right sides of the stagnation line, respectively reaching 3.5 m/s and 5.7 m/s at discharge in the Sombe Lewara River of 40 m^3/sec and 650 m^3/sec in the Palu River. Furthermore, the velocity gradually decreases towards the river bank along with the decreasing influence of secondary currents. The sediment transport rate at the river confluence is 0.21 m^3/s and 1.45 m^3/s respectively, comparable to the sediment supply from the upstream catchment. The sedimentation pattern follows the velocity distribution where the riverbed is graded on the left side of the flow stagnation line reaching 1.2 m.

Keywords: bed morphology, stream juction, secondary, 2D modelling.

INTRODUCTION

Sediment transport and bed morphology at river confluences are still interesting topics to study. In addition to the complexity of flow behavior that triggers transport, a number of variables that affect flow have not been fully revealed and accommodated in the mathematical formula for sediment transport (Ali et al., 2019). Sediment transport equations also continue to develop along with laboratory experimental results that have not been fully represented in mathematical model predictions. In various applications, existing formulas can provide deviations of more than 100%. Calibration and verification of parameters are very important in the application of mathematical models, although relatively hard to do in relation to very random bed morphology (Costabile and Macchione, 2015). The physical laboratory approach has also not been able to fully describe transport phenomena, especially due to secondary currents both at river confluences and in river beds.

The main issue as the impact of hydrodynamic behavior at river confluence is represented by the geometry shape of cross-section profile both vertically and horizontally (Schindfessel et al., 2017; Czuba et al., 2019). It is relatively hard to illustrate the base morphology at river confluence in relation to the impact of secondary currents triggered by flow turbulence (He et al., 2015; Hackney et al., 2018). As in the study location, at the confluence of the Palu River and the Sombe Lewara River, Sulawesi, Indonesia, the shape of the river bed surface is very irregular which is characterized by shallowing of the bed on the left bank of the main river (Tunas et al., 2024). This sedimentation form is very fluctuating depending on the transport rate and discharge originating from both river branches. The unbalanced transport rate in both upstream river branches causes sediment deposition on the weak side. Often, changes in the basic morphology also cause a decrease in the capacity of the river cross-section.

Research related to sediment transport analysis at river confluences was initiated by studying currents as a trigger for material transport. Various study results show that the current phenomenon at river confluences is very different from the current in rivers in general. The characteristics of currents at river confluences are relatively similar to currents at river bends, where flow turbulence triggers the formation of secondary currents that affect sediment transport. Baranya et al. (2015) have conducted a study of flow at river confluence using field data and a nested grid technique RANS model. The application of this hybrid approach shows that flow turbulence due to the meeting of two currents causes the formation of a stagnation zone that affects the streamline downstream of the junction. Nicoară et al. (2018) also reported similar results by applying 1D and 2D numerical models to study the flow pattern at river confluences. The accuracy of the model was evaluated by the results of current measurements downstream of the junction. Furthermore, Penna et al. (2018) and Shen et al. (2022) each analyzed the effect of the junction angle on the flow pattern. Both researchers agreed that the junction angle is one of the factors that influences flow turbulence.

The characteristics of the flow at the river confluence play a major role in determining the pattern and rate of sediment transport. Several researchers have published their research results related to this both in laboratory experimental scale and mathematical modeling using numerical approaches. Martín-Vide et al. (2015) specifically looked at the distribution of bedload in terms of texture and space, as well as the quantification of the overall bedload and the balance between the main river and its tributaries. They came to the conclusion that whereas tributary bedload transit occurs at capacity, main river bedload transport typically occurs below capacity. Still in the same study, Ludeña et al. (2017) conducted a numerical study on mountain river confluence hydrodynamics and its connection to sediment movement and compared it with the results of laboratory experiments. There is a connection between the flow and sediment transport because the expected patterns of bed shear stress are connected to the sediment movement channels that were observed during the laboratory trials.

Bed morphology and its influence on flow hydrodynamics in river confluences have also been studied by Sukhodolov and Sukhodolova (2019). The studies were carried out in a physical model with a large width-to-depth ratio to allow accurate identification of flow structures at various scales, while also removing the influence of bed shape. The findings demonstrate that the curvature of flow paths, which is impacted by bed morphology, is the main factor driving the helical secondary flow. Further studies on bed morphology at river confluences were carried out by Xie et al. (2020) and AlQasimi and Mahdi (2020) who studied flow and sediment behavior using Delft3D and SRH-2D models. The 3D study showed that in fluvial rivers, a diffluence and a confluence constitute a fundamental unit that influences the flow and sediment routing, ultimately resulting in changes to the river bedform. The modeling results using SRH-2D also showed the same tendency that the bedform of fluvial rivers is very dynamic depending on various triggering factors, especially secondary currents.

This paper tries to perform another approach in studying sediment transport at river confluence due to secondary current using HEC-RAS2D model. This freeware is established with 2D numerical based on finite volume method that is able to simulate sediment transport. The simplicity of the program structure, ease of application, the requirement of computer specifications and storage device space that are not too high are important reasons in choosing this model. In addition, the accuracy of the modeling results can be evaluated by setting the weighting factor in the applied numerical scheme. The application of this model to simulate sediment transport at river confluence has not been seen in scientific publications so far. Therefore, the study in this paper will be very important in relation to other approaches in modeling bed morphology at river confluences that will enrich user choices in modeling sediment transport. Ultimately, the results of this study, in addition to being beneficial in the development of science and technology, can also be a reference in managing bed morphology at the study site.

MATERIAL AND METHODS

Study area

The confluence of the Palu River and the Sombe-Lewara River as the location point of this study lies at the geographical coordinates: 119°52'11.44"E and 0°54'53.07"S (Figure 1). Administratively, this site is located in Palu City, Central Sulawesi, Indonesia. The issue of sedimentation and erosion at this location is the reason for choosing the location and topic in relation to river maintenance efforts and sediment management at the river confluence (Tunas and Maadji, 2018; Tunas et al., 2019). The Palu River is a main river with a catchment area of around 2826.005 km^2 (Figure 2a), while the Sombe-Lewara River is its tributary with a catchment area of 112.07 km^2 (Figure 2b). This tributary has very different characteristics from the Palu River, where its flow is dominated by sediment material, especially during floods. Due to the massive sediment material transported, the Sombe-Lewara River is known as one of the debris rivers in Central Sulawesi. Debris material is generally deposited almost along the river channel, especially in the downstream section as the slope of the river bed decreases. The fluctuation of river discharge is relatively large between the rainy season and the dry season. River discharge can be less than 1 m^3/s in the dry season and can reach more than 50 m^3/s in the rainy season.

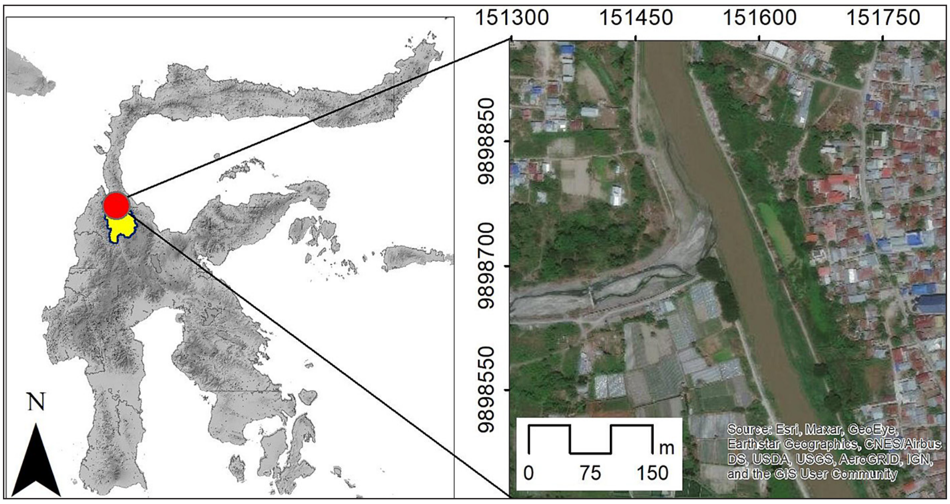


Figure 1. Study site at confluence of Palu and Sombe-Lewara river

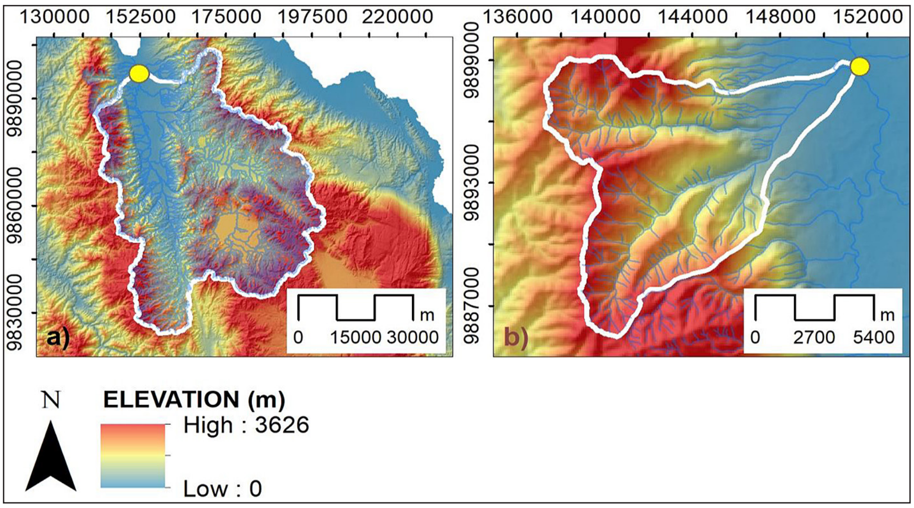


Figure 2. Topographic map of study area: (a) Palu catchment, (b). Sombe-Lewara catchment

Unlike the Sombe-Lewara River, the Palu River is a river with a relatively large discharge supply during the dry season in proportion to its catchment area. This main river has a multifunction as a supplier of irrigation water, raw water and mini hydro-power. Sediment transport generally comes predominantly from tributaries in the middle and downstream segments such as the Bangga, Rogo, Poi, Sambo and Wera rivers on the west side and the Wuno, Paneki, Mamara, Kawatuna and Poboya rivers on the east side. This sediment transport also fluctuates throughout the year following discharge fluctuations influenced by rainfall intensity and physical characteristics of the catchment, especially land use and cover (LULC). Changes in land cover in the middle and downstream parts of the Palu catchment (Figure 3a) and in almost the entire area of the Sombe-Lewara catchment (Figure 3b) have also triggered an increase in sediment transport in both the Palu River and the Sombe-Lewara River. Sediment deposits in the Palu River are generally found on the inside of river bends and in areas where the flow meets its tributaries. The massive sediment deposition at these points causes changes in the characteristics of the meander and the shape of the cross-section at the river confluence. In this regard, handling sediment at bends and river confluences is a strategic issue in the current management of the Palu catchment.

Data

Present research utilizes a number of supporting data, including: design flood, DEM with coverage area of river confluence and sediment grain gradation in both river branches. Design flood is determined based on rainfall-runoff transformation using HEC-HMS model. Discharge with a return period of 50-years is applied as input to HEC-RAS2D model that has been calibrated. 40 m^3/s and 650 m^3/s are input discharge at each upstream boundary of Sombe-Lewara River and Palu River. Furthermore, river geometry is formed from DEM transformed from hybrid data: drone coverage and terrestrial measurements. The combination of these two types of data is performed with QGIS and it is converted into DEM using GRASS plugin, one of the open source GIS software. This DEM data is applied as the main layer in RAS mapper as the basis for forming river mesh geometry.

Other important data in modeling sediment transport and bed morphology at river confluences is sediment gradation data. This data was obtained from direct measurements in both river channels: Sombe-Lewara and Palu rivers using bed-load sediment samplers. Laboratory examinations were carried out using sieve analysis to determine the gradation of sediment grains which were presented as grain gradation curves.

2D transport sediment formula

Since the release of version 5.0 in October 2014, HEC-RAS has had the ability to simulate unsteady two-dimensional horizontal (2DH) flow by implicitly applying the finite-volume and finite-difference methods on an unstructured orthogonal mesh to solve the diffusion-wave equation or the non-conservative shallow water equations. However, in the next version (6.0) in May 2021, HEC-RAS can be used for 2D analysis of sediment transport and bed morphology change. Numerous aspects of the sediment model include mixed cohesive/noncohesive transport, different grain classes, and a unique method for subgrid sediment transport and morphological change.

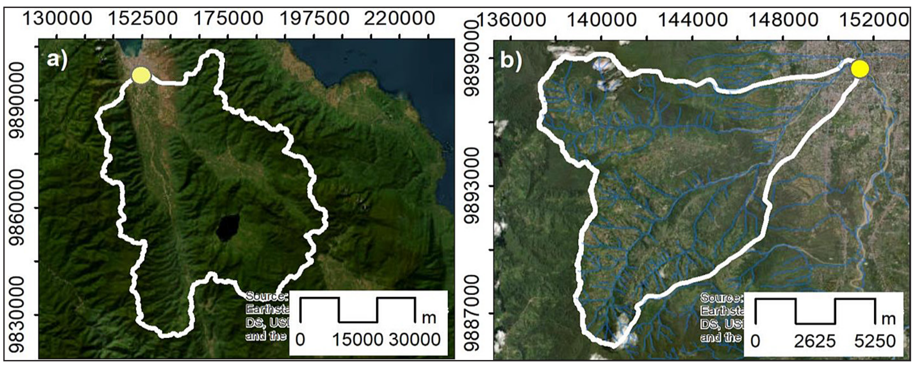


Figure 3. Land cover of study area: (a). Palu catchment, (b) Sombe-Lewara catchment

The bed-material transport equation which represents the total load transport is solved by separating into bedload and suspended-loads using empirical formulas. All particles carried together make up the total-load sediment movement. The equation for total-load transport can be expressed as (Al-Jubouri et al., 2024):

$$\frac{\partial}{\partial t}\left(\frac{hC_{tk}}{\beta_{tk}}\right) + \nabla \cdot (hUC_{tk}) = \\ = \nabla \cdot (\varepsilon_{tk} h \nabla C_{tk}) + E_{tk}^{HF} - D_{tk}^{HF} + S_{tk} \quad (1)$$

where: h – water depth (m), C_{tk} – concentration of the k[th] grain class's total-load sediment (kg/m^3), β_{tk} – adjustment factor for total load in the kth grain class, U – depth-averaged velocity of the current in j[th] direction (m/s), ε_{tk} – total-load mixing (diffusion) coefficient for the k[th] grain class, E_{tk}^{HF} – rate of erosion of the entire load in hydraulic flow (kg/m^{2}s), D_{tk}^{HF} – rate of deposition of the entire load in hydraulic flow (kg/m^{2}s), and S_{tk} – source/sink total-load term (kg/m^{2}s).

An important parameter in determining the total load transport is the bed-load velocity which describes the mean particle speed during transportation. Three formulas are adopted by HEC-RAS to define the bed-load velocity: Phillips and Sutherland, van Rijn and van Rijn-Wu, which are written respectively as (USACE, 2023):

$$u_{bk} = 8.5\left[\frac{\tau_b'}{\rho_w} max\left\{1 - \left(\frac{\tau_{crk}}{\tau_b'}\right)^{\frac{1}{2}}, 0\right\}\right]^{\frac{1}{2}} \quad (2)$$

$$\frac{u_{bk}}{\sqrt{R_k g d_k}} = 1.5\, max\left(\frac{\tau_{crk}}{\tau_b'} - 1.0\right)^{0.6} \quad (3)$$

$$\frac{u_{bk}}{\sqrt{R_k g d_k}} = 1.64\, max\left(\frac{\tau_{crk}}{\tau_b'} - 1.0\right)^{0.5} \quad (4)$$

where: u_{bk} – bed-load velocity (m/s), τ'_b – bed shear tension associated with grains (kg/m·s^2), ρ_w – density of water (kg/m^3), τ_{crk} – bed shear stress criticality for the k[th] size class (kg/m·s^2), R_k – specific gravity immersed for the k[th] grain class, g – constancy of gravity (~9.81 m/s^2). and d_k – grain diameter characteristic for the k[th] size class (mm).

As previously informed, the total load is the sum of bed load and suspended load. Suspended load in HEC-RAS2D is expressed as the fraction of suspended sediment using the equation (USACE, 2023):

$$r_{sk} = \frac{q_{sk}}{q_{tk}} \quad (5)$$

where: r_{sk} – proportion of sediments in suspension, and q_{sk} – transport rate for suspended loads (kg/m·s). The fraction of sediments in suspension is estimated by the parameter of transport mode (f_{sk}) which is ratio between suspended-load (q^*_{sk}) and total-load transport potential rates (q^*_{tk}):

$$r_{sk} \approx f_{sk} = \frac{q^*_{sk}}{q^*_{tk}} \quad (6)$$

Transport mode parameters can be estimated by a number of methods, such as: Transport capacity method, Rouse parameter method of Greimann, van Rijn and Jones and Lick. q^*_{tk} can be calculated with several formulas, as follows: Ackers and White, Engelund-Hansen, Laursen-Copeland, Meyer-Peter and Müller, Soulsby-van Rijn, Toffaleti, Van Rijn, Wilcock and Crowe, Wu, and Yang (USACE, 2023). This total-load transport potential rate can then be used to predict concentration potential of the k[th] grain class's total-load sediment (C^*_{tk}), as:

$$C^*_{tk} = \frac{q^*_{tk}}{Uh} \quad (7)$$

Based on the total load transport, the change in bed elevation as a representation of bed morphology can be calculated using the formula:

$$\rho_{sk}(1 - \phi_b)\left(\frac{\partial zb}{\partial t}\right)_k = \\ = D_{tk} - E_{tk} + \nabla \cdot (\kappa_{bk}|q_{bk}|\nabla_{zb}) \quad (8)$$

where: ρ_{sk} – particle density for grain class (kg/m^3), ϕ_b – the degraded and deposited material's porosity, zb – elevation of the bed with relation to the vertical datum (m), D_{tk} – rate of total load deposition (kg/m^2.sec), E_{tk} – rate of total load erosion empirical grain class bed-slope coefficient (kg/m^2.sec), κ_{bk} – magnitude of the bed-load mass transfer rate (kg/m·s), and $|q_{bk}|$ – empirical grain class bed-slope coefficient.

RESULT AND DISCUSSION

The flow discharge applied in this analysis is as in Table 1, with a peak discharge of 40 m^3/sec in the Sombe-Lewara River and 650 m^3/sec in the Palu

Table 1. Discharge of Sombe-Lewara River and Palu River at 50 year return period

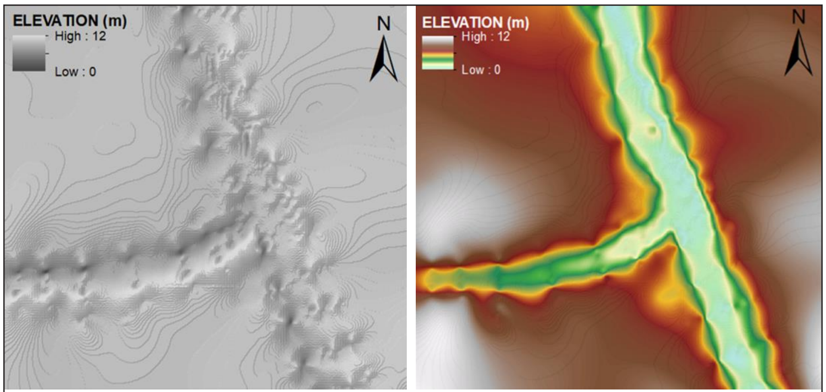
RIver	Discharge (m^3/sec)	Average channel width (m)	Catchment area (km^2)
Sombe-Lewra	40	30	112.07
Palu	650	90	2826.005

River. This return period discharge is obtained from the rainfall-runoff transformation using the HEC-HMS model with inputs of rainfall intensity, land cover and soil characteristics in each basin model. This discharge is proportional to the catchment area of each river by considering the distribution of rainfall throughout the catchment area.

Flow modelling

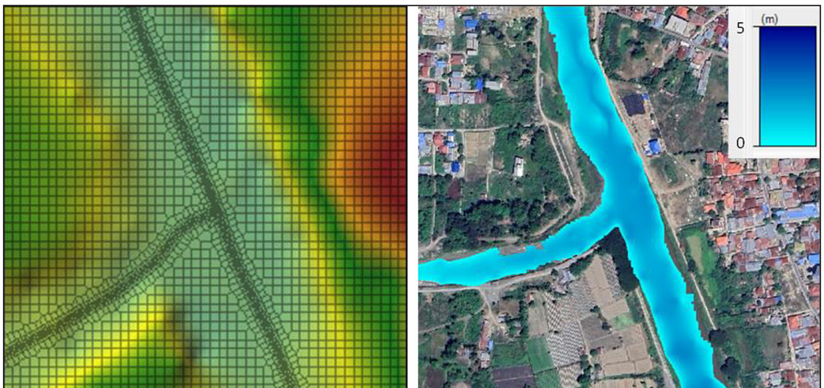
Flow modelling is intended to identify flow characteristics that affect sediment transport at river confluences based on two boundary condition, discharge as the upstream boundary condition and water depth as the downstream boundary condition. These flow characteristics include flow depth, water surface elevation and velocity distribution in the longitudinal and transverse directions of the river. Flow modelling is performed with the HEC-RAS2D model with the main geometry as in Figure 4 with the type of hillshade DEM (Figure 4a) and standard DEM (Figure 4b). This DEM was obtained from a hybrid survey using drones on land, total stations in shallow waters and eco-sounders in deep waters. The depth of the Palu River can reach more than 1 m while the depth of the Sombe-Lewara River is no more than 0.5 m. These two rivers have different typologies both in discharge and sediment transport.

Furthermore, the river geometry is transformed into a square grid (Figure 5a) with the size of the X and Y directions of 2 m each following the utilized DEM resolution. This grid size can affect the stability and accuracy of the simulation.



a) hillshade DEM b) DEM

Figure 4. DEM of river confluence



a). grid b). water depth

Figure 5. Domain grid and water surface elevations at river confluence

The grid size is set smaller in the river channel in relation to the desired simulation accuracy. The focus of the analysis applied is along the river channel. The minimum grid size limit in the river channel is 0.5 m in relation to the DEM resolution as the model geometry is generally not less than 1 m. This DEM resolution is considered very representative to describe the topography of the river bed, especially in low-slope segments.

The 2D simulation produces three main flow parameters, namely: water depth (Figure 5b), water surface elevation (Figure 6a) and velocity distribution (Figure 6b). The flow depth in both rivers varies from the edge to the middle of the river channel reaching 4.35 m (Palu River) at a 50-year return period discharge. This flow depth corresponds to the water surface elevation throughout the domain, which also varies between 5 m and 10 m. The water surface elevation at some points can exceed the river bank elevation. This implies that the capacity of the Palu River cross-section is below the 50-year return period. The flow depth trend also corresponds to the flow velocity as shown in Figure 6b. The flow velocity increases with increasing depth. The flow velocity at this river confluence can reach 6 m/sec and is distributed both in the transverse direction of the river and in the longitudinal direction of the river. The flow velocity at the river confluence is influenced by various factors, such as discharge and the geometric characteristics of the river confluence including the angle, bed slope and bed width of each river branch. As shown in Figure 6b, a stagnation zone is formed at the transition of the Sombe-Lewara River and Palu River confluence. This stagnation zone is formed due to the meeting of two flows originating from both river branches. This stagnation zone triggers secondary current movement due to turbulence on the left and right sides. As the secondary current weakens downstream, the stagnation zone gradually fades and the flow velocity returns to normal. In general, the flow velocity at the lower corner of the river confluence is very weak. This is related to the change in streamline direction due to the meeting of two flows at the river confluence (Chabokpour and Azamathulla, 2022). The angle of the river confluence has a major effect on the decrease in velocity at this point. Large streamline changes can occur at small river confluence angles. This indicates that increasing river confluence angles is inversely proportional to streamline changes.

Comparison with SMS model

Due to the complexity of flow behaviours at river confluence, hydrodynamic analysis in this study is compared with SMS modeming with the same geometry and input data. Basically, the governing equations applied are relatively similar, but the numerical solution uses a different approach. The numerical method applied in HEC-RAS2D is based on the finite volume method (FVM), while the SMS Model uses the finite element method (FEM) approach. The use of different numerical approaches has an impact on the grid assigned to the modelling domain. Structural grids are used in the HEC-RAS2D Model while in the SMS Model, the grid shape can vary which is a combination of structural grids and unistructural grids. Therefore, the grid shape in the SMS Model is better known as a mesh due to the various grid shapes and sizes. The implementation of meshes in the SMS Model can be more beneficial especially when applied to irregular domains. In areas that require special

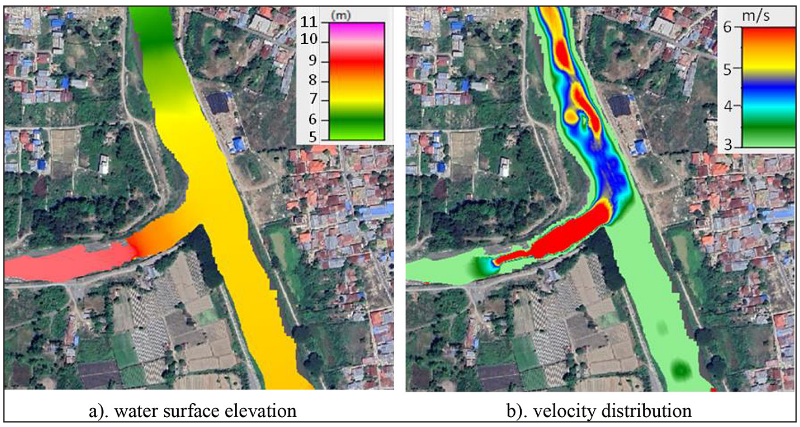
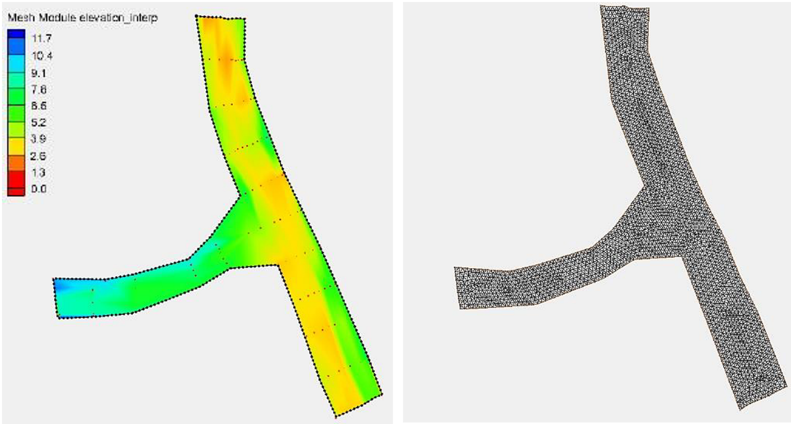


Figure 6. Water surface elevation and velocity distributions at river confluence

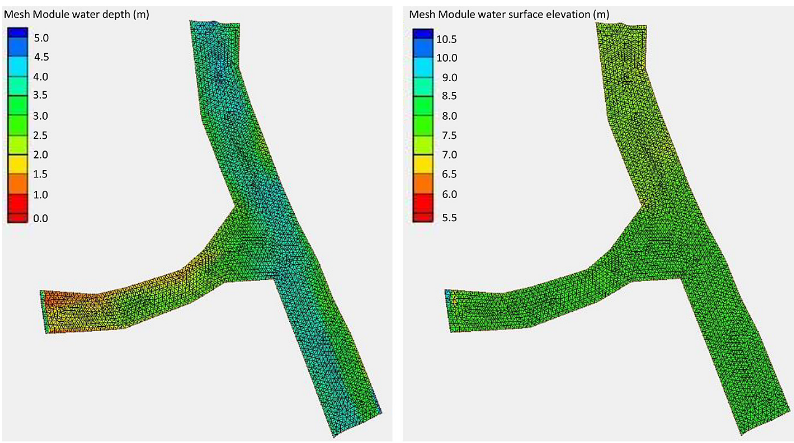


a). bed elevation b). mesh

Figure 7. Bed elevation and mesh

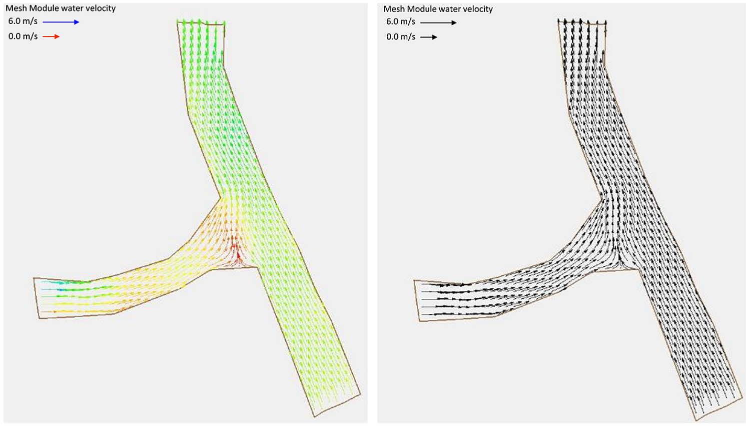
emphasis, the mesh size can be smaller depending on the accuracy of the expected results.

The geometry data in the SMS Model can be seen in Figure 7a with DEM input as applied to the HEC-RAS2D Model with elevations between 0 m and 12 m. Mesh generation is done by the triangulation method with a mesh shape as in Figure 7b. This mesh size can be adjusted to the domain shape, especially along the boundary domain. The nodes connecting the mesh boundary lines represent the elevation points throughout the domain. The number of nodes is proportional to the number of meshes that illustrate the element network. In large areas with low topographic slopes, the mesh size can be larger than the mesh size in small areas. The size and number of meshes, in addition to providing advantages in the accuracy of the results, also provide disadvantages in simulation time. Therefore, the size and number of meshes can be considered based on the characteristics of the domain. The SMS Model simulation results are shown in Figure 8 for water depth and water surface elevation and Figure 9 for velocities distribution and vector. Water depth and water surface elevation as illustrated in Figure 8a and Figure 8b are not much different from the HEC-RAS2D simulation results. These simulation results can confirm that the flow depth across the domain ranges from 0 m to 5 m. However, differences in simulation results are unavoidable due to the numerical approach applied to both models (de Arruda Gomes etv al., 2021). Likewise, the velocity distribution illustrates the similarity to the velocity distribution in the HEC-RAS2D Model. The velocity vector as shown in Figure 9 shows more clearly the stagnation line where the flow direction turns and forms a streamline. In this zone, the flow velocity weakens, indicated by changes in the velocity vector as illustrated in Figure 9.



a). water depth b). water surface elevation

Figure 8. Water depth and water surface elevation



a). velocity distribution b). velocity vector

Figure 9. Velocities distribution and vector

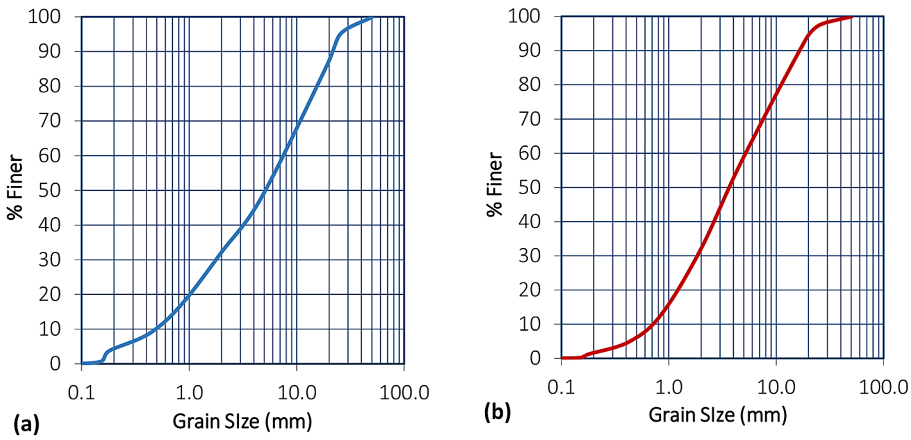


Figure 10. Sediment gradation in the middle channel study site: a) Sombe-Lewara river, b) Palu river

Sediment transport

Sediment transport analysis in the study site is based on the input of sediment grain gradation as shown in Figure 10. Figure 10a presents the sediment grain gradation curve in the Sombe-Lewara River with a D50 of 8 mm and Figure 10b displays the sediment grain gradation curve in the Palu River with a D50 of 3. Sediment grain gradation represented by D50 affects the rate of sediment transport and changes in bed morphology. It can be seen that the grain size of the Sombe-Lewara River is relatively larger than the sediment grain size of the Palu River.

The simulation results show that the sediment transport rate in the two rivers is very different, each of 0.21 m^3/sec and 1.45 m^3/sec. However, the sediment transport rate of the Sombe-Lewara River is relatively very large compared to the Palu River when referring to the catchment area of Sombe-Lewara which is relatively small compared to the catchment area of Palu. The transport rate at the confluence of these rivers affects the sedimentation pattern, especially in the stagnation zone. The shallowing of the riverbed on the left side of the stagnation zone approaching the lower corner of the river confluence can reach 1.2 m.

CONCLUSIONS

An important study was conducted by performing the HEC-RAS2D Model to simulate sediment transport and bed morphology changes at the confluence of the Palu and Sombe Lewara rivers, Central Sulawesi, Indonesia. This site is a very interesting object to study, due to the continuous sediment deposition due to the confluence of two currents originating from both river branches. Sediment gradation data directly trapped in both river branches were utilized as the main input of the HEC-RAS2D Model. In addition, the 50-year periodic design flood was employed in the hydrodynamic model as a sediment transporter.

The results of the study indicate that secondary currents formed due to flow turbulence affect the rate of sediment transport, especially in the left and right areas of the stagnation zone. The sediment transport rate in both rivers reaches 0.21 m^3/s in the Sombe-Leawara River and 1.45 m^3/s in the Palu River. Sediment deposition due to the interaction of transport rate and velocity distribution can reach 1.2 m especially in the area of current weakening around the stagnation zone.

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