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Enhancing disaster mitigation through sediment transport modelling – Development of natural based solutions for the future

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Abstract: One of the key causes of floods is the reduced river storage capacity due to sedimentation. In this context, an oxbow lake currently functions as a retention pond, serving as an alternative nature-based solution (NbS). However, because retention ponds are highly susceptible to sediment accumulation, it is crucial to undertake a comprehensive study to develop effective strategies for managing flooding and sedimentation. This study aimed to establish a sediment rating curve and a sediment transport model for the Krueng Peuto River. The sediment rating curve, which describes the relationship between flow discharge and sediment discharge, is a crucial component of the analysis. In this study, sediment transport was modelled using the HEC-RAS 6.1 application. This application is capable of dynamically updating and more accurately approximating the channel morphology as the simulation progresses,, making it very useful for long-term analyses of riverbed morphology changes due to sediment transport. The results indicated that the sediment shear stress was greater than the critical shear stress ($\tau_0 > \tau_c$), confirming that sediment transport occurs in the Krueng Peuto River. The sediment rating curve showed the following polynomial regression equation obtained of $Q_s = 0.0142Q_w^2 - 4.485Q_w$ (upstream) and $Q_s = 0.0093Q_w^2 + 4.653Q_w$ (downstream), with a coefficient of determination of 0.9957 (upstream) and 0.9995 (downstream), and Q_s is the sediment discharge and Q_w is the water discharge respectively. The modelling of sediment transport also revealed significant changes in the channel bottom. These findings have practical implications for flood risk management, Offering valuable insights for relevant stakeholders to develop strategies aimed at preventing and mitigating the adverse effects of sedimentation in the area.

Keywords: HEC-RAS, natural base solution, oxbow lake, rating curve, sediment transport

INTRODUCTION

A river is a natural or artificial channel defined by a network of water flows extending from the upstream to the estuary, with its boundaries marked by the right and left riverbanks (Peraturan, 2011). Rivers serve not only as conduits for water but also as transport sedimentary materials, ranging in size from clay particles to large stones (Noor and Talib, 2022). Sediment is produced by the erosion and weathering of materials through wind, water, or glacial activity (Hambali and Apriyanti, 2016).

Sedimentation typically occurs in rivers, at the bases of hills, in channels, floodplains, and reservoirs (Asdak, 2007; Mustafa *et al*., 2017; Raji, Turabi, and Nasimi, 2023). Several factors influence sediment transport in rivers, including particle type and size, river cross-sectional width, land cover and vegetation within the catchment area, climate and temperature changes, flooding events, and land slope (Joshi *et al*., 2019).

The sediment transport – the movement of sediment grains by flowing water – is a natural process that can lead to significant risks. The rate of sediment transport, determined by the displacement of sediment through a cross-section over a specific period (Azmeri *et al*., 2017; Armido *et al*., 2020; Azmeri, Legowo and Rezkyna, 2020a) can have serious implications. Sediment transport is classified into two categories: bedload, where particles move by sliding, bouncing, or rolling on or near the riverbed; and suspended load, where particles float and mix with water, thereby reducing water quality (Azmeri, Legowo and Rezkina, 2020; Ikhsan *et al*., 2020). Over time, excessive sedimentation can reduce the storage capacity of a river, leading to changes in the morphology of the riverbed and increasing the potential for flooding. This poses risks to humans, infrastructure, and ecological systems (Azmeri, Legowo and Rezkyna, 2020; Basri *et al*., 2020; Hidayah *et al*., 2023; Vazquez-Tarrío *et al*., 2024).

The Krueng Peuto River, a tributary of the Krueng Keureuto, North Aceh District, Indonesia, experiences nearly annual flooding, affecting several villages, including Meunasah Kumbang Village, Geulumpang Village, Meunasah Meucat Village, Meunasah Rayeuk Village, and Krueng Village. Sedimentation is the primary contributor to these floods (Dinas Pengairan Aceh, 2023; Azmeri *et al*, 2024). The sedimentation in the Krueng Peuto consists of limestone, sandstone, and dolomite, which hinder the river's flow rate (Azmeri *et al*., 2022b; Dinas Pengairan Aceh, 2023). Additionally, suspended sediments in the Krueng Peuto watershed predominantly comprise clay, silt, and sand, leading to high turbidity levels (Azmeri, Legowo and Rezkyna, 2020). During high-level flows, increased turbulence and flow velocity can alter the boundary between bedload and suspended load, causing transported particles to become suspended when velocity and turbulence increase.

Sediment transport issues in the Krueng Peuto watershed are not solely a result of natural processes, but are significantly exacerbated by rapid land development and human activities in the surrounding area. These activities have led to aggradation and soil degradation over time, causing increased surface runoff (Azmeri, Legowo and Rezkyna, 2020; Azmeri *et al*, 2024). The accelerated runoff carries large amounts of sediment into the catchment (Noor and Talib, 2022).

Empirical and analytical methods are commonly used to analyse river sediment transport. Based on physical experiments or field measurements, empirical methods examine the relationship between hydraulic characteristics and sediment behaviour. While the empirical analysis are often reliable and realistic, they require significant effort in data collection and may be affected by scale effects or distortions when physical models are used (Jha *et al*., (eds.) 2021). In contrast, analytical methods involve deriving mathematical solutions from flow and sediment transport equations. Numerous models have been established for sediment transport analysis, including HEC-RAS, developed by the US Army Corps of Engineers (USACE). The HEC-RAS is one of the most renowned numerical models capable of simulating riverbed changes (Lee and Ahn, 2023).

In this study, sediment transport modelling was conducted to quantitatively assess sediment distribution patterns along the river channel through sediment numerical simulations (Iswahyudi, Salim and Abadi, 2018). The HEC-RAS model (USGS, 2023) was employed to evaluate hydrological parameters and sedimentation processes, particularly the variation of transverse and longitudinal profiles of the river, changes in the riverbed, and total sediment in Krueng Peuto. The Laursen sediment transport formula was used as it best fits the field data (Raji, Turabi and Nasimi, 2023). The HEC-RAS was also used to identify deposition sites along the Krueng Peuto River (Joshi *et al*., 2019).

The construction of physical infrastructure such as check dams to capture sediment is a sediment management strategy that has been implemented in several rivers with high sediment transport rates. While the construction of check dams has benefits, it also has negative consequences, including changes to the river's aquatic ecosystem, disruption to riverine biodiversity migration, alteration of water flow, and in extreme cases, an increased risk of flooding upstream or downstream of the river.

Sedimentation modelling is essential for understanding changes in river morphology caused by aggradation or degradation due to increased sediment, and determining the extent of sediment transport. Therefore, this study aimed to establish a sediment rating curve and sediment transport model for the Krueng Peuto River. At the downstream section of the watershed, there is an oxbow lake that is prone to sediment accumulation. Currently, this simple water body is underutilised and has become a pond and illegal settlement area for the community. During floods, the pond receives the overflow from the river, while in other periods, it often dries up. The oxbow lake has been a functioning as a retention pond and an alternative nature-based solution (NbS). Oxbow lakes can effectively capture flood runoff and serve as water storage during dry seasons. With appropriate development, this oxbow lake can be developed into a multi-purpose retention pond aimed at flood control, irrigation, and clean water supply. A key advantage of the oxbow retention pond as a NbS is that it does not significantly alter the river's morphology, and it optimises land use by being situated within the river's designated area, eliminating the need for costly acquisition of additional land.

However, oxbow lakes are not without challenges. These threats stem from the susceptibility of retention ponds to sediment accumulation, for instance land development that leads to erosion and reduces the capacity of the oxbow lake (Chukwuka and Adeogun, 2023). It is crucial to undertake a comprehensive study to develop effective strategies for flood and sedimentation management. Therefore, the sediment rating curve, which is the relationship between flow discharge and sediment discharge, is a critical component of the study. In this research, sediment transport was modelled using the HEC-RAS 6.1 application (USGS, 2023), which provided the capability to model both sediment transport and deposition processes under normal as well as extreme flow conditions. This allows for a more detailed analysis of river morphology changes. Additionally, the advantage of the software lies in its ability to update and approximate channel morphology more accurately as the simulation progresses. This is very useful in the long-term analysis of riverbed morphology changes due to sediment transport.

MATERIAL AND METHODS

STUDY AREA

This research was conducted in the Krueng Peuto watershed, located in North Aceh District, Indonesia, a tributary of the Krueng Keureuto River (Fig. 1). Hydrometric measurement points were located at two key locations: STA 200 (upstream) at 4°54'40.4"N–97°21'11.3"E and STA 5 (downstream) at 5°01'39.2"N–97°19'17.1"E. The flowchart illustrating the research methodology is available in the supplementary materials (Fig. S1).

DATA COLLECTION AND METHOD

The research was conducted in the Krueng Peuto watershed using data from the government and direct measurements in the field. The following data have been used for this study.

1. Rainfall data: obtained from the Sumatra River Basin-I (BWS) for a period of 11 years (2011–2021). The data was gathered from five rain gauge stations: Malikussaleh Station, Blang Pante, Alur Gading, Panton Labu, and Jambo Ayee. The rainfall data was then analysed based on the rainfall area using Thiessen polygons. The data used includes the annual maximum daily rainfall in millimetres.
2. Hydrometric data from field measurements at the location of the upstream of the Krueng Peuto River in Meunasah Reuhat Village (4°54"40.4"'N–97°21'11.3"E) and downstream of the river in Meunasah Meucat Village (5°01"39.2"N–97°19'17.1"E).
3. Bedload and suspended load sample data was obtained from field collection at the location upstream of the Krueng Peuto River in Menasah Reuhat Village (4°54'40.4"N–97°21'11.3"E) and downstream of the river in Meunasah Meucat village (5°01'39.2"N–97°19'17.1"E).
4. River geometry data from Dinas Pengairan Aceh (2023) was used to describe the long and cross sections of the river in HEC-RAS.
5. River roughness data from Brunner and Gilleland (2021) was used to determine the Manning's coefficient.

EMPIRICAL SEDIMENT TRANSPORT ANALYSIS

Sediment transport analysis was conducted using two stages: the calculation of sediment transport for field measurements using empirical formulas and the calculation of sediment transport predictions for return period discharge using the HEC-RAS application (Kwon and Lee, 2008). Empirical sediment transport calculations were performed using the Engelund–Hansen method in accordance with the characteristics of data obtained. The Engelund–Hansen equation for sediment transport is as follows (Engelund and Hansen, 1967).

$$q_s = 0.05\gamma_s v^2 \sqrt{\frac{d_{50}}{g\left(\frac{\gamma_s}{\gamma_w}-1\right)}}\left[\frac{\tau_0}{(\gamma_s-\gamma_w)d_{50}}\right]^{3/2} \quad (1)$$

where: q_s = total sediment (Mg·day^{-1}), γ_s = density of soil (g·m^{-3}), γ_w = density of water (g·m–^{3}), v = velocity (m·s^{-1}), d_{50} = diameter median (mm), g = gravitational acceleration (m·s^{-2}), τ_0 = shear stress (N·s^{-2}).

Suspended load sediment transport was calculated using the direct measurements of water discharge and sediment concentration (Saud, 2008) and it was calculated by using the water discharge parameter (Q_w), combined with sediment concentration (C_s), which results in sediment discharge, using Equation (2).

$$Q_{\text{suspended}} = 0.0864 Q_w \cdot C_s \quad (2)$$

where: $Q_{\text{suspended}}$ = sediment transport (Mg·day^{-1}), Q_w = water discharge (m^3·s^{-1}), C_s = sediment concentration (mg·dm^{-3}).

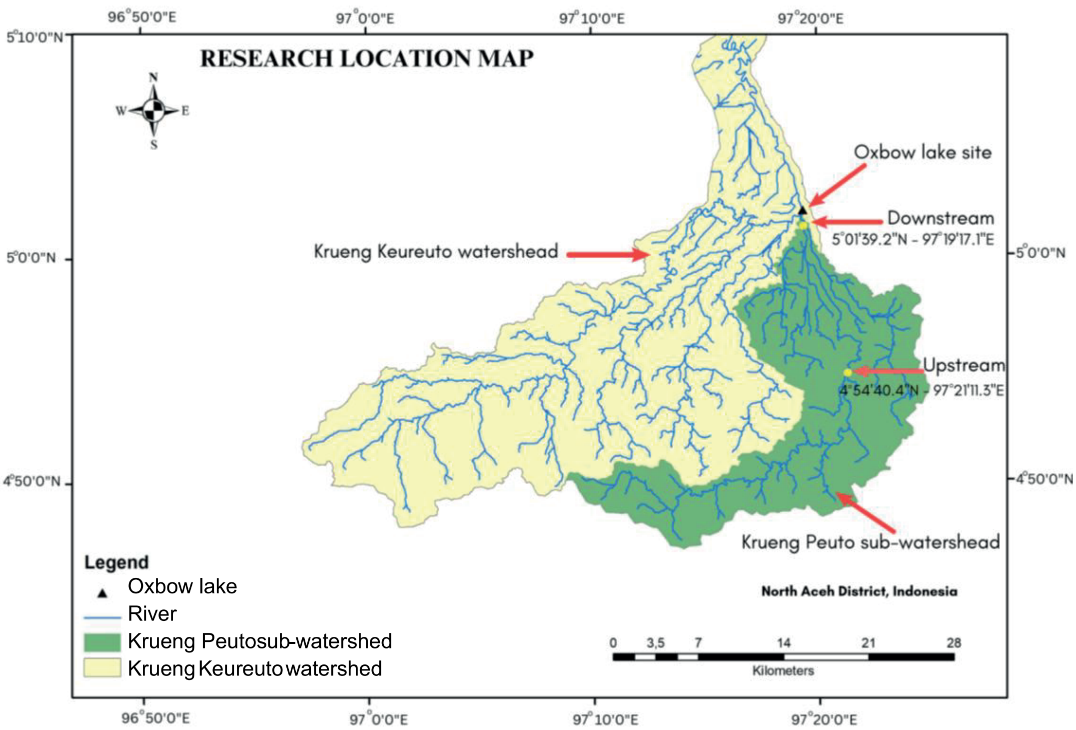

Fig. 1. The study area – Krueng Keureuto watershed; source: own elaboration

Bedload and suspended sediment samples were collected from both upstream and downstream sections. The upstream section was sampled at three points: the right, middle, and left bank of the river. The downstream site was sampled only at the right bank. This is because conditions in the downstream section of the Krueng Peuto River made it difficult to access the middle and left banks due to a depth of up to 5.30 m. Sediment characteristic data were obtained from the bedload and suspended load through sampling using a grab sampler. The sieve analysis and mass density testing were then carried out at the Faculty of Engineering Soil Mechanics Laboratory, Universitas Syiah Kuala and sediment concentration testing was done at the Environmental Quality Testing Engineering Laboratory. Before calculating sediment transport, the onset of sediment grain movement was assessed by calculating the flow shear stress (τ_0) and critical shear stress (τ_c). Sediment transport is considered to occur when the flow shear stress (τ_0) is greater than the critical shear stress (τ_c) (Hambali and Apriyanti, 2016; Cristine, 2009) (Eq. 3).

$$\tau_0 = \gamma_w \cdot D \cdot S \tag{3}$$

where: S = slope, D = channel depth (m), γ_w = density of water (g·m^{-3}).

SEDIMENT TRANSPORT MODELLING

The sediment transport modelling process was conducted using HEC-RAS 6.1 to analyse sediment data. The primary inputs for sediment transport calculations included geometry data, sediment characteristics, water discharge, and estimated Manning's coefficient (Joshi *et al.*, 2019; Rahman, Harada and Egashira *et al.*, 2022; Raji, Turabi, and Nasimi, 2023). Sediment analysis was conducted to calculate sediment deposition, riverbed changes, and erosion based on sediment continuity analysis (Joshi *et al.*, 2019; Rahman, Harada and Egashira, 2022). The Laursen method was used to predict total sediment load values, suitable for particle sizes ranging from 0.011 mm to 29 mm (Mustafa *et al.*, 2017). The sediment transport function was derived by matching data from this study, which included grain diameters ranging from 0.125 to 0.25 mm, average flow velocities of 0.43 m·s^{-1} (upstream) and 0.08 m·s^{-1} (downstream), and channel widths of 15.32 m (upstream) and 33.44 m (downstream). These characteristics confirm that this transport function is suitable for modelling sediment transport in the Krueng Peuto River.

RESULTS AND DISCUSSION

GRAIN GRADATION AND SEDIMENT CONCENTRATION

Bedload grain size distribution is required as an input in HEC-RAS for upstream and downstream river sections (Joshi *et al.*, 2019). This process involves aligning field-observed grain sizes with predefined grain size classes in the HEC-RAS software. The sediment grain sized ranged from particles passing through sieve No. 10 (2 mm) to sieve No. 200 (0.074 mm). The grain gradation of the Krueng Peuto River was within the range of 0.125 to 0.25 mm, categorised as fine sand. The median grain diameter was 0.150 mm upstream and 0.130 mm downstream.

Mass density testing yielded sediment-specific gravity values of 2.52 g·cm^{-3} in the upstream section and 2.66 g·cm^{-3} in the downstream section, which are consistent with the sand category (Hardiyatmo, 2012). Suspended sediment samples were analysed using suspended solids test parameters, and the resulting sediment concentration values are presented in Table 1.

Table 1. Specific gravity (*Gs*) and sediment concentration

Description	*Gs* (g·cm^{-3})	Average *Gs* (g·cm^{-3})	Sediment concentration (mg·dm^{-3})
Right upstream	2.51	2.52	1,347
Central upstream	2.52		1,180
Left upstream	2.54		1,265
Right downstream	2.66	2.66	1,650

Source: own study.

The analysis of suspended sediment concentrations in the Krueng Peuto River showed values ranging from 1,180 to 1,650 mg·dm^{-3}, indicating a high level of turbidity. The sedimentation in the Krueng Peuto River originates primarily from the erosion of hill cliffs, which are largely occupied by oil palm plantations. Much of the land is left exposed during the replanting process, especially during land clearing, leading to rapid surface runoff. This runoff quickly channels into ditches and enters the river, carrying significant amounts of sediment (Susanto *et al.*, 2017).

SHEAR STRESS

Sediment transport can be assessed by the magnitude of the flow shear stress (τ_0) and critical shear stress (τ_c). The values obtained were τ_0 = 11.430 Nm^{-2} and τ_c = 0.78 Nm^{-2} upstream, and τ_0 = 48.338 Nm^{-2} and τ_c = 0.78 Nm^{-2} downstream. Since $\tau_0 > \tau_c$, sediment transport is occurring in the Krueng Peuto River (Hendrasari and Adeska, 2022). The higher shear stress downstream indicates that the Krueng Peuto River can transport more sediment in that section (Nasir and Abustan, 2022).

MODEL CALIBRATION AND VALIDATION

The calibration of the HEC-RAS model is performed to ensure that the model accurately reflects real-world conditions. Several studies have developed calibration methods for sediment transport models, particularly in HEC-RAS. These include calibration based on hydrological data, geometric data, flood simulation results, parameter sensitivity, and statistical techniques. For example, Haghiabi and Zaredehdasht (2012) developed a 5-year sediment transport model for the Karun River, which was adjusted to actual river conditions and used to identify deposition hotspots. Mustafa *et al.* (2017) used cross-checking to calibrate the model by observing water levels and comparing them to obtain the Manning's coefficient value that best fits field conditions (Haghhiabi and Zaredehdasht, 2012; Mustafa *et al.*, 2017; Joshi *et al.*, 2019).

In this study, calibration was performed using a combination of river geometric methods, flood simulation, and channel roughness parameter sensitivity analysis to assess the accuracy of the simulation model and to identify the most optimal Manning's coefficient value for the Krueng Peuto River (Hicks, Gomez and Trustrum, 2004; Basim, Daham and Abed, 2020). The Manning's coefficient was adjusted through trial and error until the simulated maximum river depth closely matched the maximum depth measured in the field (Berghout and Meddi, 2016). Calibration was successful when the difference between the maximum simulated and measured depth was within 10% (Mustafa *et al.*, 2017; Zainuddin *et al.*, 2023).

The most optimal Manning's coefficient were 0.07–0.08–0.09 upstream and 0.6–0.6–0.6 downstream. Based on an upstream discharge measurement of 5.76 $m^3 \cdot s^{-1}$, the simulated depth during Manning calibration was 1.22 m. With a downstream discharge of 8.25 $m^3 \cdot s^{-1}$, a water depth of 5.03 m was obtained. The differences between the measured and simulated water depths were 1.61% upstream and 5.09% downstream, within the acceptable range for successful calibration (Zainuddin *et al.*, 2023). These Manning's coefficient values (0.07–0.08–0.09 upstream and 0.6–0.6–0.6 downstream) were used for further simulations pertaining to the Krueng Peuto River, a tributary of the Krueng Keureuto River. The downstream section of the Krueng Peuto River flows into the Krueng Keureuto River. In actual field conditions, a reverse flow has occurred, which makes the occurrence of backwater possible during the measurements. This phenomenon likely explains why the Manning coefficient in the downstream section of the river was very high, reaching a value of 0.6. The calibration of the Manning's n value was carried out using observed discharge data from both the upstream and downstream sections. These discharge values represent the actual flow rates at the time of measurement. During the rainy season, the discharge of the Krueng Keureuto River is very high, making it impossible to conduct direct measurements unless AWLR (Automatic Water Level Recorder) data is available.

Although no AWLR was installed at the measurement location, model validation was carried out using field data, such as flood observation from specific flood-prone locations, to ensure that the model can deliver accurate predictions under various conditions. A visual representation of sedimentation conditions is presented in Photo 1. The figure illustrates signs of erosion and sediment deposition, particularly on the right bank of the river, and partially on the left bank, in the downstream section of the Peuto River (Azmeri *et al.*, 2024). The sediment accumulation primarily occurs along the river channel, especially in the downstream section of the river. In addition, a significant source of sedimentation in the Peuto watershed is the erosion from the hillside cliffs, which are predominantly occupied by oil palm plantations.

RESULT OF SEDIMENT SIMULATION

Empirical sediment transport calculation

The bedload sediment transport was calculated using the Engelund–Hansen formula in accordance with the sediment diameter of 0.12–0.25 mm. Based on the calculation for the upstream section, the bedload sediment transport was 0.00000245 $Mg \cdot day^{-1}$, while the suspended load sediment transport was 629.05 $Mg \cdot day^{-1}$. Thus, the total sediment transport rate was 629.05 $Mg \cdot day^{-1}$. These results indicate that suspended load transport is the dominant mechanism in the upstream section

Photo 1. Sediment deposits on river side at the downstream section of the Krueng Peuto River (phot. *A. Azmeri*)

(Saud, 2008; Mananoma, Halim and Wuisan, 2014; Hisyam and Shodiq, 2019). In the downstream section, the total sediment transport was 1,176.12 $Mg \cdot day^{-1}$.

HEC-RAS sediment transport calculation

Sedimentation modelling using HEC-RAS was undertaken to model channel bed changes and the amount of sediment transport, using the Laursen–Copeland transport function, which was deemed most suitable given the conditions of Krueng Peuto. The Laursen–Copeland transport function was chosen to model Krueng Peuto because of the dominance of very fine sand (Noor and Talib, 2022). Sediment transport modelling was conducted with quasi-unsteady flow simulation, using sediment data input (grain gradation) and return period discharge hydrograph. Quasi-unsteady flow simulations were carried out at discharge return periods of 2, 5, 10, 25, 50, and 100 years to predict the amount of sediment transport in the upstream and downstream parts of the Krueng Peuto River. The results of quasi-unsteady flow analysis in the form of sediment transport (Tab. 2) are illustrated in the rating curve (Fig. 2).

The water discharge (Q_w) at the downstream section is 10% greater than at the upstream section. This is considered normal, as downstream discharge is typically higher than upstream discharge in a collector river system. In this case study, the Krueng Peuto River also has small channels that serve as lateral inflows. This results in a higher discharge at the downstream section, which is a logical occurrence in river hydraulics.

The relationship between water discharge and sediment discharge with regression obtained $Q_s = 0.014Q_w^2 - 4.485Q_w$ (upstream) and $Q_s = 0.0093Q_w^2 + 4.653Q_w$ (downstream) is shown

Table 2. Sediment discharge at the upstream and downstream of the river

Upstream		Downstream		Description
Q_w ($m^3 \cdot s^{-1}$)	Q_s ($Mg \cdot d^{-1}$)	Q_w ($m^3 \cdot s^{-1}$)	Q_s ($Mg \cdot d^{-1}$)	
5.76	629	8.25	1,176	observation
574.864	3,055	638.334	7,152	2-year return period
985.730	8,800	1,094.565	16,134	5-year return period
1,282.527	14,834	1,424.131	24,705	10 year return period
1,791.013	39,331	1,988.760	46,721	25 year return period
1,998.218	48,147	2,218.841	56,057	50 year return period
2,328.943	64,360	2,586.082	73,929	100 year return period

Source: own study.

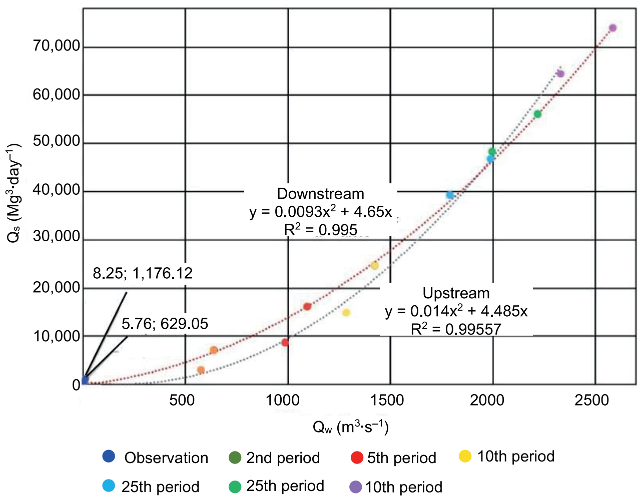

Fig. 2. Rating curve indicating the relationship between water discharge (Q_w) and sediment discharge (Q_s) at the downstream and upstream sections of Krueng Peuto River; source: own study

in Figure 2. The coefficient of determination (R^2) is 0.9957 (upstream) and 0.9995 (downstream), respectively. The correlation value falls within the excellent category because it is close to 1, indicating a strong correlation between water discharge (Q_w) and sediment discharge (Q_s). The higher the water discharge value (Q_w), the higher the sediment discharge value (Q_s) (Reynaldo and Pranoto, 2019).

HEC-RAS sediment transport modelling

Modelling of sediment transport using a 2-year return period discharge was conducted to determine changes in the riverbed in the Krueng Peuto River (Fig. 3). This return period discharge was selected due to its high probability of occurrence and its alignment with field conditions observed during the flood event on 26 December 2023 (Zuhri, Sisinggih and Asmaranto, 2023).

The longitudinal profile of the Krueng Peuto River shows riverbed changes due to degradation and aggradation (Fig. 3). The total volume of sediment in the Krueng Peuto River is presented in the supplementary materials (Fig. S2). In the upstream section, the dominant degradation is primarily caused by a relatively high flow velocity of 0.43 $m \cdot s^{-1}$. In contrast, the downstream section exhibits significant sediment deposition due to a reduced flow velocity of 0.08 $m \cdot s^{-1}$ (Rusdi *et al.*, 2023). This runoff impacted the villages of Meunasah Meucat, Meunasah Jok, and Krueng LT. The validation of the flood locations aligns with research by Keumalasari *et al*, 2024) on the Krueng Peuto flood inundation area and corroborates reports of flooding along the Krueng Peuto River on 20 December 2022 and 4 September 2023. The HEC-RAS simulation results show silting of the riverbed in several segments (Rusdi *et al*, 2023). At the upstream review point (STA 200), a degradation of 0.7605 m was observed. In Figure 3, the solid blue line shows the current riverbed, while the dashed red line shows the predicted degradation profile. At the upstream review point (STA 5), aggradation of 0.0851 m was recorded, where the solid red line shows the existing riverbed, and the dashed blue line shows the predicted aggraded profile. The sedimentation is predominant in Krueng Peuto River. The amount of sediment transported is closely related to the shear stress (τ_0). In the upstream section, the shear stress was calculated at 11.430 $N \cdot m^{-2}$, while in the downstream section, it was significantly higher at 48.338 $N \cdot m^{-2}$, indicating a greater shear stress in the downstream section. It indicates that the Krueng Peuto River has a higher capacity to move sediment in that area (Nasir and Abustan, 2022). Details of channel cross-sections affected by bed elevation changes in the upstream and downstream reaches are presented in the supplementary materials (Figs. S3 and S4).

The settled sediments in the Krueng Peuto River exhibit variations in grain size depending on the location, suggesting ongoing sediment transport (Noor and Talib, 2022). The particle size distribution pattern of the sediment falls within the fine sand

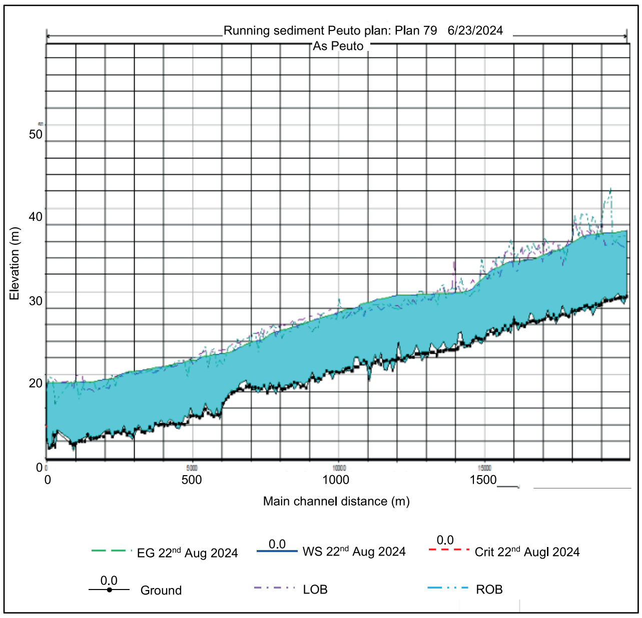

Fig. 3. Riverbed changes due to aggradation and degradation; EG = energy grade line, WS = water surface, Crit = critical, LOB = left over bank, ROB = right over bank; source: own study

grain category, with grain sizes measuring 0.150 mm in the upstream section and 0.130 mm in the downstream section.

The high sediment concentration in the Krueng Peuto River, ranging from 1,180 to 1,650 mg·dm^{-3}, underscores the river's significant sediment transport capacity (Noor and Talib, 2022). This high sediment load contributes to dominant aggradation, reducing the river's storage capacity and leading to overflows and flooding during periods of large flow discharges (Azmeri, Legowo and Rezkyna, 2020; Vazquez-Tarrío *et al*., 2024).

The findings of this study offer insights into sediment potential through the use of rating curves and more advanced sediment modelling. The research emphasises the role of an oxbow lake, which serves as a retention pond, providing a viable alternative as a nature-based solution (NbS). This oxbow lake demonstrates significant potential for development into a multi-functional retention system, capable of addressing flood mitigation while fulfilling the needs for both irrigation and potable water. Given the vulnerability of retention ponds to sediment accumulation, these findings highlight the necessity of formulating effective flood and sedimentation management strategies. Looking ahead, this research will contribute to the optimisation of operational management for the oxbow retention pond as a sustainable, nature-based solution. Future research will focus on the precise design and broader utilisation of oxbow lakes. The use and optimisation of oxbow lakes as NbS with multifunctional roles include flood and drought mitigation, provision of clean water and irrigation, and support for the river ecosystem. The NbS can be implemented at both small scales (urban/local scale, such as bioretention, vegetated swales, green roofs, and trees) and large scales (regional scale, such as rural areas, mountains, or river basins) (Vojinovic *et al*., 2021). Large-scale NbS implementations may include retention ponds, mangrove forests for coastal areas, flood channels, and other interventions. The application of small-scale NbS for flood risk mitigation aims to reduce flood peaks (Ercolani *et al*., 2018), delay flood peak timing (Ishimatsu *et al*., 2017), and reduce runoff volume (Shafique and Kim, 2018).

CONCLUSIONS

Sedimentation modelling is crucial for analysing changes in river morphology driven by aggradation or degradation due to elevated sediment deposition, as well as for assessing the extent of sediment transport. The study takes into account the presence of an oxbow lake, which functions as a retention pond and presents an alternative natural based solution (NbS). This oxbow lake has the potential to be developed into a multifunctional retention pond that addresses flood control, while also meeting irrigation and potable water needs. Considering the susceptibility of retention ponds to sediment build-up, it is necessary to undertake a comprehensive study to develop effective flood and sedimentation management strategies. The rating curve results show the relationship between flow discharge (Q_w) and sediment discharge (Q_s). The regression equations derived from the data are: $Q_s = 0.014Q_w^2 - 4.485Q_w$ (upstream) and $Q_s = 0.0093Q_w^2 + 4.653Q_w$ (downstream). The coefficient of determination (R^2) indicates the level of correlation between Q_w and Q_s, where an increase in flow discharge (Q), corresponds to an increase in Qs. The results of this research provide information on sediment transport potential based on the rating curve and more detailed sediment modelling. In the future, these findings are expected to support operational planning and management of the oxbow retention pond as a nature-based solution.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at https://www.jwld.pl/files/Supplementary_material_66_Azmeri.pdf.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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