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POST-DISASTER ENGINEERING STRATEGY FOR ANAI RIVER DEBRIS FLOW MANAGEMENT ON ANAI VALLEY NATIONAL ROAD WEST SUMATRA INDONESIA

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ABSTRACT
One of the causes of flash floods is eruption material from Mount Marapi that is carried downstream, disrupting transportation access and the local economy. This study aimed to design and implement an effective post-disaster engineering strategy for debris flow management in the Anai River and evaluate its long-term success. Data were collected through field observations to measure river profiles, photogrammetry, and sediment sampling. Secondary data were used to calculate rainfall intensity and flood discharge in the Anai River to plan debris flow control. The study results showed that the large catchment area and high rainfall contributed significantly to the high peak discharge. Disturbed soil samples taken from the river surface were saturated, indicating the influence of sediment from the debris flow from the eruption of Mount Marapi. The removal of material from the riverbed needs to be controlled to avoid overexploitation that could exacerbate erosion of the riverbanks, ultimately threatening bridge structures and other infrastructure along the Anai River. To overcome this problem, it is necessary to build sediment control structures such as check dams and groundsills, as well as secure riverbanks in the management of debris flows in the Anai River.
Keywords : *Debris Flow, Sediment, Mitigation, Post-Disaster Management.*

1. Introduction

Debris flow is a natural phenomenon that often occurs after volcanic eruptions and auses the accumulation of volcanic material and sediment along the river (Bari et al., 2023; Chester et al., 2000; Mizuyama, 2008; Prabowo et al., 2017). Debris flows or flash floods on May 11, 2024, occurred in the Anai River upstream from Mount Marapi, Mount Tandikat, and Mount Singgalang which resulted in heavy damage to the national road on the banks of the Anai River between Anai resort and the Padang Panjang City boundary along 3 km. One of the causes of flash floods is material from the eruption of Mount Marapi was carried downstream, thus disrupting access to transportation and the economy of the local community (Department of Water Resources and Construction Development, 2024).

There are 23 rivers upstream from Mount Marapi, of which Anai River is one, all of which have the potential to debris flows or flash floods if the rain intensity increases (PVMBG, 2024). It is estimated that the eruption material on Mount Marapi has reached 1 million cubic meters. Some of the material has accumulated in the upper reaches of rivers, which can cause debris flows, and it is hoped that mapping activities on priority rivers that are most dangerous and have the potential to cause flash floods will be carried out immediately by the government. River degradation in the downstream Anai River is already very worrying because it has collapsed the bridge and threatened the Anai River irrigation weir building that irrigates 13,060 ha of rice fields.

Previous research on debris flow management includes various engineering approaches such as the use of retaining dams, diversion canals and early warning systems. Zeng et al. (2009) showed that retaining dams can retain up to 70 percent of debris material, although they require regular maintenance to prevent excessive material accumulation. This study highlights the importance of ongoing maintenance to ensure the long-term effectiveness of retaining dams.

Poland and Anderson (2020) found that well-designed diversion canals are effective in protecting infrastructure, but require detailed analysis of topography and hydrology. According to East et al. (2018), switching canals must be adapted to specific geographical conditions to achieve optimal results. Cassidy et al. (2019) and Michellier et al. (2020) developed sensor-based early warning systems that provide real-time alerts but require large initial investments. Tingsanchali (2012) and Oldfield and Stevenson (2024) emphasized that a combination of these techniques provides more comprehensive protection, but needs to be adapted to local conditions.

Sediment control dams are structures designed to reduce the impact of sediment and debris flows in mountainous and volcanic areas. These dams are essential for managing sediment transport, preventing erosion, and protecting downstream areas from flooding and sediment-related disasters. Mizuyama et al. (2008) highlighted that Sabo dams significantly reduce the speed and volume of sediment transported downstream, thereby reducing potential damage to infrastructure and communities. While much research has been conducted, there is limited research on the application of holistic and integrated post-disaster engineering strategies on the ground. In particular, there is limited detailed research on the adaptation of existing engineering techniques to local conditions and the evaluation of their long-term success. Therefore, further research is needed that focuses not only on technology development but also on the implementation and evaluation of sustainable debris flow management strategies.

This study aims to design and implement an effective post-disaster engineering strategy for debris flow management in the Anai River and evaluate its long-term success. This will improve the resilience of national transportation infrastructure to natural disasters, reduce the risk of economic loss and loss of life, and support sustainable development in West Sumatra. This research is expected to make a significant contribution to the development of adaptive and innovative engineering solutions for debris flow management in disaster-prone areas by conducting an in-depth study of the impact of natural disasters on the Anai River flow and related infrastructure around the Anai Valley National Road and formulating innovative and scientifically based engineering strategies to manage the Anai River flow after a disaster, which includes river engineering, infrastructure strengthening, and implementation of the latest technology that encourages the development of new technologies in the field of river engineering and disaster mitigation, which can be applied in other areas with similar conditions. From a scientific perspective, this research is urgently needed to add to the literature on disaster risk reduction in disaster-prone areas. By developing effective and sustainable river flow management strategies, to improve the quality of life of the surrounding community. This will be achieved by creating safer and more reliable infrastructure based on the development of better public policies in disaster management and natural resource management. Many existing studies need to focus on empirical measurements and simulations of specific Anai River cross-sections, especially those related to the effects of post-disaster erosion and sediment deposition.

Although technologies such as HEC-RAS have been widely used, their application in the Anai River has not been optimal. This study will fill the gap by implementing a comprehensive HEC-RAS simulation to analyze flow, sediment, and flood potential. Many current flood management strategies are fragmented and not well integrated, especially in the context of sediment control. Considering the sediment analysis results, this study will develop an integrated and specific flood management strategy for the Anai River area.

2. Literature Review

Debris Flow Phenomena

Debris flow is a type of highly destructive land mass movement that is common in mountainous areas or steep slopes (Fathani et al., 2022; Hadiranti et al., 2024; Tsana et al., 2022). This phenomenon is a mixture of soil, rock, water and vegetation material that moves rapidly down the slope due to the force of gravity. Debris flows differ from regular landslides due to the significant presence of water and their much higher velocity. They are usually triggered by heavy rains, volcanic eruptions, earthquakes or human activities that cause slope instability. Characteristics of Debris Flows Debris flows are generally characterized by rapid and often abrupt material movement. Debris flows have very high viscosity and can carry large materials, including boulders (Iguchi, 2019; N. Kim et al., 2019; Vinogradova & Vinogradov, 2017). The combination of material moving together with water makes debris flows highly destructive, as they can damage infrastructure such as bridges, roads, houses and agricultural land. In addition, debris flows can clog waterways, potentially causing flooding. Debris flows can be defined as mass movements caused by excessive rainfall that result in slopes being saturated by water (Y. Kim et al., 2017; Takebayashi et al., 2022; Vagnon, 2020). This then decreases the shear strength of the soil, so the material becomes unstable and starts to flow. Intense rainfall, especially in tropical regions like Indonesia, is a major trigger for debris flows.

The process of debris flow formation occurs when a large amount of water, either from heavy rainfall, ice melt or other water sources, enters the loose material on a mountain slope. The soil material on the steep slope becomes saturated with water, this causes the pore water pressure to increase, which reduces the cohesion strength between soil particles. When the water pressure exceeds a certain threshold, the loose material will start to flow, forming a debris flow (Ikhsan et al., 2020; Nugraha et al., 2019). Slopes made of less stable materials such as volcanic ash, clay, and rock fragments tend to be more prone to debris flows. In many volcanic areas, including the West Sumatra region, ash and unconsolidated volcanic materials provide a substrate that is highly susceptible to debris flow events, especially after high rainfall events or earthquakes (BPBD West Sumatra Province, 2024; Purwaningsih et al., 2024). In addition, Cassidy et al. (2019) noted that areas with volcanic activity, such as those in Indonesia, are often more prone to debris flows due to the presence of unstable volcanic ash layers. This volcanic ash, when saturated by water, can easily erode and flow with the water, creating large volumes of debris. Therefore, the physical characteristics of the West Sumatra region, with the presence of Mount Marapi and Mount Singgalang, add to the potential debris flow hazard, especially on major transportation routes such as the Anai Valley Road.

Debris Flow Impact on Infrastructure

Damage Caused by Debris Flows Debris flows have the potential to cause enormous damage, both in economic and social terms. In many vulnerable areas, road and bridge infrastructure very often fall victim to debris flow damage. Mizuyama (2008) points out that since debris flow materials often contain boulders and fallen trees, their destructive power is enormous and can destroy man-made structures within seconds. In addition, debris flows can cause drastic changes in river morphology and water flow, potentially creating catastrophic flooding in downstream areas. Vinogradova & Vinogradov (2017) explain that when debris flows reach river valleys or low-lying areas, the material they carry can clog waterways and create temporary lakes that can collapse suddenly, causing flash floods.

Infrastructure such as roads and bridges in mountainous areas are vulnerable to damage from debris flows. These flows can quickly close roads, destroy structures and cause major disruptions to transportation. According to studies conducted by Wei & Xu (2024) and Ikhsan et al. (2020), the rapid and destructive nature of debris flows means that road infrastructure in vulnerable areas must be designed to take into account the volume and velocity of the flow, as well as the type of material involved. Damage to infrastructure not only causes economic loss, but also poses a high risk to life safety. When landslide materials cover roads or destroy bridges, access to remote areas can be cut off, hampering evacuation and aid distribution at critical times (Nugraha et al., 2019; Prabowo et al., 2017; Purwaningsih et al., 2024). Therefore, infrastructure design in vulnerable areas should consider this risk, as advocated by several geotechnical studies that have discussed how roads in mountainous areas should be built with more resilient disaster mitigation techniques.

Engineering Mitigation Techniques

Engineering mitigation techniques for debris flows can be grouped into two main categories, namely structural measures and non-structural measures. Physical structures involve the construction of infrastructure designed to contain, redirect or slow down debris flows from reaching critical infrastructure such as roads, bridges and settlements. According to Zeng et al. (2009), one of the most common methods is the construction of check dams, which serve to capture solid materials from upstream debris flows before they reach downstream areas. These dams are often combined with conveyance systems that direct water and material into specific pathways to reduce the risk of blockages in rivers or streams. In addition to retaining dams, other techniques such as retaining walls and debris basins are also used to control the movement of debris flows (Y. Kim et al., 2017; Malik et al., 2020; Miyahara et al., 2023; Vinogradova & Vinogradov, 2017). These structures are effective at preventing infrastructure damage and reducing the impact of large material flows that could potentially damage nearby facilities.

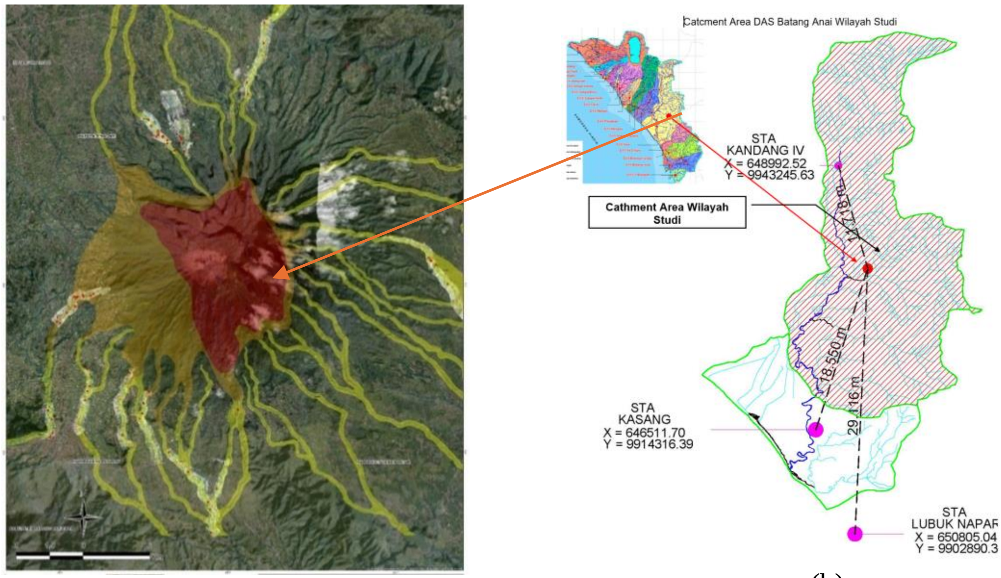
The application of Sabo works technology, as popularized in Japan, is a particularly relevant example for debris flow management in vulnerable areas such as West Sumatra. This technology consists of constructing a series of terraced dams along a river or valley prone to debris flows. Horiguchi & Richefeu (2020) state that this technique not only retains solid material, but also slows down the flow velocity, reducing the risk of damage to infrastructure. The Sabo Dam repair technique has the advantage of being able to hold large volumes of cold lahar and direct its flow to safer areas, preventing cold lahar from reaching settlements and critical infrastructure. But it has disadvantages because the construction of sabo dams requires high costs, especially for lahar resistant materials and complex construction techniques, requires regular monitoring and maintenance to prevent structural damage and ensure optimal function, there are limitations in the storage volume depending on the size and design of the dam (Lee et al., 2023; Lyu et al., 2024; Piton et al., 2019).

On the other hand, non-structural measures also play an important role in mitigating debris flow risks. One of the most important non-structural approaches is early warning systems. According to Cassidy et al. (2019), these systems use technologies such as rain sensors, soil moisture monitoring, and real-time topographic monitoring to provide early warnings to communities and authorities when environmental conditions indicate the potential for debris flows. Vegetation restoration recovery strategies can also be carried out because vegetation can help stabilize soil and reduce erosion, and accelerate ecosystem recovery so that it can improve soil and water quality and support local biodiversity, replanting vegetation can be done at a lower cost than civil engineering techniques. The limitations of vegetation restoration techniques are that they take a long time to grow and provide full protection, require maintenance and attention to ensure optimal growth and prevent damage by pests or unfavorable environmental conditions, and are not effective enough to manage large volumes of cold lava without support from other control techniques. In addition, land-use planning is also important in mitigating long-term risks. By limiting development in areas prone to debris flows and ensuring that conservation areas or buffer zones are provided along flow paths, risks to infrastructure and settlements can be reduced. This approach also includes community education and participation, which aims to improve the preparedness of local communities in the face of potential debris flows, so that they are more responsive and prepared in emergency situations.

3. Research Methods

Study Location

Mount Marapi is located in the districts of: Tanah Datar Regency and Agam Regency of West Sumatra. There are 23 sub-watersheds around Mount Marapi that are located in the disaster prone area (Fiantis et al., 2017; Purwaningsih et al., 2024). One of the main watersheds is the Anai River, which originates from Mount Marapi and Mount Singgalang and crosses 4 regencies/cities, namely Tanah Datar Regency - Padang Panjang City - Agam Regency - Padang Pariaman Regency and Padang City. The study location map can be seen in Fig. 1.



(a) (b)

Fig. 1. Study location: (a) lava and debris flow map; (b) catchment area of the Anai River.

Potential lava flows from Mount Marapi are marked with red lines indicating the direction and path of the lava flow. The path of the lava flow passes through villages and infrastructure around Mount Marapi, including areas close to the Anai Valley. The Anai Valley is quite close to Mount Marapi, so the lava flow caused by the volcanic eruption can reach this valley. The lava flow can directly affect the national road that passes through the Anai Valley, which can cause road damage and disrupt transportation. This national road is vital because it is the main transportation route for the distribution of goods and the mobility of the population. By understanding the location and potential risks of the Mount Marapi lava flow, appropriate steps can be taken to reduce the impact of the disaster and protect critical infrastructure, such as the national road in the Anai Valley.

Data Collection Method

Data sources in this study consist of primary and secondary data. Primary data collection was conducted by field observation to measure river profiles, photogrammetry, and sediment sampling. River profile measurements were taken at various points along the Anai River to obtain geometric data that included the depth, width and slope of the river. These data are crucial for understanding the physical structure of the river and changes in its morphology due to debris flow. Photogrammetric technology was used to create a three-dimensional model of the study area to analyze river morphology and sediment distribution with high precision (East et al., 2018; Major et al., 2019). This technique provides a detailed and accurate visualization of topographic changes and sedimentation. Meanwhile, sediment samples were taken from several strategic locations for physical and chemical analysis. These analyses help in identifying sediment characteristics, such as grain size, mineral composition and organic content, which are important for understanding sedimentation dynamics. River cross-section measurements and sampling were carried out every 100 meters along the road from upstream to downstream of the Anai River to obtain more detailed and representative data. The depth of the soil sample was taken at the surface and then tested for soil physical properties to determine soil stability and erosion behavior. Measurements of the Anai River cross-section were carried out every 50 m - 100 m to obtain important data and information regarding the physical characteristics of the river that can be used to understand water flow patterns, speed, and volume of water flowing through the river in various weather conditions, predict potential flooding and identify areas prone to waterlogging, identify sediment deposition zones that can affect water quality and aquatic habitats. The Global Positioning System (GPS) was used to determine the sample collection and measurement location. Soil samples were taken in a disturbed manner and then sieve analysis tests were carried out to determine the grain gradation.

Secondary data were obtained from various sources to complement the primary data. Rainfall data were collected from local meteorological stations to analyze rainfall patterns and their relationship with river flow and sedimentation. This information is essential to understanding the hydrological factors that influence sedimentation processes. Rainfall data is used for 2020, 2021 and 2022 which comes from the nearest station.

Data Analysis

Analysis was performed with Hydraulics Engineering Center River Analysis System (HEC-RAS) 6.4.1 software which was used for hydraulic modeling and sediment transport (Gibson et al., 2022; Ismail et al., 2024; Pramesthi et al., 2024). HEC-RAS, developed by the U.S. Army Corps of Engineers, is an excellent tool for modeling river flow and open channels and can be used for one-dimensional (1D) sediment transport analysis. The model is designed to simulate unsteady flow along the main channel of rivers and streams. The 1D simplification was chosen because it is appropriate for many situations where lateral variations in flow and sediment transport are relatively small compared to longitudinal variations.

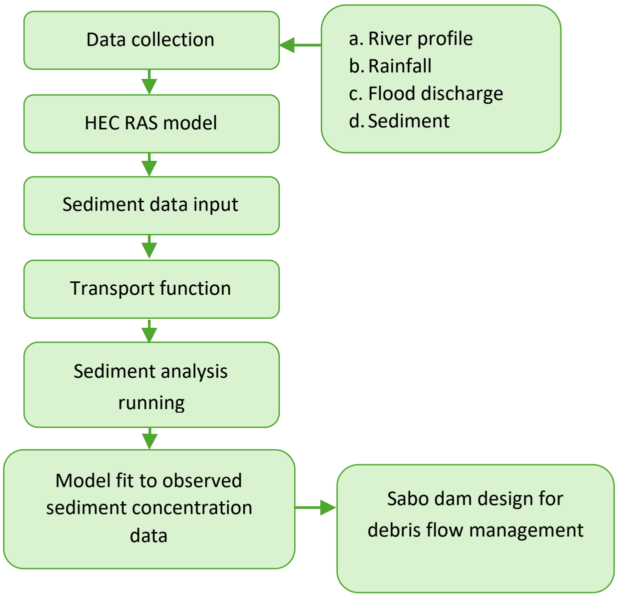


Fig. 2. Anai River debris flow management planning procedure

Model development involved the use of key components, including flow velocity, river geometry, flow plan, and sediment data. These data were input into HEC-RAS to simulate the flow dynamics and sediment distribution along the Anai River. Simulation results were analyzed to understand sedimentation patterns and their impact on downstream river degradation. This analysis enables the identification of critical areas that require technical intervention and the development of effective disaster mitigation strategies. The planning procedure for debris flow management in the Anai River is shown in Fig. 2.

Figure 3 shows the flood discharge modeling on HEC RAS 1D flood discharge Q25 on the transverse profile of Sta. 79 in one sample with a river width at the time of flood discharge of 1073 m3/sec and a flood water level of 7 m from the bottom of the Anai River as shown in the following figure:

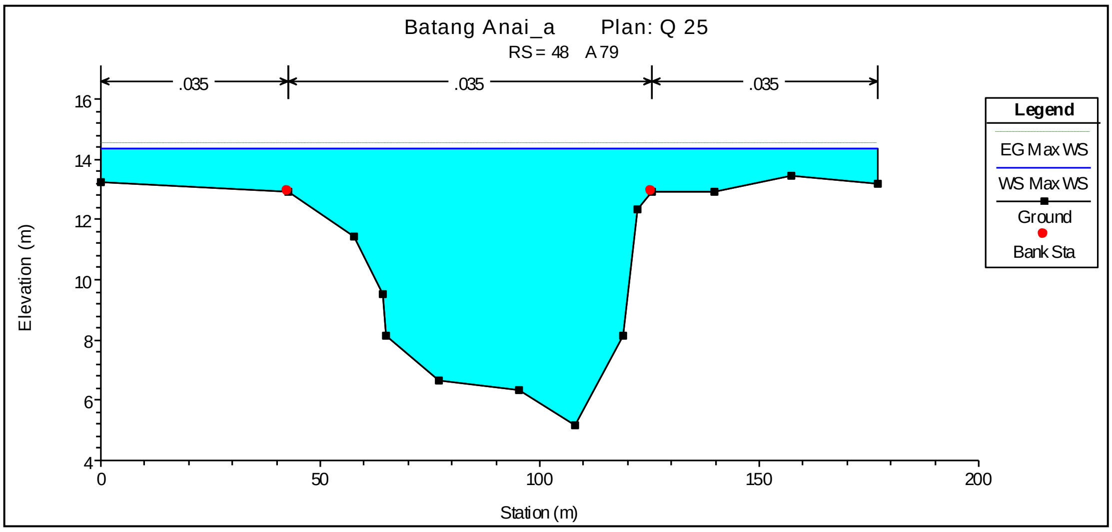


Fig. 3. Modeling on HEC RAS 1D flood discharge Q25 on the transverse profile of Sta. 79

It using HEC-RAS can predict the area inundated under various flood conditions and simulate sediment transport, helping to understand sediment deposition and erosion along river cross-sections.

4. Results and Discussions

Rainfall Analysis

Based on the literature study and topographic study (Geospatial Information Agency Map), the boundaries of the Cathment area of the Anai River study area from Anai Dam to Pasar Usang are 518.49 km^2 with a river length of 38.27 km, w While the overall catchment area from the upstream to the estuary is 709.05 km^2, with a river length of 54.50 km. The availability of rainfall data and the position of the rainfall gauge post in the Anai River watershed study area can be seen in Table 1.

Table 1 - Amount of Rainfall in the Anai River Watershed

Month	Rainfall (mm^3)			Rainy Days (Days)		
	2020	2021	2022	2020	2021	2022
January	356.00	457.40	464.10	15.00	14.00	20.00
February	332.30	168.50	294.60	14.00	15.00	13.00
March	421.60	808.40	426.80	20.00	27.00	18.00
April	807.10	308.90	318.10	25.00	19.00	14.00
May	363.00	354.20	119.30	21.00	21.00	15.00
June	244.30	246.60	674.60	18.00	16.00	23.00
July	415.60	133.90	197.20	24.00	14.00	11.00
August	279.20	648.50	361.10	19.00	25.00	17.00
September	340.90	767.40	616.70	24.00	23.00	21.00
October	294.10	399.60	461.00	25.00	17.00	24.00
November	633.40	269.00	650.20	27.00	18.00	25.00
December	243.20	769.90	366.80	19.00	24.00	22.00

Source: Mateorology, Climatology and Geophysics Agency, 2020-2022

High intensity rainfall has a significant impact on the flood discharge that occurs in Anai River. In relation to flood management, mapping of flood-prone areas (flood plains) and validation of flood overflow patterns in Anai River have been carried out.

Flood Discharge Analysis

From the calculation of the Nakayasu synthetic unit hydrograph method, the resulting peak discharge (peak discharge, Qmax) is 1073,000 m^2/s. This calculation is based on several important parameters, namely the area of catchment of 709.00 km^2, rainfall intensity of 54.5 km, and an unusual runoff coefficient of 3.00 hours. This figure seems unrealistic, considering that runoff coefficients usually range from 0 to 1. In addition, there are additional factors of 0.40

and 3.0, which may be correction or adjustment factors in the calculation. Recapitulation of Anai River design flood hydrograph calculations using Nakayasu and Snyder methods can be seen in Table 2 and Fig. 4.

Table 2 – Flood Discharge Analysis

No.	Calculation Methods	Flood Discharge (m^3/s)							
		$Q_{2\ th}$	$Q_{5\ th}$	$Q_{10\ th}$	$Q_{20\ th}$	$Q_{25\ th}$	$Q_{50\ th}$	$Q_{100\ th}$	$Q_{200\ th}$
Watershed Anai River Study Area (Upstream to Pasar Usang Bridge)									
1.	Nakayasu	780.00	921.04	994.76	1.055.64	1.073.38	1.124.16	1.169.84	1.211.65
2.	Snyder	590.53	701.54	759.57	807.49	821.45	861.42	897.38	930.29
Watershed Anai River (Upstream to Estuary)									
1.	Nakayasu	853.15	1.007.95	1.088.86	1.155.68	1.175.15	1.230.89	1.281.02	1.326.91
2.	Snyder	659.29	783.24	848.03	901.53	917.11	961.74	1.001.89	1.038.63

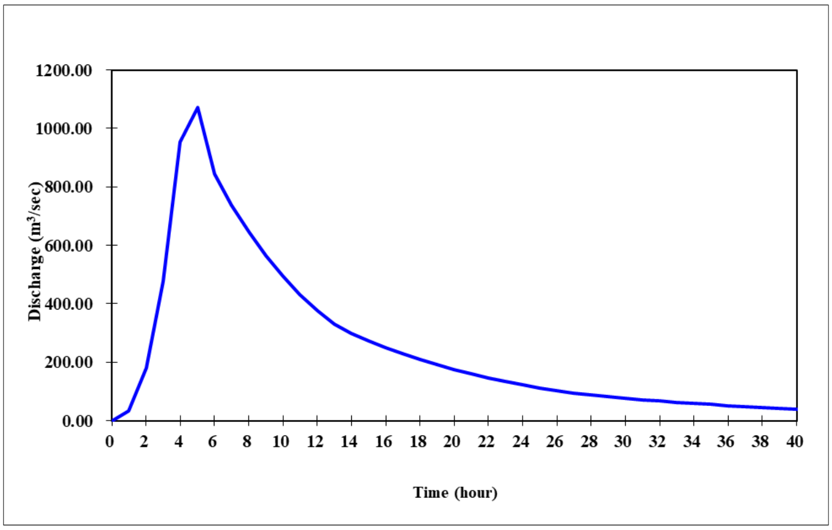


Fig. 4. Flood discharge graph

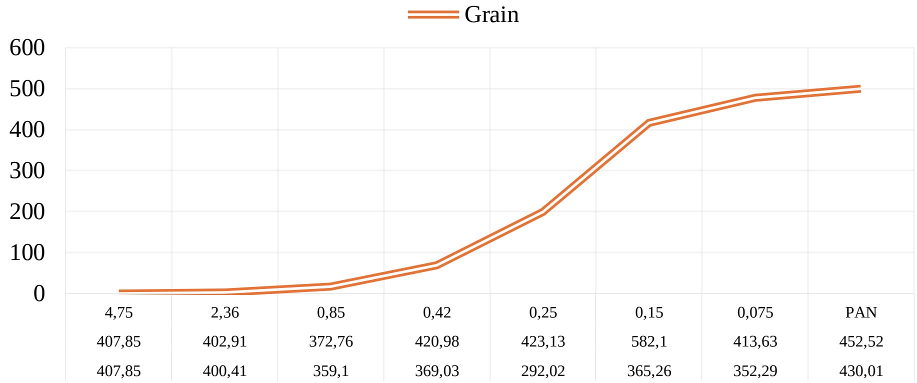
In the context of hydrological studies, peak discharge is an important parameter for identifying flood potential and planning flood control infrastructure. The large catchment area and high rainfall intensity contribute significantly to the high peak discharge.

Sediment Grain Analysis

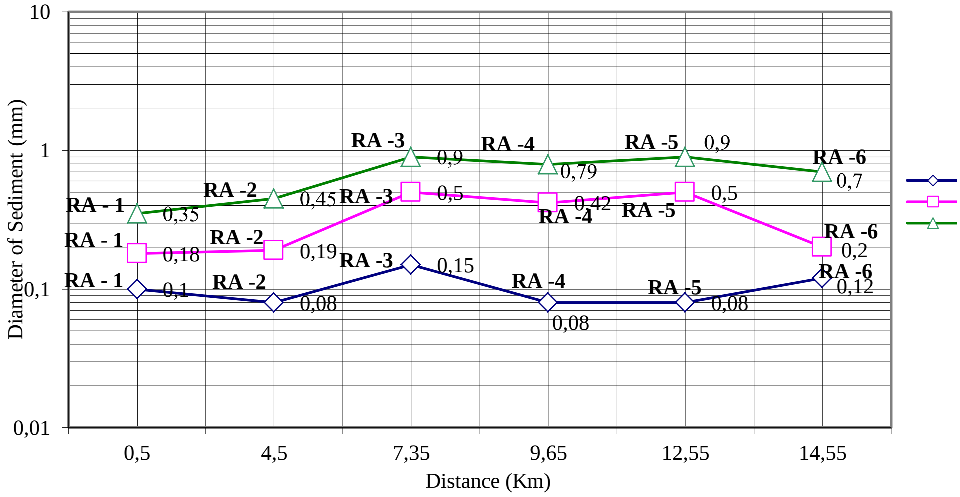
Sediment grain analysis is one of the important methods in understanding the characteristics of sediments present in streams and how they can be effectively managed (Andriani et al., 2024; Aprisal et al., 2019). The characteristics of sediment grains, such as their size, shape, composition, and distribution, play a key role in determining sediment transport dynamics and the effectiveness of various sediment control techniques (Zeng et al., 2009). D60 grain values in the Anai River are distributed in the range of 0.35 - 0.9 mm and specific gravity ranges from 2.64 - 2.68. The results of sediment sampling tests in the Anai River can be seen in Table 3 and Fig. 5.

Table 3 - Anai River Sediment Sieve Analysis

No. Sieve	Weight of empty sieve (gr)	Sieve weight + soil (gr)	Grain size (mm)	Restrained weight (gr)	% Weight Restrained	%Cumulative	
						Restrained	Escaped
4	407.85	407.85	4.75	0	0	0.000	100.000
10	400.41	402.91	2.36	2.5	2.5	0.500	99.500
20	359.1	372.76	0.85	13.66	16.16	3.233	96.767
40	369.03	420.98	0.42	51.95	68.11	13.624	86.376
60	292.02	423.13	0.25	131.11	199.22	39.851	60.149
100	365.26	582.1	0.15	216.84	416.06	83.227	16.773
200	352.29	413.63	0.075	61.34	477.4	95.497	4.503
PAN	430.01	452.52	PAN	22.51	499.91	100.000	0.000
Total				499.91	1679.36		



(a)



(b)

Fig. 5. (a) Sediment sieve analysis graph and (b) grain size sediment in Anai River

Based on visual soil classification and screen analysis at the study site, the soil was identified as belonging to the sand soil type, characterized by the presence of fine to medium sized sand grains. Disturbed soil samples taken from the river surface were saturated, indicating that the soil had been affected by sediments from the debris flows of the Mount Merapi eruption. The influence of sediment grains resulting from sieve analysis affects the rate of sediment transport at several points that have experienced degradation due to sand mining activities in the river body and post-flood sediment aggradation.

Sediment Transport and Morphology Change

To understand the physical mechanisms of oceanographic driving forces on sediment transport processes from upstream to estuary such as hydrodynamics (currents), waves, littoral currents, sand transport. A 2-D numerical model of hydraulic and sediment transport module combined with a 1-D shoreline development model was applied to the coastal study which also influenced the improvement efforts of the Anai River estuary. The detailed methodology procedure and simulation results are described in Fig. 6.

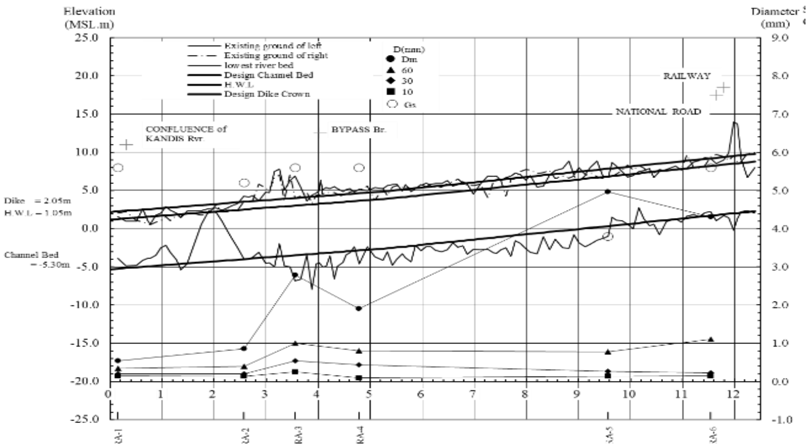
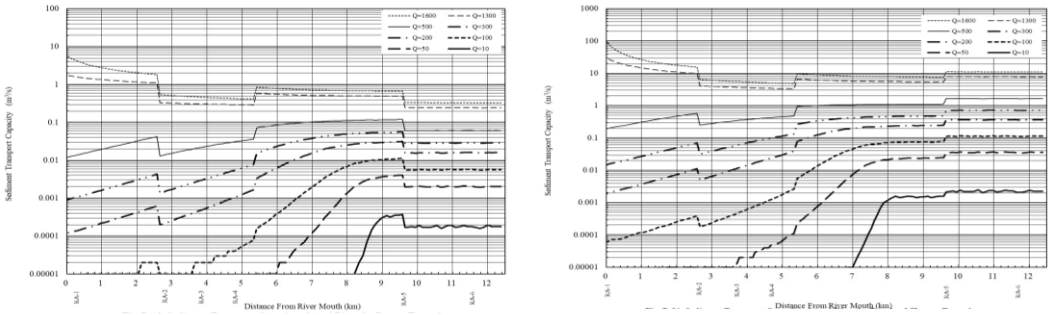


Fig. 6. Longitudinal profile and grain size distribution in Anai River to estuary

The results of observations and simulations have degraded the riverbed along 8 km (3-11 km from the mouth of the Anai River) with depths ranging from 1-8 meters. This is characterized by the erosion of the river bank reinforcement building on the right side of the Anai River to the estuary.



(a) (b)

Fig. 7. Sediment transport capacity of Anai River: (a) Brown Formula method; (b) Engelund-Hansen Formula method

Sediment transport capacity ranges from 0.00001-0.001 m^3/s with a return period discharge Q10 - Q100, an average of 0.00055 m^3/s (47.52 m^3/day) is relatively small because it is dominated by loose sand grains that are easily dislodged during floods. Sediment transport of 47.52 m^3/day (17,344.8 $m^3/year$) is distributed along 12 km with a river width of 30-286 m to the estuary with a depth of 1 - 8 meters.

Sediment discharge is calculated as the sediment transport capacity in the river using two formulas, namely the Engelund-Hansen Formula and Brown Formula methods. As a result, the sediment volume calculated in this study shows different values in each formula. It is seen that the longitudinal fluctuation of the river bed tends toward degradation and this indicates the flushing tendency of sediment deposits and the lack of supply from downstream deposits. In the case of normal flow, the river channel bed in the vicinity of the river mouth is considered to be prone to sedimentation, but will be flushed during the flood discharge that occurs (Major et al., 2019; Sclafani et al., 2018).

Material extraction from the riverbed needs to be controlled to avoid over-exploitation. Excessive material extraction can cause scouring of the riverbanks to worsen, which in turn can threaten the structure of bridges and other infrastructure crossing the Anai River. To overcome this problem, the construction of sediment control structures such as check dams and groundsills, as well as securing the riverbanks, are needed (East et al., 2018; Major et al., 2019; Mizuyama, 2008; Sclafani et al., 2018; Zeng et al., 2009).

Sabo Dam Design for Debris Flow Management

The management of debris flows in the Anai River structurally includes several important things. First, the source of sediment comes from pyroclastic flows and debris flows due to the eruption of Mount Marapi, from which large amounts of sediment flows downstream. Second, the rivers in the Mount Marapi area that have their headwaters around the summit receive sediment supply from pyroclastic material deposits from the eruption. Third, to prevent riverbed rise that can cause lava runoff, it is necessary to prepare sediment control facilities to manage the sediment flow. The location of the Sabo dam construction for debris flow management is located in two locations between the border of Padang Panjang City and Tanah Datar Regency, which can be seen in Fig. 7.

(a) (b)

Fig. 8. Location of Sabo dam on the Anai River

In an effort to optimally control sediment, the Sabo dam is designed to handle sediment volume based on several important parameters. First, unstable sediment per meter estimated from the multiplication of the thickness of unstable sediment shows that its thickness is two meters with the width of the river. The Sabo dam with a height of more than five meters was chosen because it is able to effectively hold, control and contain sediment. Second, the effective longitudinal length of a dam is the horizontal measure of the dam which plays a role in the sediment control process along the river flow. The closed type Sabo dam is used when there is a small and moderate flood. Third, the sediment discharge factor is set at 0.8, which means that 80 percent of the sediment moving through the dam can be controlled or held by the dam structure. Taking these three parameters into account, the volume of sediment held by the Sabo dam is restrained. East et al. (2018) highlighted that a Sabo dam significantly reduces the speed and volume of sediment transported downstream, thereby reducing the potential for damage to infrastructure and communities.

The application of the Sabo dam with this approach is expected to control sediment flow efficiently, reduce the risk of disasters such as flash floods or debris flows, maintain stability, and maintain the health of the ecosystem in the Anai River. The typical design of the Sabo dam in the management of debris flows in the Anai River can be seen in Fig. 9.

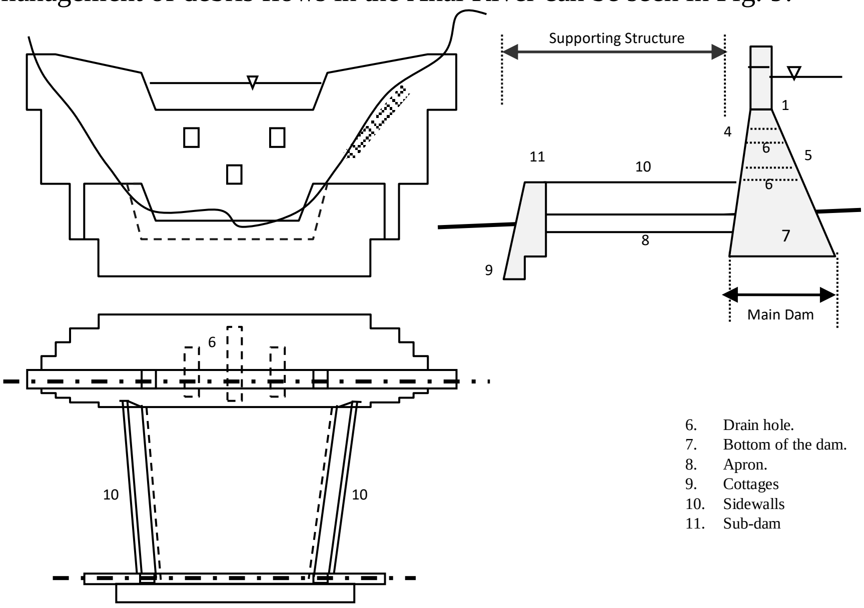


Fig. 9. Sabo dam design in Anai River

The Sabo dam planning aims to efficiently manage sediment, maintain a balance between sediment production and flow, and ensure sediment can safely pass through control points. Various Sabo building facilities are designed to accommodate excess sediment (Ve) volumes through several mechanisms. Dams, as the main components, function critically in sediment storage, regulation, and restriction. Zeng et al. (2009) emphasized the need for periodic inspections and sediment removal to ensure the dam remains functional. The development of this control infrastructure requires careful planning so as not to disturb the natural balance of the river (Malik et al., 2020; Piton et al., 2019; Schmidt et al., 2016). The materials needed for this construction must be managed wisely, ensuring that the material extraction process does not interfere with the supply of natural sediments that are essential for the balance of the river ecosystem.

5. Conclusion

Debris and lava flows from Mount Marapi are an important source of sedimentation for the balance of the Anai River bed from upstream to estuary and the surrounding coastal area. The supply of this sediment needs to be maintained, especially in areas prone to erosion that threaten settlements, bridges, roads, and other strategic areas. Protection of natural sediment supply is essential to maintain the stability and integrity of infrastructure and the surrounding environment. Control of overexploitation in the extraction of materials in the riverbed is very necessary. Excessive material extraction can worsen the erosion conditions on the river banks, which in turn threatens the bridges that cross the Anai River.

To overcome this, it is necessary to build sediment control buildings such as check dams, groundsills, and river bank security. The management of debris flows in the Anai River structurally involves several important aspects. First, the source of sediment comes from pyroclastic flows and debris due to the eruption of Mount Marapi, which carries large amounts of sediment to the downstream area. Second, the rivers around Mount Marapi which have their headwaters receive sediment supply from pyroclastic material deposits due to the eruption. Third, to prevent riverbed rise that can cause lava runoff, effective sediment control facilities are needed to manage the flow of sediment. The construction of this controlling infrastructure also requires materials, so it needs to be regulated properly so as not to disturb the natural balance of the river.

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