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Evaluating Flash Flood Hazards in West Sumatra: Insights from Topographic and Meteorological Data

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Abstract

Flash floods, defined by the rapid flow of water mixed with landslide debris, represent a significant threat to areas with sloped or mountainous terrains. In Tanah Datar Regency, West Sumatra, a region dominated by hills and mountains, these natural disasters are particularly concerning due to the region's topographical and meteorological characteristics. The steep slopes and high rainfall intensity create conditions favorable for large-scale debris flows, making this area highly vulnerable to flash floods. To understand the extent of this hazard, a numerical analysis was conducted using topographic and meteorological data, incorporating rainfall records from 2020 to 2023. The analysis revealed a peak flow discharge of approximately 1017.3 cubic meters per second (m^3/s), which has the potential to cause riverbank flooding extending 15 to 30 meters beyond the river boundaries. This level of discharge poses significant risks to communities living near rivers, as the flooding could result in substantial damage to property, infrastructure, and livelihoods. Moreover, the numerical models suggest that future discharges may surpass the recorded peak levels, further increasing the potential for catastrophic impacts. These findings highlight the urgent need for increased awareness and preparedness among the population, particularly those residing along riverbanks. Proactive measures, such as the implementation of early warning systems, improved disaster education, and reinforcement of riverbanks, are critical to mitigating these risks. Additionally, sustainable land-use practices and stricter regulations on hillside developments can help reduce the likelihood of landslides contributing to debris flows. With coordinated efforts from local authorities, policymakers, and the community, the resilience of Tanah Datar Regency can be enhanced, minimizing the devastating consequences of flash floods in the future.
Keywords: Flash Flood Potential, Galodo, Tanah Datar Regency, Numerical Analysis.

Abstrak

Banjir bandang, yang didefinisikan sebagai aliran air yang deras bercampur dengan material longsoran, merupakan ancaman serius bagi wilayah dengan medan miring atau pegunungan. Di Kabupaten Tanah Datar, Sumatera Barat, sebuah wilayah yang didominasi oleh perbukitan dan pegunungan, bencana alam ini menjadi perhatian khusus karena karakteristik topografi dan meteorologinya. Lereng yang curam dan intensitas hujan yang tinggi menciptakan kondisi yang mendukung terjadinya aliran puing berskala besar, menjadikan daerah ini sangat rentan terhadap banjir bandang. Untuk memahami sejauh mana bahaya ini, dilakukan analisis numerik menggunakan data topografi dan meteorologi dengan memasukkan catatan curah hujan dari tahun 2020 hingga 2023. Analisis tersebut mengungkapkan debit aliran puncak sekitar 1017,3meter kubik per detik (m^3/s), yang berpotensi menyebabkan banjir di sekitar tepi sungai dengan luapan mencapai 15 hingga 30 meter dari batas sungai. Tingkat debit ini menimbulkan risiko signifikan bagi masyarakat yang tinggal di sekitar sungai, karena banjir dapat menyebabkan kerusakan besar pada properti, infrastruktur, dan mata pencaharian. Selain itu, model numerik menunjukkan bahwa debit di masa depan mungkin melampaui tingkat puncak yang tercatat, sehingga meningkatkan potensi dampak yang lebih buruk. Temuan ini menekankan perlunya peningkatan kesadaran dan kesiapsiagaan di kalangan masyarakat, terutama mereka yang bermukim di sepanjang tepi sungai. Langkah-langkah proaktif, seperti penerapan sistem peringatan dini, pendidikan bencana yang lebih baik, dan penguatan tepi sungai, sangat penting untuk mengurangi risiko ini. Selain itu, praktik tata guna lahan yang berkelanjutan dan peraturan yang lebih ketat terhadap pembangunan di lereng bukit dapat membantu mengurangi kemungkinan longsor yang berkontribusi pada aliran puing. Dengan upaya terkoordinasi dari pemerintah daerah, pembuat kebijakan, dan masyarakat, ketahanan Kabupaten Tanah Datar dapat ditingkatkan, sehingga meminimalkan dampak buruk dari banjir bandang di masa depan.
Kata kunci: Potensi Banjir Bandang, Galodo, Kabupaten Tanah Datar, Analisis Numerik.

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INTRODUCTION

The potential for flash floods in hilly areas is a serious threat to the safety of residents and the surrounding environment. Flash floods usually occur suddenly, without warning, due to high rainfall quickly, so water flows very quickly from the hillsides to the lowlands (Chandra Wijaya, 2021; Rubinato et al., 2019). Topographic factors in hilly areas greatly influence the rate of water flow. (Kasus Agustus & Binoto Tampubolon, 2022). When heavy rain falls, rainwater cannot fully seep into the ground due to the steep surface slope, so the water tends to flow directly downwards. In addition, the soil condition which may have been saturated due to previous rain worsens the situation. This accumulation of water then triggers a strong current that carries mud, rocks, and other materials from the slope, causing major damage to the areas it passes through.(Farida & Dwangga, 2022). Flash floods not only cause material losses but can also threaten lives, especially in densely populated areas..

Another factor that increases the risk of flash floods in hilly areas is deforestation or clearing of forests. (Damanik et al., 2020). Natural vegetation, such as trees and shrubs, has an important role in absorbing rainwater and preventing soil erosion (Cressendo et al., 2023). When forests on hillsides are cleared to make way for agriculture, plantations, or development, the topsoil becomes unstable and easily eroded. The loss of vegetation cover accelerates the erosion process so that loose soil and rocks are carried away by rainwater. In addition, deforestation also reduces the soil's ability to absorb water, which in turn increases the volume of water flowing on the surface. Thus, areas that were previously relatively safe from flash floods can become very vulnerable if there is a change in the ecosystem due to human activity.

In addition to deforestation, infrastructure development that does not consider natural conditions can also worsen the potential for flash floods.(Ivana et al., 2021). The construction of roads, housing, and other facilities in hilly areas is often not accompanied by an adequate drainage system. Narrow or irregular water channels will make it difficult for rainwater to flow properly, so that water stagnates and accumulates in one location. When the water can no longer be held back, flash floods will occur quickly, carrying materials that can damage buildings and disrupt human activities. Unsustainable development also often ignores aspects of land conservation, such as replanting trees on hillsides (Parmelian et al., 2022). Therefore, it is important to ensure that every development project in hilly areas pays attention to environmental sustainability and prioritizes flood risk mitigation. Research on flash flood analysis has been extensively conducted in previous studies; however, analyzing flash floods specifically in Tanah Datar Regency remains an area that has yet to be explored. The need for such an analysis in this study area arises from information provided by the local community.

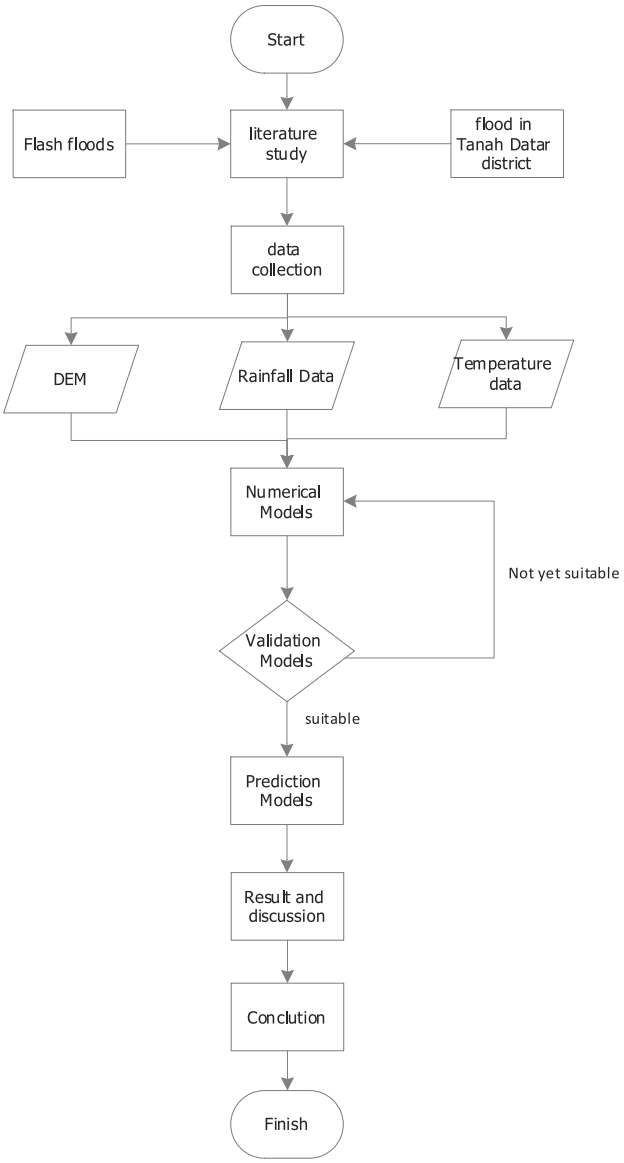
To reduce the potential for flash floods in hilly areas, a holistic approach is needed through synergy between the government, community, and private sector. The first step that must be taken is to improve environmental governance by strengthening forest protection and reforestation in critical areas. Mitigation programs such as terracing and maintaining good drainage systems on hillsides are also very important (Rubinato et al., 2019). In addition, there needs to be intensive socialization among local communities about the importance of maintaining the balance of nature, such as avoiding land clearing activities in areas prone to erosion. The government must also set strict regulations for development in hilly areas, including ensuring that infrastructure projects are equipped with efficient water handling systems (Burandt et al., 2024). With these steps, the risk of flash floods in hilly areas can be minimized, so that people can live more safely and the environment remains sustainable. Tanah Datar Regency, Lintau Buo area has a dark history of flash floods in the past. Galodo, which is better known there as another name for flash floods in the past, has claimed many lives. High debris in a short time came and flowed rapidly in the river causing everything to be destroyed and residents who did not have time to evacuate were swept away at that time. Thus, disaster mitigation needs to be carried out with a map of the potential for flash flood disasters in several areas. In this study, an analysis of the potential areas affected by flash floods was carried out in one area in Tanah Datar Regency. This study aims to predict the potential extent of flood inundation during a flash flood event. The analysis is conducted using minimum conditions during annual maximum rainfall. With this information, it becomes possible to estimate the broader impacts of flooding

if a flash flood occurs. This analysis was carried out using a numerical method accompanied by hourly rainfall data from 2020 to 2023. In addition, forecasting of return period rainfall data was carried out to simulate the flash flood discharge that occurred and an analysis of the potential volume of water retained in the hilly areas which would become deadly debris if it flowed suddenly.

METHOD

a. Data collection

The data used in this study are topographic data and meteorological data. The data are analyzed to be adjusted to the needs of the numerical analysis to be carried out. The research process is briefly illustrated in the following figure 1.



Picture 1. Flow Chart of the Riset

b. Numerical Analysis

Numerical analysis is done by combining basic hydraulic equations in the form of continuity equations, momentum equations, conservation of energy, and hydrological equations which are done with the help of computers(El-Saoud & Othman, 2022; Yassin et al., 2023; Zhang et al., 2022).

The energy equation is written as follows.

$$Z_2 + Y_2 + \frac{a_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{a_1 V_1^2}{2g} \quad (1)$$

Where Z_1,Z_2 is the elevation of bed river, Y_1, Y_2 is the depth of the water in the cut sectionn, V_1, V_2 is the velocity rate, a_1,a_2 is the flow load coefficient, g is the gravity coefficient (9,81 m/s^2), h_c is the energy losses (Armanini, 2017; Guo & Sharp, 1996; James, 2020). While the energy loss equation is given by:

$$h_c = L\bar{S_f} + C\left|\frac{a_2 V_2^2}{2g} - \frac{a_1 V_1^2}{2g}\right| \quad (2)$$

Where L is a discharge weighted by the length of the river, $\bar{S_f}$ is a representation of the friction slope between two parts, and C is the expansion or contraction of the loss coefficient (Knight, 2013; "Research on Hydraulics and River Dynamics," 2023). While the continuity equation is given by the formula.

$m_1 = \rho_1 v_1 A_1$ dan $m_2 = \rho_2 v_2 A_2$

Continuity means that mass 1 and mass 2 do not change or it is assumed that no energy is lost so that:

$$\rho_1 v_1 A_1 = \rho_2 v_2 A_2 \quad (3)$$

Where m is the mass of fluid per time (slug atau kg), V is the velocity of cross section in the channel (ft/s atau m/s) , A is the area of water (ft^2 atau m^2), ρ is density of fluid (slug atau slug/ft^2 or kg/m^3)(Chaudhry, 2013).

c. Hydrology Analysis

Hourly rainfall determination is carried out to determine the planned rainfall for a return period of several hours. In this study, hourly rainfall determination was carried out for 5 hours. Some of the equations used in determining hourly rainfall are::

$$R_t = R_0 \left(\frac{5}{T}\right)^{2/3} \quad (4)$$

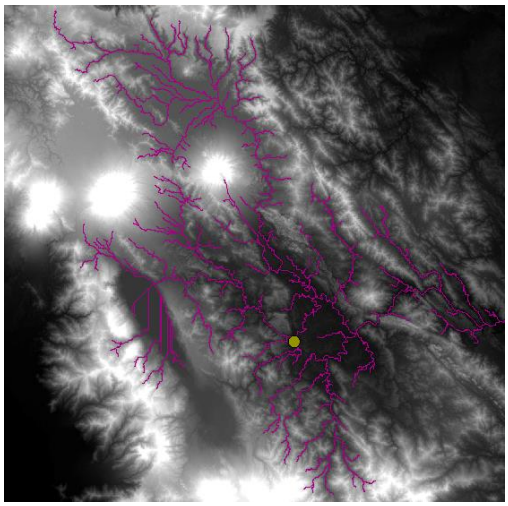
Where R_t = average rainfall from the beginning to hour T, $R_0 = \frac{R_{24}}{5}$, T = Rain time from the beginning to the T-hour, R_{24} = daily rainfall efective (net rainfall causing runoff), Next, to determine the amount of rainfall at hour T, the following equation can be used (Herrmann & Bucksch, 2014; Walling, 1978):

$$R_T = t.R_t - (t-1)R_{(t-1)} \quad (5)$$

Where R_T = the amount of rainfall at hour T, t = Rain time from the beginning to hour T, R_t = average rainfall from the beginning to hour T, $R_{(t-1)}$ = average rainfall from the beginning to hour (t-1)(Herrmann & Bucksch, 2014).

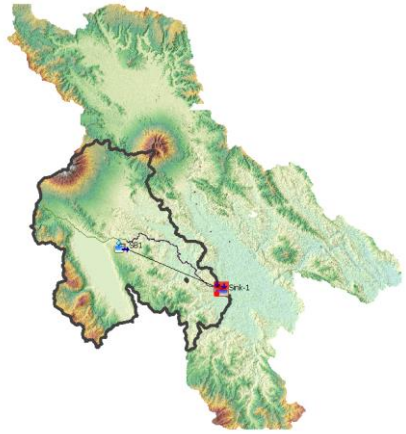
RESULTS

The topography of the West Sumatra region is classified as a steep hilly area. Many locations have steep cliffs that have the potential for high water currents. This is evidenced by the display of the results of the topographic analysis carried out as in Figure 2 below.



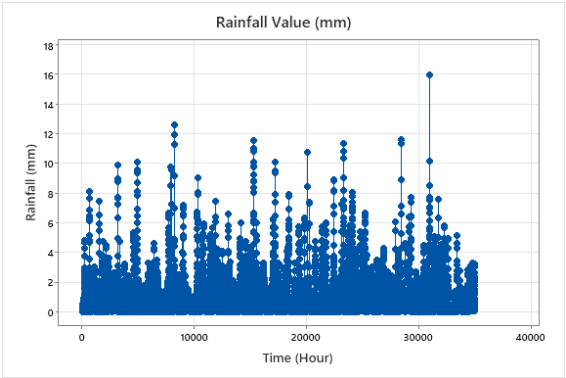
Picture 2. Digital Elevation Model West Sumatra Tanah Datar Regency

It can be seen from the image above that there are several mountains and steep hills marked with bright white. This indicates a steep slope in several locations that will have an impact on the high water flow that will occur if there is high rainfall. Based on the topographic conditions of the River Basin Area (DAS) up to the observation point, the area can be determined. Hydrologically, the DAS is determined by the existing ridge boundaries. The results of the analysis show that the DAS used in this study is as in Figure 3 below.



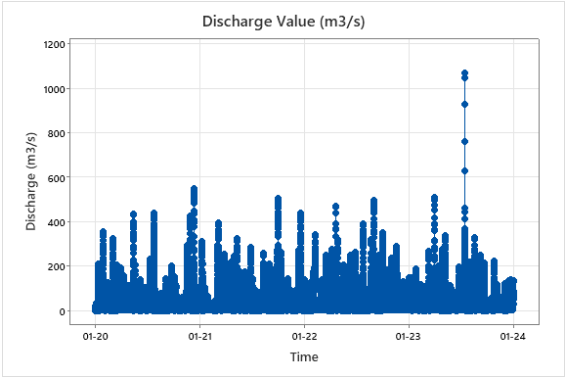
Picture 3. Watershed

In the analysis conducted, the watershed was made into one basin to calculate the flow rate that occurred. Based on the analysis, it is known that the watershed area is around 1574.1 km^2. Using hourly rainfall data from 2020 to 2023, the analysis process was carried out. The height of rainfall at that time is displayed graphically as in Figure 4 below..



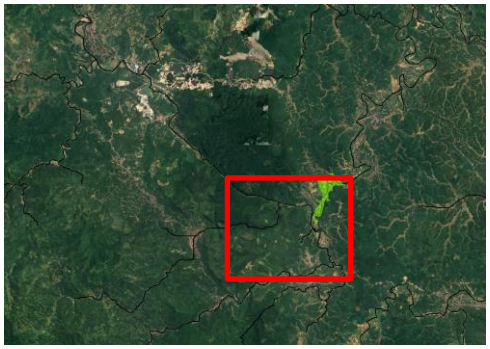
Picture 4. Hourly rainfall in 2020 to 2023

With the hydrological analysis carried out, the relationship between rainfall and discharge is known. The hourly discharge from 2020 to 2023 can be displayed as in Figure 4 below.



Picture 5. Hourly debit from 2020 to 2023

If observed, the hourly discharge that occurs is still relatively small and not dangerous for the daily rainfall that occurs. In 2023 around July, there was a large extreme discharge of around 1071.3 m^3/s. This extreme discharge must be watched out for for the existing river conditions. Based on this discharge, a flood analysis was carried out at the study location, namely in an area with latitude coordinates of -0.666684° and longitude 100.833328°. The simulation results are shown in Figures 6 and 7 below.



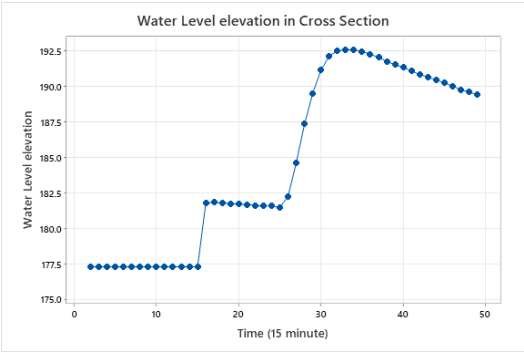
Picture 6. Flood simulation study area for extreme rainfall in 2023



Picture 7. Flood conditions at the study location

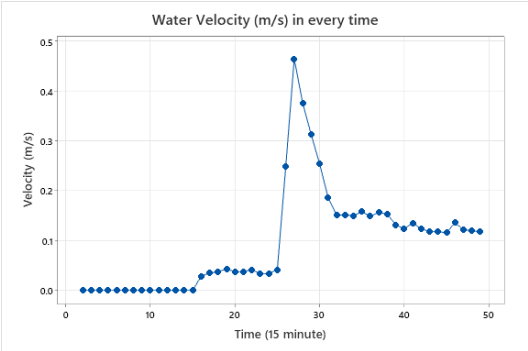
Based on the image above, it can be seen that the area of flood inundation has reached the houses of residents around the river. The area of flood inundation ranges from 15 to 30 meters on the riverbank. There are even several houses that are inundated and affected by the momentum of the water flow. This certainly shows the potential for loss of life if a flash flood hits the Tanah Datar district. The area of flood inundation is certainly not that large compared to the condition of a flash flood that carries high debris and is increasingly threatening. This should be watched out for by the local community.

The increase in water level over time can be found in the graph of the relationship between water level elevation and time as follows the figure 8.



Picture 8. Water surface elevation in every 15 minute

The graph shows the change in water surface elevation in a cross-section over a 50-minute period, with 15-minute intervals. Initially, the water level is stable at around 177.5 meters, then experiences a sudden increase around the 15th minute, reaching 182 meters. After a short stable period, there is a second, more significant spike starting at the 25th minute and reaching a peak of around 192.5 meters at the 35th minute. After that, the water level begins to decrease slowly until it reaches around 190 meters at the end of the observation. In addition to the increase in river water levels, this influence also affects the speed of water flow. This can be seen in the following graph in figure 9.



Picture 9. Water velocity in every 15 minute

This graph shows the change in water flow velocity (m/s) over 50 minutes with 15-minute intervals. Initially, the water velocity was in the low range, around 0 to 0.1 m/s, and was relatively stable until around the 20th minute. After that, there was a rapid spike at the 25th minute, where the velocity peaked at around 0.5 m/s. The velocity then dropped sharply until the 30th minute, followed by small fluctuations with a stable velocity of around 0.1 to 0.2 m/s until the end of the observation at the 50th minute.

Previous studies have conducted various analyses, including social community impacts, flood potential based on ground elevation, and flood extent in specific rivers within certain regions (Abedi et al., 2022; Archer & Fowler, 2021; Wu et al., 2023; Zhai et al., 2021). The impact of flash floods is significant, often leading to the collapse of riverbanks, damage to river infrastructure, and potential loss of life(Buslima et al., 2018; Li et al., 2024; Ma et al., 2021; Terti et al., 2019). The extent of flash flooding is primarily influenced by the ground elevation conditions surrounding the river. Vulnerable riverbanks that are easily eroded can contribute to the collapse of river walls and expand the impact of flooding(Duan et al., 2022; Pham et al., 2020; Saleh et al., 2022; Yao et al., 2022).

In this study, it was found that the impact of flash floods in Tanah Datar Regency is substantial. This is evident from the normal flood inundation extent, which ranges between 15 and 30 meters. Additionally, the flow velocity during normal flooding conditions reaches approximately 0.5 m/s, which is likely to increase significantly during a flash flood event.

CONCLUSIONS

Flash floods are extreme conditions of water mixed with landslides that occur suddenly. The debris discharge is very large which will come with great momentum. Based on the numerical simulations carried out from this study, it shows that extreme rain conditions alone are very dangerous for the community around the Tanah Datar Regency River. This shows that the potential for deadly flash floods is very large. Therefore, rehabilitation of hilly areas needs to be carried out immediately and maintained so that the potential for flash floods is small to occur.

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