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Flood Vulnerability Assessment in Ambon City: A Morphometric Approach of Wai Batu Merah and Wai Tomu Watershed

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Abstract: Ambon City faces high flood vulnerability due to heavy annual rainfall, complex topography, and rapid urbanization. This study evaluates the influence of morphometric parameters on flood susceptibility in the Wai Batu Merah and Wai Tomu watersheds by analyzing the bifurcation ratio (Rb), drainage density (Dd), and texture ratio (Rt). Morphometric parameters were derived from 8-meter resolution DEMNAS data and calculated using a GIS based quantitative approach. The results show that Rb values range from 1.3 to 2.0 reflecting a complex stream network influenced by structural deformation, which triggers a rapid hydrological response. Dd values exhibit a clear spatiial contrast ranging from 2.7 to 7.0; sub-watersheds WT3 and WT4 display the highest densities, associated with impermeable lithology and steep slopes, potentially generating high surface runoff and rapid peak discharge. Meanwhile, Rt is dominated by very coarse classes, indicating runoff accumulation susceptibility within the Ambon volcanic rock and coral limestone units. Sub-watersheds WT3, WT4, BM1, BM2, and BM6 are identified as high priority areas for mitigation. This study addresses the research gap in flood risk mapping for data scarce regions by demonstrating that integrated morphometric analysis provides a precise scientific basis for watershed management prioritization. These findings serve as a strategic foundation for spatial planning and vegetation conservation to minimize disaster risks in complex urban geological settings.

Keywords : Wai Batu Merah and Wai Tomu watershed; morphometric; quantitative geomorphology; flood vulnerability; Ambon City

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Introduction

Flood are natural disaster (Khosravi et al., 2019) that commonly occur in Indonesia and have a significant impact on communities and infrastructure (Pourghasemi et al., 2018). The city of Ambon as a center of growth in eastern Indonesia is one of the areas with a high level of vulnerability to flooding (Lasaiba, 2023). High annual rainfall (Kurniawan, 2019), varied topography, and uncontrolled land use development make Ambon City prone to flooding (Lasaiba, 2023; Sinay et al., 2020).

One approach that can be used to evaluate flood risk physically is through watershed morphometric analysis (Sukiyah, 2012; Rendra & Sukiyah, 2021; Haryanto et al., 2019; Rendra, 2023; Fahira et al., 2025). Watershed morphometry involves quantitative measurements of the shape and structure or river networks, which provide important insights into the hydrological response of a watershed to rainfall (Horton, 1945; Schumm, 1956; A. Strahler, 1964). Parameters such as drainage density (Dd), texture ratio (Rt), and bifurcation ratio (Rb) have been proven effective as early indicators of flood susceptibility (Soewarno, 1991; Nag & Chakraborty, 2003; Víg et al., 2022). Rb reflects the control of geological structures on river networks, Dd indicates the efficiency of watersheds in draining surface water, while Rt provides an overview of infiltration capacity and subsurface lithological conditions. These three parameters were selected because they are considered the most sensitive indicators for assessing physical flood vulnerability in areas with complex topographical characteristics such as Ambon City. So, that the analysis results remain accurate even when using efficient parameters.

Drainage density (Dd) is the ratio between the total lengths of river flow and the watershed area, which indicates how quickly surface runoff flows into the main river. A high Dd value indicates a rapid hydrological

response and an increased risk of peak discharge during extreme rainfall (Víg et al., 2022). Meanwhile, the bifurcation ratio (Rb) reflects the degree of river channel branching and is influenced by the geological structure and topography of the watershed. A high Rb indicates a complex flow system and has the potential to accelerate surface runoff downstream (Horton, 1945; A. Strahler, 1964). The high Rt suggests that the watershed has a high density of stream segments relative to its perimeter, which is typically associated with impermeable lithology, low infiltration capacity, and high relief, all of which contribute to a more hydrological response.

Previous studies have utilised morphometric parameters to assess disaster risk (Fahira et al., 2025), including flood potential in the Maluku region, particularly in Ambon City. Research by Tuanany and Sukiyah (2021) and Tuanany et al. (2024) on the Wairuhu watershed shows that morphometric characteristics are closely correlated with flood susceptibility. Meanwhile, Pattiselanno (2017) studied the Wai Loning watershed in Negeri Laha and concluded that GIS-based analysis and morphometric parameters can map areas prone to flooding. Similar analyses were also applied by Rakuasa et al. (2024) in modelling flood hazards in the Wai Batu Gantung watershed and by Tuanany et al. (2025), who emphasized the role of morphometry and land cover in flood assessment in Ambon City.

The Wai Batu Merah and Wai Tomu watersheds are located in the coastal area of Ambon City (see figure 1), which is one of the important watersheds with high pressure due to urbanization in the central downstream area and changes in hydrological conditions (Rakuasa et al., 2022; Latue et al., 2023). To complement the flood susceptibility analysis that has been conducted previously, this study will use a watersheds morphometric approach, specifically by examining the drainage density (Dd) and bifurcation ratio (Rb) parameters in the Wai Batu Merah and Wai Tomu watersheds through a morphometric approach, it is hoped that the results of this study can provide a more scientific basis for more targeted flood risk management in Ambon City.

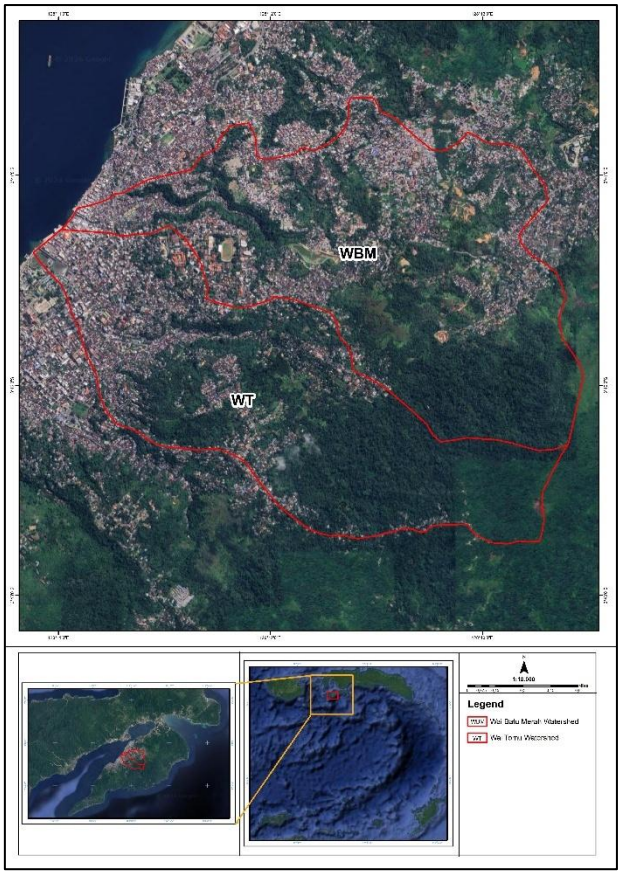


Figure 1. Location of Wai Batu Merah and Wai Tomu watersheds as study Area

Methodology

Morphometric indices are crucial data in climate change studies, environmental protection, and disaster monitoring. To produce quantitative geomorphological spatial distribution maps, raster data from Digital Elevation Model (DEM) imagery is required. This study analyses the characteristics of Watershed Areas (DAS) using DEMNAS data with a resolution of 8 metres (Badan Informasi Geospasial, 2024) on the UTM Zone 52S projection system, which refers to the World Geodetic System 1984 (Siahaan et al., 2022).

The process of delineating and extracting river networks in this study was carried out digitally using DEMNAS 8m data as the main database. The initial stage began with preprocessing (Fill Sinks) of elevation data to ensure flow continuity. Next, landform identification was carried out through Flow Direction analysis using the D-Eight (D8) algorithm to determine the direction of water movement based on the steepest slope. The river network was determined through Flow Accumulation analysis, in which the valley area was defined as a river channel. These river lines were then classified using the Strahler method to determine the river order. At the same time, the outer boundaries of the watershed or sub-watershed were defined based on ridgelines that functioned as drainage divides. After the watershed polygons and river network are formed, the next step is to transform spatial data into quantitative data through the calculation of watershed dimensions and morphometric parameters. These parameters, which include area, river length, Bifurcation Ratio (Rb), Drainage Density (Dd), and Texture Ratio (Rt), are used to understand the physical characteristics and hydrological response of the region to rainfall and to map the level of flood vulnerability. The research flow can be seen in figure 2.

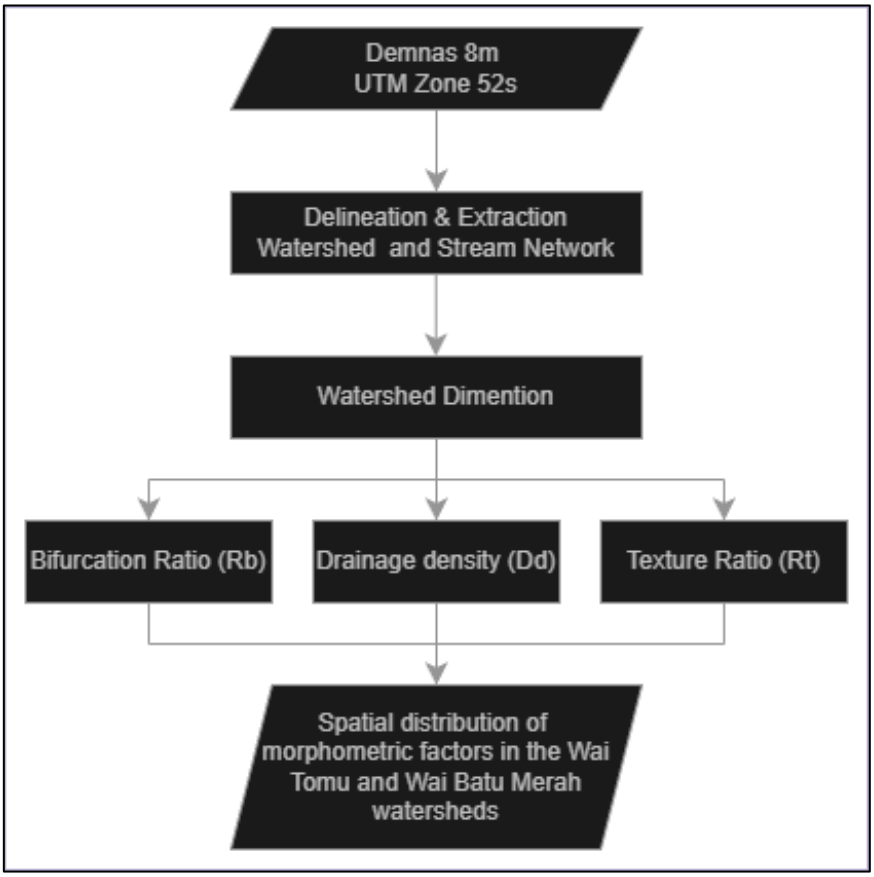


Figure 2. Methodological flowchart of the study in Wai Batu Merah and Wai Tomu Watershed

Bifurcation Ratio (Rb)

The bifurcation ratio (Rb) is the ratio between the number of stream segments of a given order and the number of stream segments of the next higher order (Schumm, 1956; Rai et al., 2017). The bifurcation ratio value of first-order streams is highly sensitive to stream development and can be used as an indicator of geological

structures or tectonic activity (Keller & Pinter, 1996; Winarto et al., 2019). A bifurcation ratio value of 3.0–5.0 usually has the characteristics of a homogeneous and stable geological condition (lithology, morphology, and geological structure) in a watershed or sub-watershed (A. N. Strahler, 1957; Sukiyah, 2012). The classification of Rb values can be seen in Table 1. A. N. Strahler (1957, as cited in Javed et al., 2009) demonstrated that the bifurcation ratio value differs only slightly between different areas, unless there is a dominant geological structure influence. The first variable used in watershed morphometric analysis is the Bifurcation Ratio (Rb). The Rb value is calculated using the formula (1):

$$Rb = \frac{\sum \mathrm{Nu}}{\sum \mathrm{Nu+1}} \qquad (1)$$

Where:

Rb = River bifurcation ratio

Nu = Number of stream segments of order u

Nu + 1 = Number of stream segments of order u+1

Table 1. Classification of bifurcation ratio

Rb Value	Description (Soewarno, 1991)	Description (A. Strahler, 1964, as cited in Verstappen, 1983)
<3	The rise of floodwater level is very fast, and sedimentation occurs rapidly.	Experiences slight tectonic deformation, and the drainage pattern remains unchanged or has an old structure.
3-5	The rise of floodwater level is moderate, and sedimentation occurs at a moderate rate.	Not affected by tectonic deformation.
>5	The rise of floodwater level is fast, but sedimentation occurs slowly.	Experiences tectonic deformation.

Drainage density (Dd)

Drainage density is the ratio of river length to watershed area (Horton, 1945). The drainage density of a watershed or sub-watershed is usually influenced by various factors such as the weathering resistance of the bedrock, the permeability of the overlying rock, climate, and vegetation (Javed et al., 2009). A low drainage density value indicates that the area has rocks with high permeability and coarse drainage texture, while a high value indicates the opposite (Sukiyah, 2017; Van Zuidam, 1985) The classification of Dd values can be seen in Table 2. The drainage density can also be used to indicate the hardness of the rock. Rocks with low Dd values tend to be harder than rocks with high Dd values (Sukiyah, 2012). The drainage density index value can be obtained using Horton's (1945) formula (2):

$$Dd = \frac{L}{A} \qquad (2)$$

Where :

Dd = Drainage density index (km/km2)

ΣL = Total length if stream (km)

A = Watershed area (Km2)

Table 2. Classification of Drainage Density (Sukiyah et al., 2009)

Class	Texture	Dd (km/km^2)
1	Very Rough	0.00 – 1.37
2	Rough	1.38 – 2.75
3	Medium	2.76 – 4.13
4	Smooth	4.14 – 5.51
5	Fine	5.52 – 6.89
6	Very Fine	6.90 – 8.27

Texture Ratio (Rt)

The texture ratio is the ratio between the number of river segments in a watershed or sub-watershed and the perimeter of the watershed or sub-watershed. Smith (1950, as cited in Mani et al., 2025) divide texture categories into five classes, based on their relationship with the drainage density (Dd) value. The classification of RB values can be seen in Table 3. The texture ratio value is calculated using the following formula (3):

$$Rt = \frac{\sum N}{P} \qquad (3)$$

Where :

Dd = Drainage density index (km/km2)

ΣL = Total length if stream (km)

A = Watershed area (Km2)

Table 3. Classification of Texture Ratio (Smith, 1950; Mani et al., 2025)

Rt Value	Classification
<2	Very Coarse
2-4	Coarse
4-6	Moderate
6-8	Very fine

Results and Discussion

The dimensions of the sub-watershed in table 4 consisting of area, perimeter, length, and width, are measured in kilometres (km) (Table 4). Area and perimeter measurements are calculated using ArcGIS software. Meanwhile, the length of the sub-watershed is obtained by measuring the distance of the main river flow from upstream to downstream following the highest order river. This process is also carried out by measuring distances in ArcGIS, and can be seen on the map in figure 3.

Table 4. Dimensions of the Wai Batu Merah and Wai Tomu sub-watersheds

Watershed	Sub-Watershed	Area (km^2)	Perimeter (km)	Main river length (km)	Width (km)
Wai Batu Merah	BM1	0.83	4.57	2.25	0.369
	BM2	0.27	2.22	0.89	0.303
	BM3	1.59	8.74	1.57	1.274
	BM4	0.34	2.52	0.79	0.430
	BM5	0.65	4.08	1.61	0.404
	BM6	0.31	2.41	1.05	0.295
Wai Tomu	WT1	0.92	4.56	1.78	0.517
	WT2	1.5	6.49	2.96	0.507
	WT3	0.19	2.08	0.93	0.204
	WT4	0.12	1.46	0.54	0.222
	WT5	0.44	3.45	1.6	0.275

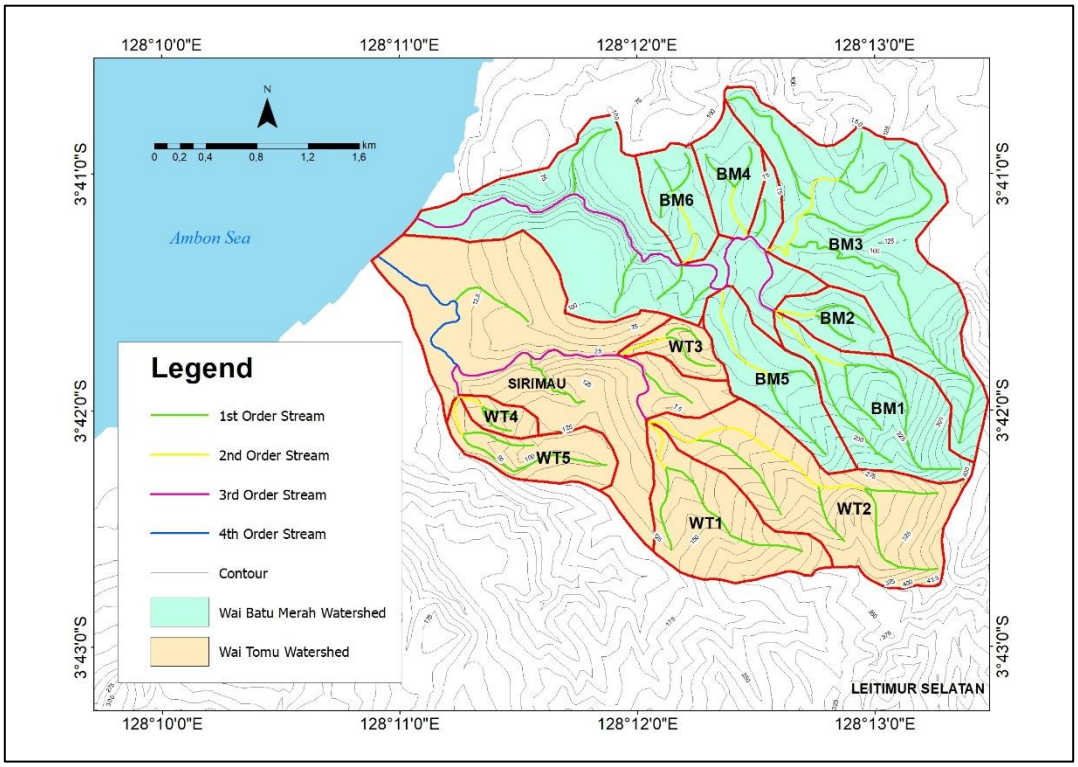


Figure 3. Watershed and stream order map of the Wai Batu Merah and Wai Tomu watersheds.

Bifurcation Ratio (Rb)

Based on the calculations in table 5, the Rb value ranges from 1.3 to 2.0. Which, according to Verstappen's (1983) equation indicates subduction if the value obtained is <3 and >5. The watershed has undergone deformation due to tectonic movement or volcanic activity in the past, which is reinforced by the geological conditions of the study area being dominated by deformed volcanic rocks (figure 4). Both watersheds have a river bifurcation ratio of around 1.3–2.0, reflecting the complexity of the river network in the region. Sub-watershed BM3 recorded the lowest Rb value of 1.3 indicating the highest level of deformation among the other areas. In contrast, some other sub-watersheds such as BM2, BM4, WT1, and WT3, had an Rb value of 2.0. Which, although higher was still within the range that had a dominant lithological influence.

Table 5. Results of River Branch Ratio (Rb) Calculations

Watershed	Sub-Watershed	Number of stream order		The Number of stream segments		Rb 1_2	Classification
		1	2	1	2		
Wai Batu Merah	BM1	3	1	3	2	1.5	Deformed
	BM2	2	1	2	1	2.0	Deformed
	BM3	5	1	5	4	1.3	Deformed
	BM4	2	1	2	1	2.0	Deformed
	BM5	2	1	2	1	2.0	Deformed
	BM6	3	1	3	2	1.5	Deformed
Wai Tomu	WT1	2	1	2	1	2.0	Deformed
	WT2	4	1	4	3	1.3	Deformed
	WT3	2	1	2	1	2.0	Deformed
	WT4	2	1	2	1	2.0	Deformed
	WT5	2	1	2	1	2.0	Deformed

Geologically, an Rb value < 3 indicates that the sub-watershed has a rapid rise in flood water levels, as well as a rapid decline (Soewarno, 1991). The entire watershed area is classified as a deformed area (see figure 4) , and most of it is composed of Ambon volcanic rock, ultramafic rock, and coral limestone. In some parts, these lithologies have low permeability and limited water absorption, thereby increasing the potential for surface runoff (Langbein, 1964; Howard, 1967). Thus, it can be concluded that although the river network has a low Rb value, this condition actually increases susceptibility to flooding, especially when combined with high rainfall, impermeable lithology, and suboptimal land use management.

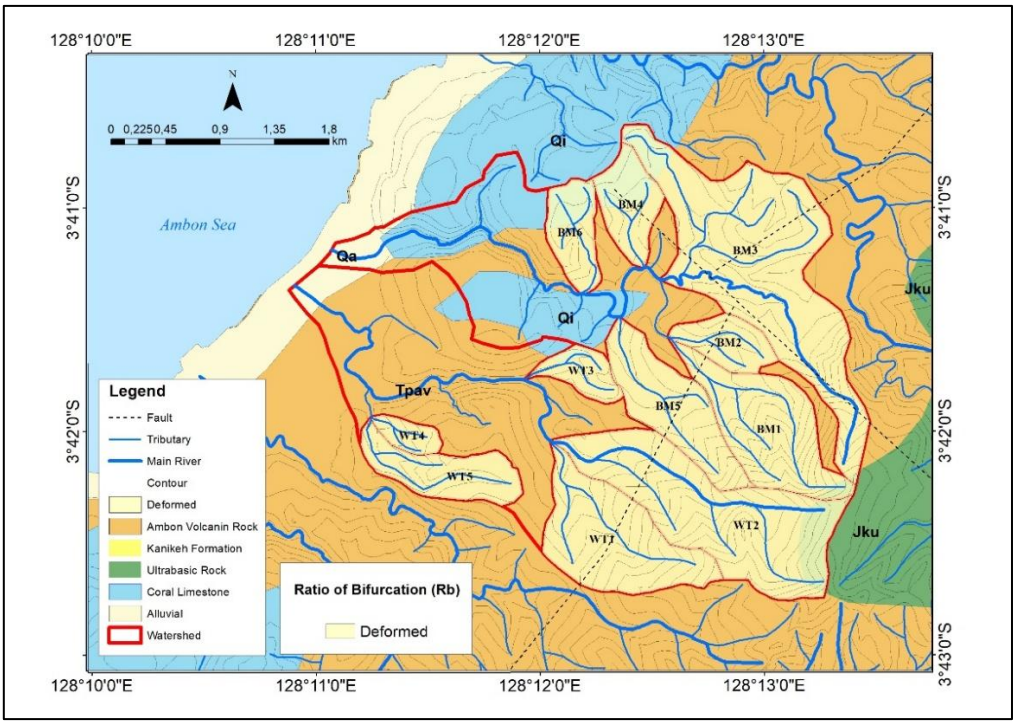


Figure 4. Map of Spatial Distribution of Bifurcation Ratio (Rb) in the Wai Tomu and Wai Batu Merah Watersheds

Drainage density (Dd)

Drainage density was first introduced by Horton (1945) and its use has been reinforced in hydrological disaster analysis (Rudraiah et al., 2008). The Dd value is greatly influenced by lithology, soil texture, slope gradient, rainfall, and vegetation cover, and is closely related to the potential for runoff and flood risk in an area.

Table 6. Results of Drainage Density (Dd) Calculations

Watershed	Sub-Watershed	Total Stream Length	Aera	Dd	Texture	Class
Wai Batu Merah	BM1	3.95	0.83	4.8	Smooth	4
	BM2	1.3	0.27	4.8	Smooth	4
	BM3	7.39	2	3.7	Medium	3
	BM4	1.15	0.34	3.4	Medium	3
	BM5	2.02	0.65	3.1	Medium	3
	BM6	1.57	0.31	5.1	Smooth	4
Wai Tomu	WT1	2.46	0.92	2.7	Rough	2
	WT2	4.98	1.5	3.3	Medium	3
	WT3	1.3	0.19	6.8	Fine	5
	WT4	0.84	0.12	7.0	Very Fine	6
	WT5	2.19	0.44	5.0	Smooth	4

The results of the two watershed calculations in table 6 show values ranging from 2.7 to 7.0. Sub-watershed WT4 has a Dd value of 7.0 with a very fine texture and class 6 indicating an impervious surface and high potential for surface runoff. Meanwhile, the lowest Dd value is found in sub-watershed WT1 which is 2.7 with a coarse texture and class 2 indicating that the area has higher infiltration and low surface runoff. Most sub-watersheds show a fine to medium texture (See figure 5a & 5b) with classes 3 and 4 indicating moderate conditions in terms of surface runoff. Sub-watersheds WT3 and WT4 have a fine to very fine texture which is associated with steep topography and indicates a dense river network due to low permeability lithology such as coral limestone and Ambon volcanic rock which can accelerate surface runoff and increase the risk of flooding (Montgomery & Dietrich, 1989). Sub-watersheds WT1 has a coarse texture indicating a fairly large watershed area but a limited number of channels. This allows for a long infiltration time and groundwater storage, resulting in a relatively lower potebtial for flooding (Sreedevi et al., 2005). The coarse texture of the WT1 watershed is closely related to its volcanic lithology. The volcanic bedrock in this area tends to have high resistance to weathering and high rock permeability (Javed et al., 2009; Sukiyah, 2012)

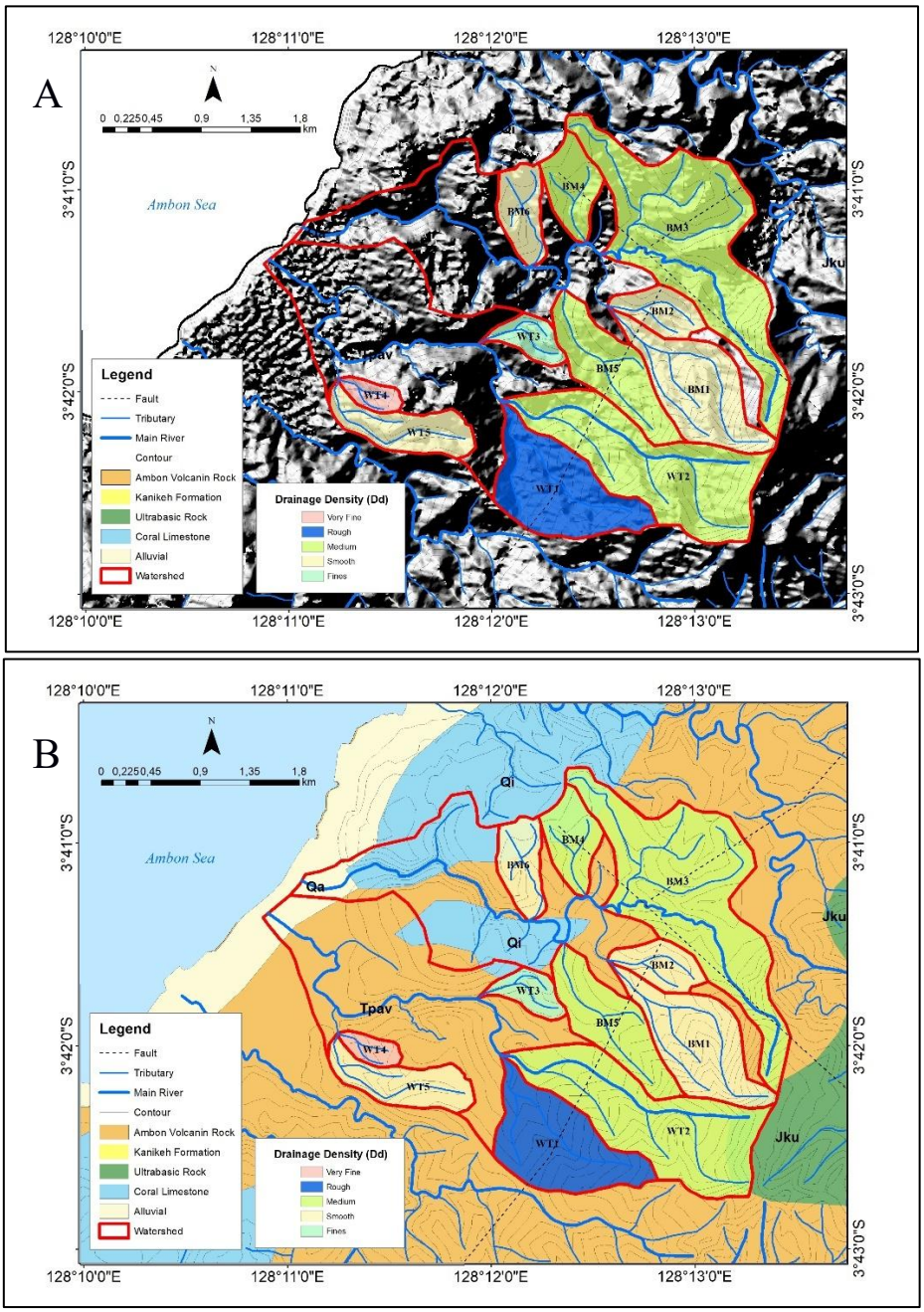


Figure 5. Map of Spatial Distribution of Drainage density (Dd) in the Wai Tomu and Wai Batu Merah Watersheds

Texture Ratio (Rt)

A high Rt value indicates high drainage density, which can increase the potential for surface runoff and the risk of flooding (Sutradhar & Mondal, 2023). The results of the analysis of 11 sub-watersheds in both watersheds in table 7 show that most are classified as very coarse (Rt < 2.0), and only two sub-watersheds are classified as coarse (Rt 2.0 ≤ Rt ≤ 4.0). Very coarse texture tends to reduce infiltration capacity due to the ultramafic and volcanic lithology found in this region. As a result, most of the rainwater flows as runoff directly into rivers without being absorbed first. Conditions with a majority of very coarse values, reflecting an undeveloped natural drainage system, will have implications for a slow response to rainfall, resulting in a high potential for flooding. The risk of flash floods is relatively low in most of the watershed, except in two sub-watersheds (see figure 6) with Rt values close to 2.0 (BM 6, WT 4), which are beginning to show an increase in channel density and may cause rapid flows downstream.

Table 7. Results of Texture Ratio (Rt) Calculations

Watershed	Sub-Watershed	Number of Stream Segments (Order)		Total	Perimeter	Rt	Classification
		1	2				
Wai Batu Merah	BM1	3	2	5	4.57	1.09	Very Coarse
	BM2	2	1	3	2.22	1.35	Very Coarse
	BM3	5	4	9	8.74	1.03	Very Coarse
	BM4	2	1	3	2.52	1.19	Very Coarse
	BM5	2	1	3	4.08	0.74	Very Coarse
	BM6	3	2	5	2.41	2.07	Coarse
Wai Tomu	WT1	2	1	3	4.56	0.66	Very Coarse
	WT2	4	3	7	6.49	1.08	Very Coarse
	WT3	2	1	3	2.08	1.44	Very Coarse
	WT4	2	1	3	1.46	2.05	Coarse
	WT5	2	1	3	3.45	0.87	Very Coarse

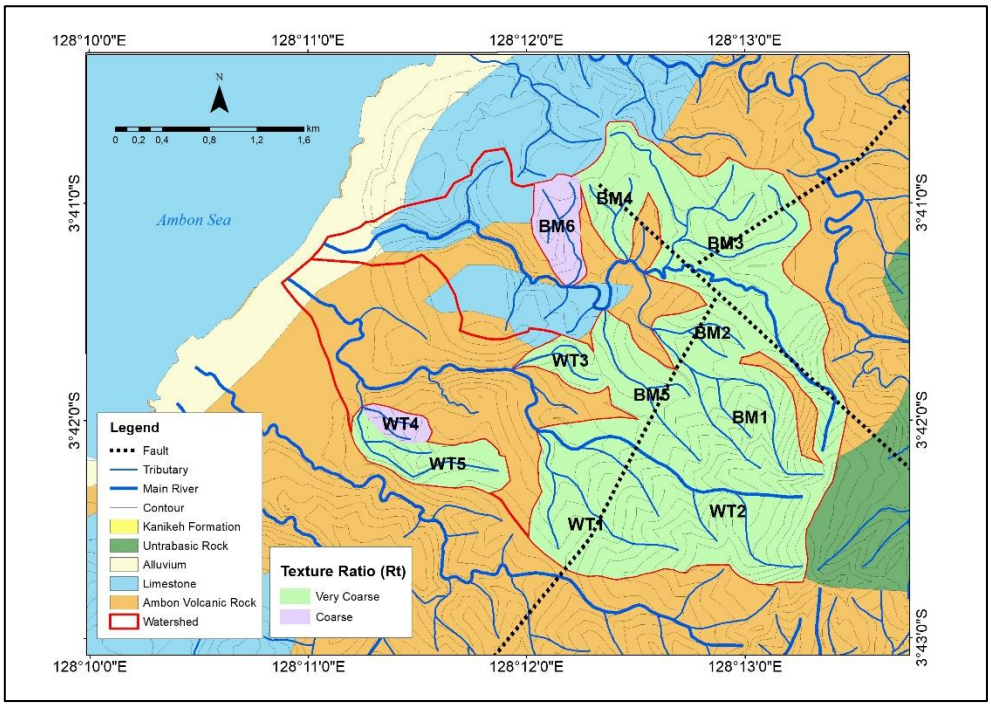


Figure 6. Map of Spatial Distribution of Drainage density (Dd) in the Wai Tomu and Wai Batu Merah Watersheds

Based on the integration of the three calculated morphometric parameters (Rb, Dd, and Rt), flood vulnerability across the entire Wai Batu Merah and Wai Tomu sub-watersheds can be comprehensively classified. Theoretically, sub-watersheds with high Dd and Rt values combined with low Rb values indicate the most critical level of flood vulnerability. A low Rb value (close to 2) indicates a rounded watershed shape, where flood peaks from various tributaries tend to arrive at the outlet point at the same time. This phenomenon is exacerbated by high Dd and Rt values, which reflect a very dense river network and high surface drainage efficiency, thereby shortening the time of concentration (Tc) and increasing the peak runoff discharge..

Conversely, sub-watersheds with low Dd values indicate greater infiltration capacity or more permeable lithological control, which directly reduces the risk of flash flooding. Spatial analysis of these parameters reveals that sub-watersheds WT3, WT4, BM1, BM2 and BM6 have the most responsive hydrological characteristics to high rainfall, making them a top priority in structural mitigation efforts. Thus, flood vulnerability assessment is no longer viewed from a single parameter but is the result of synergy between geological structure (Rb), flow density (Dd), and texture ratio (Rt), which collectively determine the flood risk profile across the entire study area.

Conclusions

The Rb value ranges from 1.3 to 2.0, reflecting complex deformation and stream networks, resulting in a rapid hydrological response. Dd shows a clear spatial contrast of 2.7 to 7.0 sub-watershed with very high Dd, particularly WT4 and WT3 associated with low permeability lithology and steep slopes thus potentially producing large surface runoff and rapid peak discharge. Rt is dominated by very coarse classes and only a small portion is coarse. The combination of high Dd and very coarse Rt indicates a drainage system that is prone to runoff accumulation, especially in the Ambon volcanic rock and coral limestone units. Mitigation priorities are directed towards higher risk sub-watersheds, namely WT3, WT4, BM1, BM2 and BM6. Recommended actions include increasing infiltration upstream through soil and vegetation conservation, controlling land use change, normalising channels in critical segments, and spatial planning that restricts development in zones with high Dd. The results confirm that the integration of Rb, Dd, and Rt analyses provides a scientific basis for flood vulnerability mapping and the prioritisation of sub-watershed-based management. The accuracy and precision of the results can be improved through the use of daily rainfall time series, soil moisture parameters, land cover changes, and validation using flood records.

Author Contributions

Conceptualization, N.K.T. and E.S.; methodology, N.K.T. and E.S.; software, N.K.T.; validation, E.S. and B.Y.C.S.S.A.; formal analysis, N.K.T.; investigation, N.K.T.; resources, N.K.T.; data curation, N.K.T.; writing—original draft preparation, N.K.T.; writing—review and editing, E.S. and B.Y.C.S.S.A.; visualization, N.K.T.; supervision, E.S. and B.Y.C.S.S.A.; project administration, N.K.T.; funding acquisition, N.K.T. All authors have read and agreed to the published version of the manuscript.

Declaration of Generative AI Usage

The authors used Gemini (Google) only to improve the English of this manuscript. It was not used for data processing, analysis, or interpretation. The authors checked all edits made with the tool and take full responsibility for the content of the published article.

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