Riverine Flood Susceptibility Analysis Through Frequency Ratio Model – A Case Study in the Sepik River Basin, Papua New Guinea

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Abstract

Riverine Flooding occurs when the rivers exceed the capacity of their natural channels to accommodate water flow and water overflows the banks, spilling out into adjoining low-lying land. A fishnet analysis generated 206 flood locations based on the historical flood inventory database of the Papua New Guinea Resource Information System (PNGRIS). 144 (70%) flood sample locations were selected randomly for model building. The Frequency Ratio (FR) model was used for flood susceptibility analysis in the Sepik River basin based on eight independent variables, namely, landforms, slope, rainfall, hydrological soil group, land use, distance from the river, soil drainage, and elevation. The developed flood susceptibility database was reclassified into five (5) flood susceptibility zones segmenting on the FR values, namely very low (less than 5.0), low (5.0-7.5), medium (7.5-10.0), high (10.0-12.5) and very high (more than 12.5). The FR model output was validated with the remaining 62 (30%) flood points, where 55 points were marked as correct predictions which shows an accuracy of 88.71%. The assessment report identifies a total population of 125936 residing within the very high-risk zone. The findings provide valuable insights for local authorities and stakeholders in flood risk management and mitigation strategies.

Keywords: *Flood susceptibility, Frequency ratio, GIS, Riverine flood, Sepik River basin*

1. Introduction

Flooding is one of the most significant natural hazards worldwide, with profound implications for human safety, economic stability, and environmental health (UNISDR, 2015). Among various flood-prone regions, the Sepik River Basin in Papua New Guinea presents a unique case for analysis due to its complex hydrological characteristics and socio-economic context. This basin, characterized by its extensive river system and rich biodiversity, is vulnerable to inland flooding, particularly during the rainy season (Bourke & Harwood, 2009). The Sepik River Basin in Papua New Guinea is prone to frequent and intense floods, which have significant impacts on the local population, including loss of livelihood, and damage to displacement (Koloa and Samanta, 2024). The basin is also home to several important agricultural areas, including rice paddies and cocoa plantations which are sensitive to flooding (Klaus et al., 2016). However, the existing flood risk management strategies in the region are largely based on empirical observations and ad-hoc approaches which may not be effective in predicting and mitigating flood risks (Brath et al., 2006). Understanding flood susceptibility in this area is crucial for effective risk management and disaster preparedness, especially as climate change exacerbates the frequency and intensity of extreme weather events (Legg, 2021). The lack of a comprehensive flood susceptibility mapping approach in the Sepik River Basin has been identified as a major challenge in flood risk management (Megahed et al., 2023). The current flood risk assessment methods in the region are limited by their reliance on coarse scale data and simple models, environment variables, and flood events (De Moel et al., 2015). Therefore, this study's problem statement is to develop a comprehensive GIS-based flood susceptibility mapping approach for the Sepik River Basin in the Sepik Province, using an advanced frequency ratio model and spatial data analysis techniques to improve the accuracy and reliability of flood risk assessments and inform effective flood risk management strategies.

Geographic Information System (GIS) technology has emerged as a powerful tool for analyzing spatial data related to flood susceptibility. GIS facilitates the integration of various datasets, enabling researchers to visualize and assess the relationship between geographical features and flood risk (Chen et al., 2003). Furthermore, the Frequency Ratio Model has been widely utilized in flood susceptibility assessments, as it quantifies the relationship between the presence of flooding and contributing factors such as topography, land use, rainfall, and soil characteristics (Bañados et al., 2023). This statistical approach provides valuable insights into identifying areas at high risk of flooding, thereby assisting local authorities in planning and mitigating flood impacts. The Sepik River Basin, with its diverse environmental and socio-economic landscape, has not been extensively studied using GIS-based flood susceptibility models. Existing research primarily focuses on specific aspects of flooding, such as its impacts on agriculture and local communities (Idoko et al., 2016). However, comprehensive assessments that integrate multiple factors influencing flood risk are lacking. This gap in research highlights the need for a systematic analysis of flood susceptibility in the region, particularly using contemporary GIS methodologies and statistical modeling techniques.

This study goals to fill this gap by conducting an inland flood susceptibility analysis in the Sepik River Basin using GIS and the Frequency Ratio Model (Samanta et al. 2018) by integrating various spatial datasets, including historical flood occurrences, rainfall patterns, and land use. This study aims to be able to create a flood susceptibility map on the Sepik River Basin using GIS and the Frequency Ratio Model. There are four (4) objectives to achieve the aim of this study. They are (i) to identify inland flood conditioning factors based on expert knowledge and effective literature review, (ii) to assess the flood susceptibility of the Sepik River Basin using a GIS-based Frequency Ratio model, (iii) to analyze the statistical relationship between flood susceptibility dataset and conditioning factors and finally (iv) to validate the flood susceptibility using historical flood events and legacy datasets on flood events

2. Study location

The Sepik River at 1126 km in length and covering an area of 7.7 million hectares is one of the world's greatest river systems. The portion of the basin within Papua New Guinea was selected for this study. The basin drains the water of the northern part of the Western Province, the western portion of the Madang Province, the north-east parts of Enga Province, the northern section of Western Highlands Province, and the major portion of West Sepik Province and East Sepik Province (Figure 1a). The highest altitude is recorded as 4394m in the south and southeast portion of the basin (Figure 1b). It is the largest unpolluted freshwater system in New Guinea and among the largest and most intact freshwater basins in the Asia Pacific.

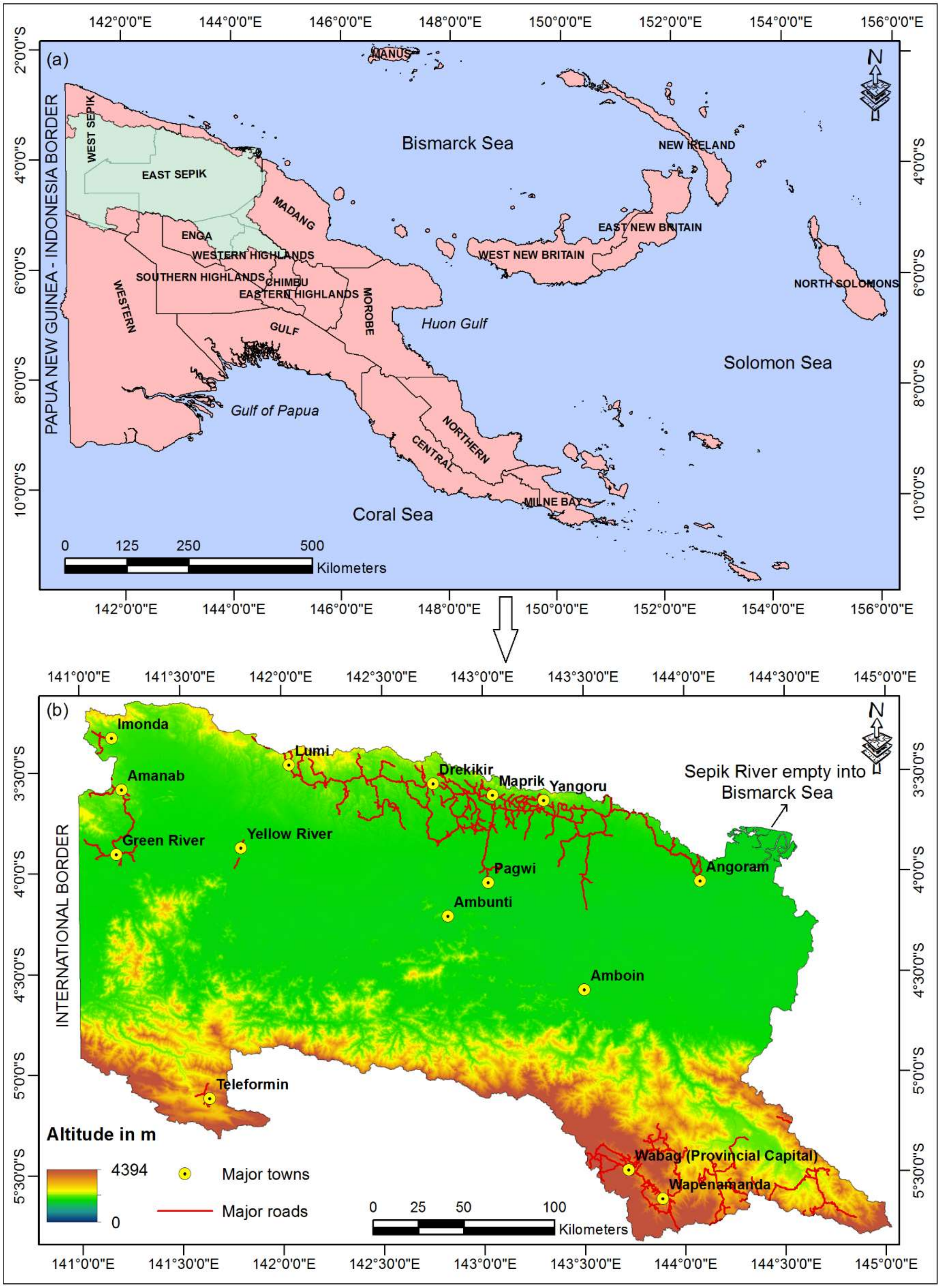

Fig. 1 Location of the Study area (a) Sepik River basin within Papua New Guinea overlaid with provincial boundary, (b) the elevation characteristics of the Sepik River basin

3. Methodology

The Frequency Ratio (FR) model is a statistical method that assesses the relationship between flood occurrences and various contributing factors. This model quantifies the probability of flooding about specific environmental variables, making it a valuable tool for flood susceptibility mapping (Megahed et al., 2023). The effectiveness of the Frequency Ratio Model in identifying high-risk areas in different geographical contexts is very effective (Bañados et al., 2023; Eid et al., 2024). Many other studies found that the FR model successfully predicted flood-prone regions by analyzing correlations with topographical and hydrological factors (Sahana and Patel, 2019; Sarkar and Mondal, 2020; Arora et al., 2021; Malla & Ohgushi, 2024). Advanced space-borne thermal emission and reflection radiometer (ASTER) provide a digital elevation model (DEM) with a spatial resolution of 90m that was used in this research. Elevation and slope databases were derived from the ASTER DEM. Land use and land cover were derived from optical bands with false color combinations of the Landsat 7 ETM+ data set. Soil, rainfall, and landform data were derived from the PNGRIS database. All the data were corrected and reprojected into a common coordinate system (UTM projection, zone 55S, and WGS-84 datum). The flood susceptibility analysis in the Sepik River basin was conducted based on eight independent variables, namely, landforms, slope, rainfall, hydrological soil group, land use, distance from the river, soil drainage, and elevation (Figure 2).

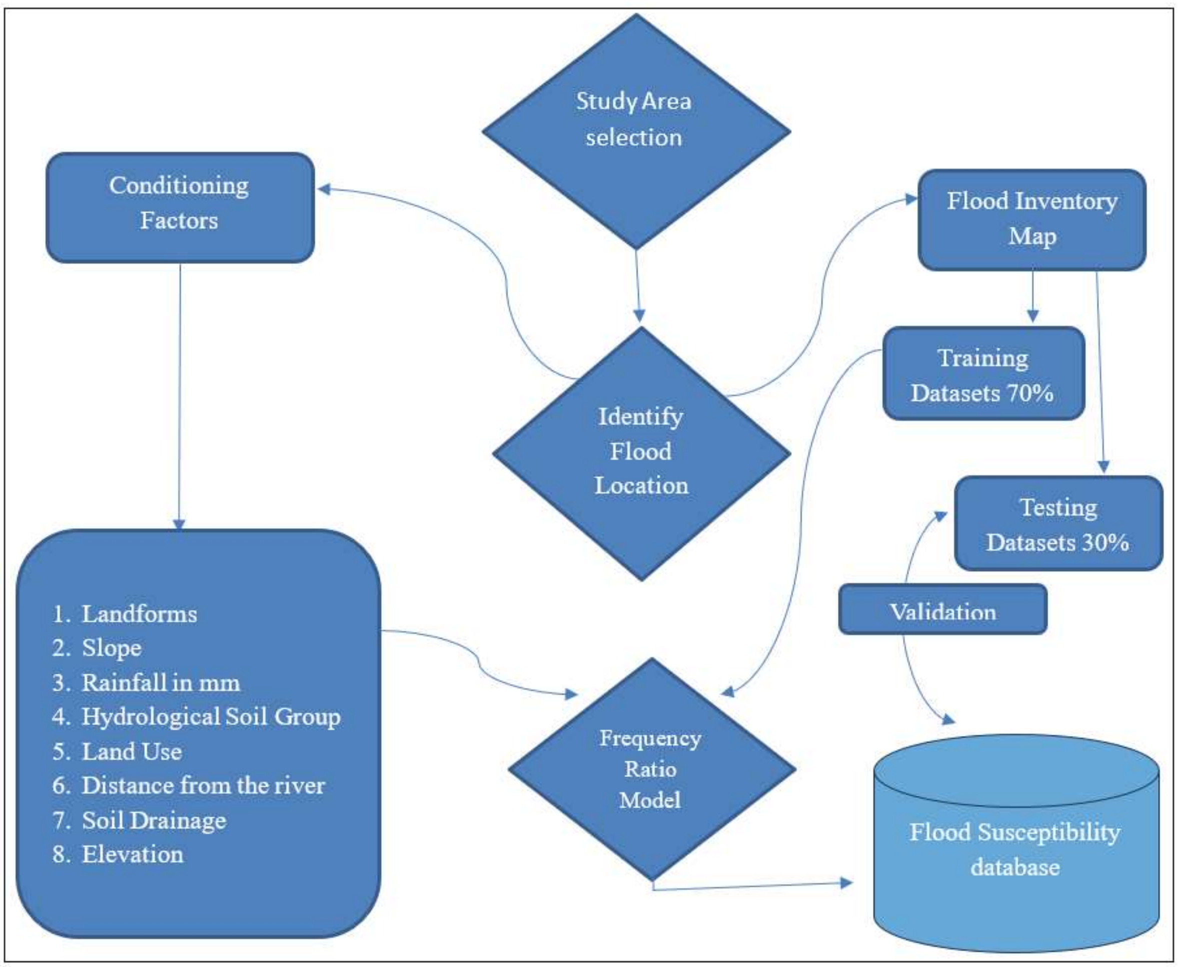

Fig. 2 Methodological flow chart of the flood susceptibility analysis

A flood inventory database was prepared using the PNGRIS national database, field investigation, and by examining remote sensing data. A total of 206 flood points were generated through a “create fishnet” analysis of inundation characteristics of the PNGRIS national database. Seventy percent (70%) of the flood points which is 144 points, were selected randomly as the training data set for flood modeling; the rest thirty percent (30%), or 62 points, were used for validating the flood modeling. The frequency ratio model calculates the frequency ratio value for each parameter and their subclasses. The histogram of each subclass of individual parameters and the flood frequency (training flood points) to each were used to calculate the FR value based on equation 1 (Lee and Pradhan, 2007; Samanta et al., 2028). Finally, the flood susceptibility index (FSI) was developed based on equation 2 (Tehrany and Pradhan, 2015; Samanta et al., 2018).

$$\mathrm{FR} = (\mathrm{E}/\mathrm{F})/(\mathrm{M}/\mathrm{L}) \qquad (1)$$

$$\mathrm{FSI} = \Sigma\,\mathrm{FR} \qquad (2)$$

Where E represents the number of flood episodes for each factor, F denotes the total number of flood episodes, M symbolizes the histogram of a class, L refers to the total histogram of the study area, FSI stands for the flood susceptibility index and FR represents frequency ratio for each factor.

To perform the FSI, all subclasses within the selected parameters were reclassified based on the FR value using reclass tools, and the spatial variation map was developed after the “overlay sum” operation in ArcGIS spatial analyst.

4. Results and discussion

Eight conditioning factors, that play an important role in flooding: elevation, slope, land use/ land cover, hydrological soil group, landforms, distance from the river, soil drainage, and rainfall, were used for flood susceptibility analysis.

The elevation database was prepared from the Digital Elevation Model (DEM) ranging from 0 to 4394m. The maximum elevation is found in the south and southeast portion of the study area. The elevation database was categorized into five (5) classes, namely 0 to 100m, 100 to 500m, 500 to 1000m, 1000 to 2000m, and >2000m (Figure 3a). The dominated class is 0 to 100 m covering 43.67% of the basin area and generating an FR value of 2.26 (Table 1). The DEM-driven slope data was generated with five (5) distinctive classes, namely less than 2 degrees, 2 to 5 degrees, 5 to 10 degrees, 10 to 15 degrees, and more than 15 degrees (Figure 3b). The flat terrain refers to the gentle slope (0 to 2 degrees) in the middle part of the catchment area covering 37.01% land area and contributing a higher FR value of 2.33 (Table 1).

The Sepik River basin area is classified into nine (9) land use/land cover classes using Landsat 7 ETM+ satellite data after a supervised classification, namely dense forest, less dense forest, shrub lands, Outcrop/cleared Lands, upland grassland, settlement, lake, river, wetlands/flooded Lands, and lowland grasslands (Figure 3c). The basin area is dominated by 54.76% of dense forest land (Table 1). Based on soil infiltration rate the soil of the basin was classified into 4 standard hydrological soil groups (Al Marsumi et al., 2017). These groups are A, B, C, and D. Group D refers to the higher water-holding capacity as it allows very little infiltration through it.

This group is the dominant soil group in the Sepik River basin and occupies about 83.70% of the basin area (Figure 3d and Table 1).

Mainly three broad categories of landforms are found in the basin area, namely depositional landforms, erosional landforms, and volcanic landforms. The erosional landform is the dominant class in the study area (Figure 3e and Table 1). Soil drainage is another important factor that was considered in the flood susceptibility mapping (Mahmoud and Gan, 2018). Poorly drained soil produces more surface runoff than well-drained soil (Pal et al. 2012). There are mainly 4 types of soil drainage found in the basin area, namely (i) well-drained, (ii) imperfectly drained, (iii) poorly drained, and (v) waterlogged (swampy) (Figure 3g). The waterlogged (swampy) class showed the highest FR value of 3.33, followed by a Poorly drained area with an FR value of 2.07 (Table 1).

Rainfall is the most important parameter for flooding (Arnaud et al., 2002). The study area was classified into 5 rainfall classes based on the amount of rainfall that occurs annually. These classes are, below 3500mm, 3500 to 4000mm, 40000 to 4500mm, 4500 to 5000mm, and more than 5000mm. Maximum rainfall was found in the southwest part of the study area (Figure 3h). Eighty (80) percent of the basin area is characterized below 3500mm of annual rainfall contributing FR value of 1.22 (Table 1). FR value varies from 0 to 3.97, where less than 1 is weak and more than 1 has stronger correlations with flood occurrence (Tehrany et al., 2015) (Table 1).

Table 1. Conditioning parameters and subclasses with histogram and historical flood points used for flood susceptibility analysis through the FR model

Value	Class Name	Histogram	% of Histogram	Flood Points	% of Flood Points	FR
Elevation in m						
1	0 -100	4105913	43.67	142	98.61	2.26
2	100 - 500	2445197	26.01	2	1.39	0.05
3	500 - 1000	1025709	10.91	0	0	0
4	1000 - 2000	1170043	12.45	0	0	0
5	More than 2000	654755	6.96	0	0	0
Slope in Degree						
1	0 - 2	3479834	37.01	124	86.11	2.33
2	2 - 5	1305251	13.88	15	10.42	0.75
3	5 - 10	1050038	11.17	3	2.08	0.19
4	10 - 15	964105	10.26	0	0	0
5	More than 15	2602387	27.68	2	1.39	0.05
Land use/ land cover						
1	Dense Forest	51364297	54.76	53	36.8	0.67
2	Less Dense Forest	23319272	24.86	31	21.53	0.87
3	Shrubs	7813655	8.33	24	16.67	2.00
4	Outcrop/Burnt Lands	1474915	1.57	4	2.78	1.77
5	Upland Grassland	280709	0.30	0	0	0
6	Settlement	29504	0.03	0	0	0

7	Lake	332420	0.35	2	1.39	3.97
8	River	1315579	1.40	4	2.78	1.99
9	Wetlands/Flooded Lands	507308	0.54	3	2.08	3.85
10	Lowland Grasslands	7353363	7.84	23	15.97	2.04
Hydrologic Soil Group						
1	Group A	5028429	6.00	0	0	0
2	Group B	6627936	7.90	5	3.47	0.44
3	Group C	1971000	2.40	0	0	0
4	Group D	70097519	83.70	139	96.53	1.15
Landform Type						
1	Depositional Landforms	38029778	45.40	143	99.30	2.19
2	Erosional Landforms	44073070	52.70	1	0.70	0.01
3	Volcanic Landforms	1586327	1.90	0	0	0
Distance from the river						
1	Less than 1000	445886	5.86	15	10.42	1.78
2	1000 -2000	390454	5.13	13	9.03	1.76
3	2000 - 3000	361383	4.75	10	6.94	1.46
4	3000 - 4000	346577	4.55	12	8.33	1.83
5	More than 4000	6067583	79.71	94	65.28	0.82
Soil drainage						
1	Well Drained	46604440	55.30	2	1.39	0.03
2	Imperfectly Drained	7814482	9.30	0	0	0
3	Poorly Drained	12997304	15.40	46	31.94	2.07
4	Waterlogged (swampy)	16820285	20.00	96	66.67	3.33
Rainfall in mm						
1	Less than 3500	67425347	80.00	140	97.20	1.22
2	3500 - 4000	13319232	15.80	3	2.08	0.13
3	4000 - 4500	2521197	3.00	0	0	0
4	4500 - 5000	847935	1.00	0	0	0
5	More than 5000	146122	0.20	1	0.72	3.60

The resulting FSI database ranged from 1.5 to 17.05, where the higher value refers to the higher probability of flooding (Figure 4). The FSI was classified into five (5) flood susceptibly zones, namely (i) very low (less than 5.0), (ii) low (5.0 to 7.5), (iii) medium (7.5 to 10.0), (iv) high (10.0 to 12.5), and (v) very high (greater than 12.5). Approximately 35.29 percent of the land area of the Sepik River basin in the middle stretched from east to west characterized as a very high flood susceptibility zone (Table 2). The lower altitude, flat slope, deposition landform, higher water holding capacity (HSG group D), and closeness to the river are mainly characterized in this zone (Figure 5).

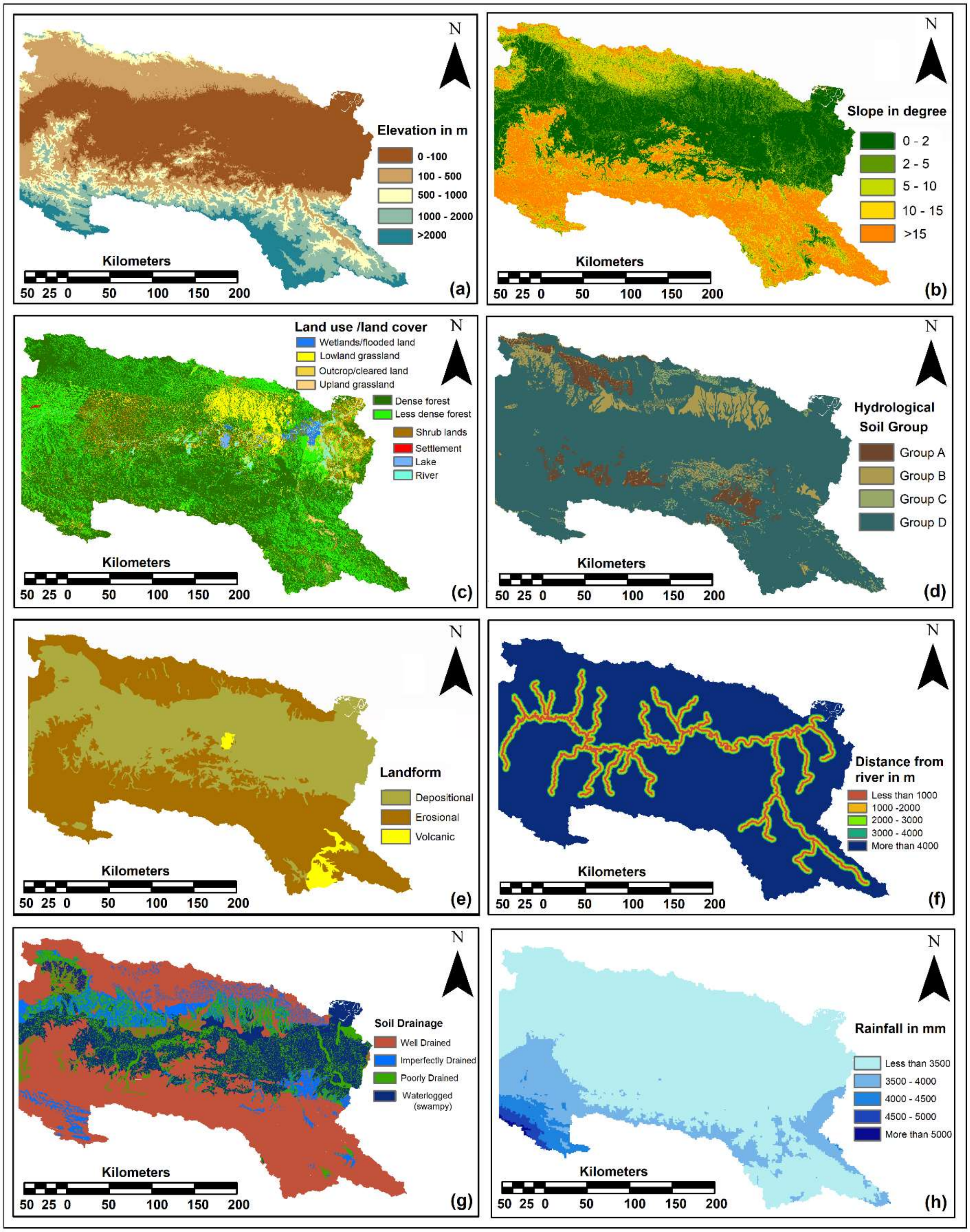

Fig. 3 Conditioning parameters used for flood susceptibility analysis using the FR model: (a) elevation, (b) slope, (c) land use /land cover, (d) hydrological soil group, (e) landforms, (f) distance from the river, (g) soil drainage and (h) rainfall characteristics of the study area

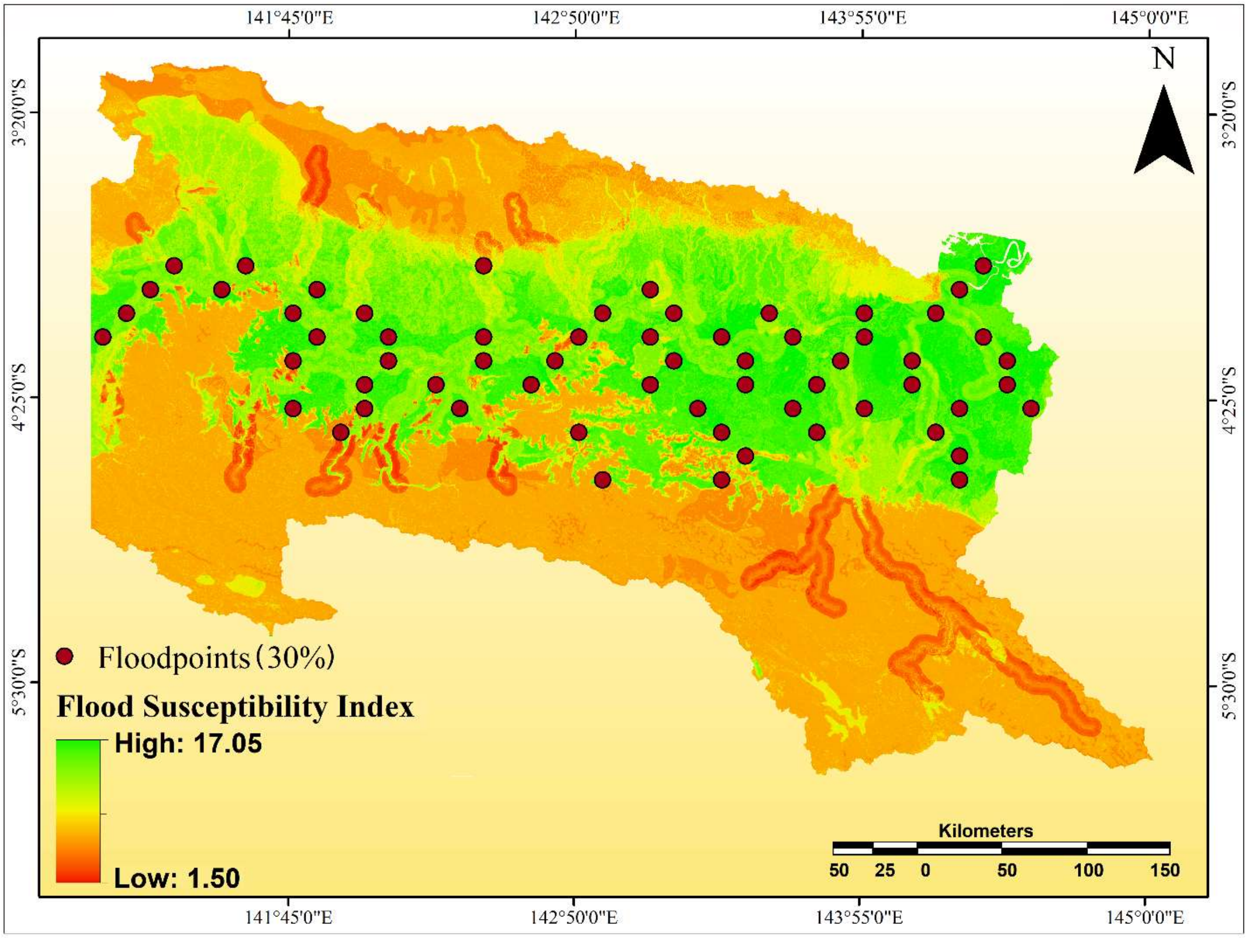

Fig. 4 The resulting FSI database with 30% flood points validation of the model

Table 2. Classified flood susceptibility zones with class statistics

Sl. No.	Flood Susceptibility zones	FSI value range	Histogram	% Area
1	Very Low	< 5	349352	4.59
2	Low	5.0 - 7.5	3274325	43.04
3	Medium	7.5 - 10.0	624361	8.21
4	High	10.0 - 12.5	675135	8.87
5	Very High	> 12.5	2685321	35.29

Thirty percent (30%) of flood points were used to validate the quality of the model output. Fifty-five (55) out of 62 flood points are in the very high flood susceptibility zone (Figure 4). The remaining 7 flood points are found in the high susceptibility zone. The model's prediction accuracy was calculated as 88.71 (Table 3). The success rate was calculated as 92.36 after comparing the total training flood points (133) within the very high susceptibly zone and the total number of training flood points (144) (Table 3).

Table 3. Calculations of prediction accuracy and success rate for the flood susceptibility analysis

Sl. No.	Susceptibility Class	Verification (30 % flood points)	Accurate (very high class)	Prediction Accuracy	Training (70% flood points)	Success (Very high class)	Success Rate
1	Very Low	0			0		
2	Low	0			0		
3	Medium	0	55	88.71	1	133	92.36
4	High	7			10		
5	Very High	55			133		

The risk assessment was performed using the village data and major road infrastructure based on the existing PNGRIS database. Almost 478 villages (19.27%) of the Sepik River basin are situated in the very high flood susceptibility zone and a total of 125936 people are living in this highly susceptible zone with risk (Figure 5 and Table 4).

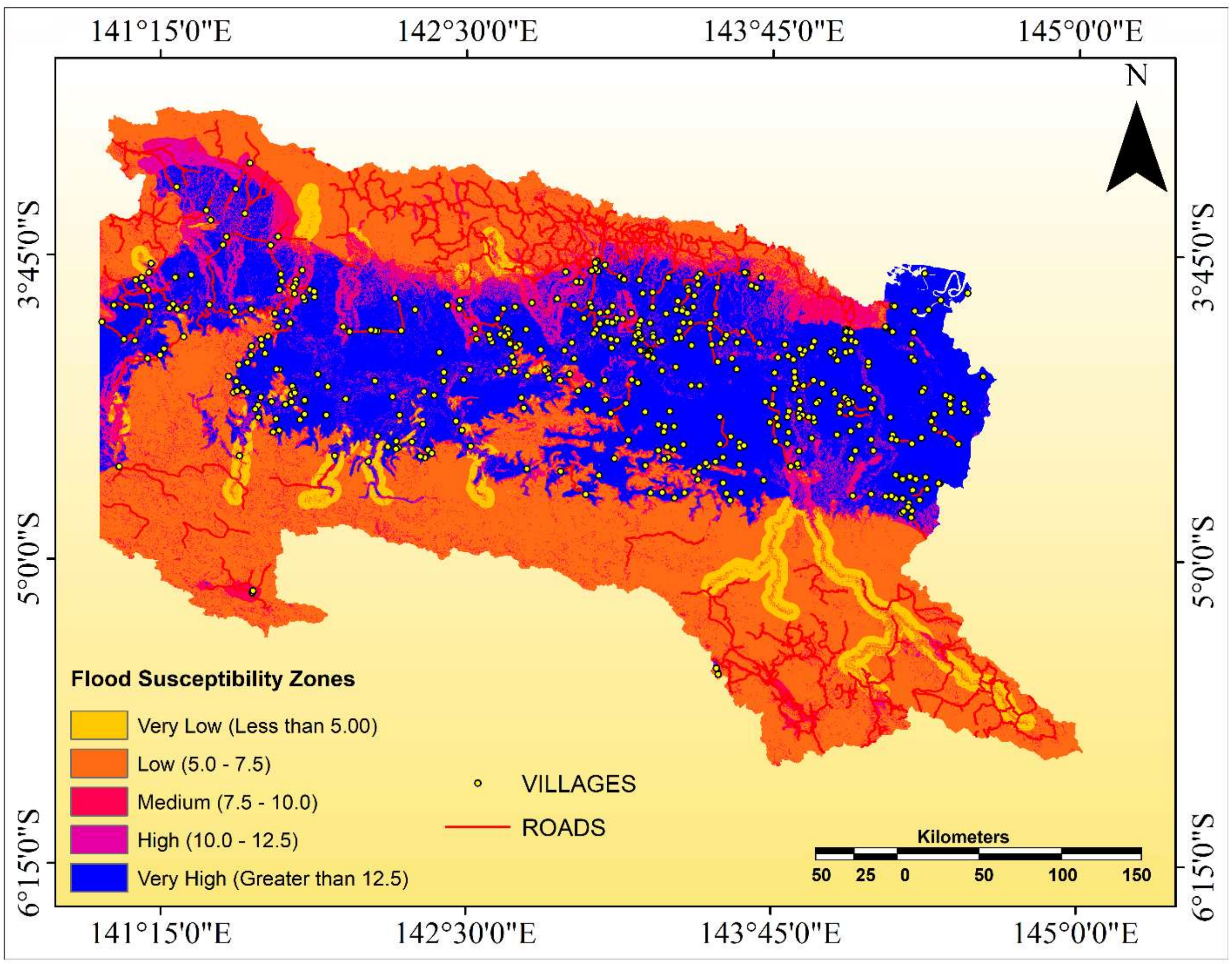

Fig. 5 Flood susceptibility zones overlaid with villages and roads of the Sepik River basin

Table 4. Flood susceptibility zones with risk factor

Sl. No.	Flood Susceptibility zones	FSI value range	Village	% of villages under flood vulnerability	Total population
1	Very Low	< 5	104	4.19	374097
2	Low	5.0 - 7.5	1211	48.81	273399
3	Medium	7.5 - 10.0	462	18.62	181746
4	High	10.0 - 12.5	226	9.11	69766
5	Very High	> 12.5	478	19.27	125936

5. Conclusion

The integration of GIS and the Frequency Ratio model offers a comprehensive approach to flood susceptibility analysis. By combining spatial analysis with statistical modeling, researchers can develop more accurate predictions of flood risk and identify vulnerable areas effectively. This integrated methodology not only enhances the understanding of flood dynamics but also supports evidence-based decision-making in flood management. Future research should focus on refining these methodologies to address the unique challenges presented by the Sepik River Basin's hydrological characteristics. For instance, incorporating local knowledge and community engagement in the flood risk assessment process can enhance the relevance and effectiveness of flood management strategies. Additionally, exploring the impacts of climate change on flooding patterns will be crucial for developing adaptive strategies that account for future risks.

The analysis of inland flood susceptibility in the Sepik River Basin using GIS and the Frequency Ratio model provides valuable insights into the spatial distribution of flood risk within the region. Through a systematic assessment of various factors including elevation, land use, soil types, rainfall patterns, and lithology characteristics identify areas with varying degrees of susceptibility to inland flooding. Ultimately, by leveraging the findings of this study and implementing targeted mitigation measures, we can work towards reducing the impacts of inland flooding, safeguarding communities, and promoting sustainable development in the Sepik River basin.

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