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Analytical Hierarchy Process based on Flood Susceptibility Assessment; A Study from Attanagalu Oya River Basin

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Abstract

Flood is one of the natural or manmade hydrological events in a river basin hydrological cycle. This is the one of the major disasters in Sri Lanka. Flood susceptibility mapping and assessment is essential for identifying flood risk zones and flood prevention and mitigation strategies because it identifies the most vulnerable areas based on the physical factors that determine susceptibility to flooding. This study aims to define the flood susceptibility zones in Attanagalu Oya River Basin using a multi-criteria approach, especially the Analytical Hierarchy Process (AHP). The secondary data used in this study was obtained from global open-source databases and institutions. Seven flood conditioning factors were chosen in this study such as Elevation, Distance from the river, Drainage density, Rainfall, Slope, Soil type and Normalized Difference Vegetation Index (NDVI). The AHP technique was used to calculate the factor weights using the pairwise comparison method. Finally, the weighted overlay method in ArcGIS was used to create the final flood susceptibility map for the study area. It was classified into five classes based on the risk of flooding such as Very high risk, High risk, Moderate risk, Low risk and Very low risk. The total area of these classes is equal to 21.71 km^2 (very high risk), 172.99 km^2 (high risk), 440.73 km^2 (moderate risk), 194.40 km^2 (low risk) and 2.38 km^2 (very low risk). It has been found that the southwest area of the river basin is vulnerable to very high-risk flooding. This kind of studies will open new pathways for flood risk management in Sri Lanka.

Keywords: Flood susceptibility, analytical hierarchy process, geographic information systems, weighted overlay method, flood management

1. Introduction

Flood is one of the natural or manmade hydrological events in a river basin hydrological cycle. However, in recent decades, there has been a tendency toward rising flood frequency and magnitude in several river basins around the world. Impacts of Climatic change, Extreme Hydrological Events (EHEs) and Anthropogenic activities are recognized as the main reasons for this situation (Fohrer *et al.*, 2001; Hirabayashi *et al.*, 2013; Sofia *et al.*, 2017; Vojtek and Vojteková, 2019). Many countries have focused on flood management to prevent its adverse impact. However, due to changes in the nature, frequency, timing and regional characteristics of floods, it has been a difficult task to explore the underlying situations and give popper management

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strategies for flood prevention and management. Therefore, developing suitable management strategies and prevention measures has been difficult in many countries including Sri Lanka.

Flooding is one of the most severe natural disasters in Sri Lanka. Sri Lanka is located in the Bay of Bengal and as a result it has pressure variation of high winds and heavy rainfall patterns. Unexpected heavy rains due to these factors can be detected and flooding is one of the most common phenomena in this heavy rainy season (Chathurani *et al.*, 2022a). Climate changes and the anthropogenic impact on the natural environment have increased the severity and frequency of floods in the past few decades. It causes a substantial loss of human life, destruction of agricultural output and loss of farmland and massive and irreparable damage to property and communication infrastructure as well. This situation can be identified in Attanagalu Oya river basin located in the western part of the country (Chathurani et al., 2022; Hewawasam & Matsui, 2022; Manawadu & Wijeratne, 2021).

One of the most crucial components of the early warning systems for the prevention and mitigation of future flood crises is the mapping and analysis of flood susceptibility because it identifies the most vulnerable locations based on physical factors that affect the propensity for flooding. Susceptibility may therefore be seen as one of the elements of vulnerability evaluation (Adger, 2006; Jacinto *et al.*, 2015; Vojtek and Vojteková, 2019).Flood susceptibility mapping procedures have studied several physical qualities of the region using elements such as geological conditions, lithology, morphometric characteristics, river network, soil types, hydrological components, land use and land cover and anthropogenic conditions. These conditions and factors selection have a significant impact on the desired flood susceptibility study (Kourgialas and Karatzas, 2017; Zhao *et al.*, 2018; Vojtek and Vojteková, 2019).

Due to the rapid climate change in the last decades, the study of floods around the world is increasing gradually. They have studied the flood disaster through spatial and temporal dimensions using various types of data and analytical methods. But at present, it can be recognized that the studies of this nature has been conducted using New Technical Cartographic Methods. Flood is a multi-dimensional phenomenon that can be analyzed according to the spatial and temporal perspectives. In order to create flood susceptibility maps, geographic information systems (GIS) are helpful tools for the synthesis of various input data and variables utilizing certain logical and mathematical relationships. When considering the historical evidence of identifying and assessing flood susceptible areas, various methods have been developed and applied in different regions (Carver, 1991a; Hu *et al.*, 2017).

When considering the studies that have been regarding floods, it can be recognized that various analytical methods have been used for that purpose. But when considered from a geographical point of view, attention can be drawn to some of the most prominently used field analysis methods. Multi-criteria Decision Analysis (MCDA) is one of the most common approaches and methodologies that are used to determine susceptibility to flooding in a region. In multi-criteria decision analysis, a variety of weighting techniques such as a pairwise weighing method or expert judgmental method can be used to rank the relative significance of the chosen influencing variables according to the flood characteristics of an area (Carver, 1991b; Mahmoud and Gan, 2018; Tang *et al.*, 2018). The analytical hierarchy process (AHP), is a most frequently used method for defining weights, which employs pairwise comparisons to determine how much one choice outperforms the other on the given criteria.

According to the past literature survey, it can be observed that there are several methods that can be used for flood susceptibility assessment in different geographic areas (Khosravi *et al.*, 2016; Vojtek and Vojteková, 2019). These include the study of geomorphologic characteristics, statistical methods (Frequency ratio and Logistic regression) and machine learning methods. Numerous research studies have employed techniques that depend on a basin's geomorphologic features (Nardi, Vivoni and Grimaldi, 2006; Degiorgis *et al.*, 2012). However, these techniques cannot be used for traditional hydraulic modeling but may be employed in large-scale analyses. Frequency ratio and logistic regression are two statistical techniques that rely on predicted input variables that are related to different explanatory parameters and on the number of datasets (Samanta, Pal and Palsamanta, 2018; Siahkamari *et al.*, 2018). Moreover, the use of advanced methods such as machine learning algorithms which may include artificial neural networks can be observed in flood susceptibility analysis in different regions (Tehrany, Pradhan and Jebur, 2015).

However, when it comes to mapping flood susceptibility, each of the aforementioned methodologies has significant drawbacks that could cause a variety of uncertainties. Therefore, it is essential that the chosen technique effectively captures the geographically continuous and cumulative nature of the parameters' influence on flood-generating mechanisms. When selecting a suitable methodology for mapping flood susceptibility, the spatial scale (Local, Regional, National, or Global) should also be taken into account (Vojtek and Vojteková, 2019).

The aim of this article is to present a methodology for identifying and assessing flood susceptible areas on a catchment scale of Attanagalu Oya

River Basin in Sri Lanka, using the Analytical Hierarchy Process (AHP) and Geographic Information System (GIS).

2. Materials and Methods

Study Area: Attanagalu Oya River basin (Basin No 103) is located in the western part of Sri Lanka. This river basin is situated between two major river basins, named Kelani and Maha Oya. Aththanagalu oya river basin has a catchment area of 839 km^2. The elevation of the catchment area ranges between 0 – 400m from the MSL. The main river path of this basing originated from Kegalle District. The three streams, named Deyella Oya, Attanagalla Oya, and Uruwal Oya, are discharged into Negombo Lagoon as Dadugam Oya through the Ja-Ela area. Several streams, originated from other areas of the river basin join to the main river network which include Wahakadura Oya, Basangoda Oya and Algama Oya (Perera and Wijesekera, 2012; Wijesekera and Rajapakse, 2013a; Chathurani *et al.*, 2022b). This area receives average annual rainfall ranging between 1400 – 2500 mm in both monsoons and is vulnerable to frequent flooding(Chathurani *et al.*, 2022c). Figure 1 shows the relative and the absolute location of the study area.

Data Collection: The secondary data used in this study was obtained from global open-source databases and institutions. Seven flood conditioning factors were chosen in this study such as levation, distance from the river, drainage density, rainfall, slope, soil type and Normalized Difference Vegetation Index (NDVI). The elevation data was created using the Shuttle Radar Topography Mission (SRTM) -1 Arc-Second Digital Elevation Model (DEM) (2014.09.27) obtained from USGS Earth Explorer website (https://earthexplorer.usgs.gov/). The slope of the Attanagalu Oya river basin was calculated using Spatial Analyst tools in Arc GIS 10.8. The annual rainfall data was obtained from the NASA Power Weather Database for the year 2022. The river basin data and stream network data were obtained from the Survey Department of Sri Lanka. The drainage density of the Attanagalu Oya River basin was calculated using the line density tool in Arc GIS.

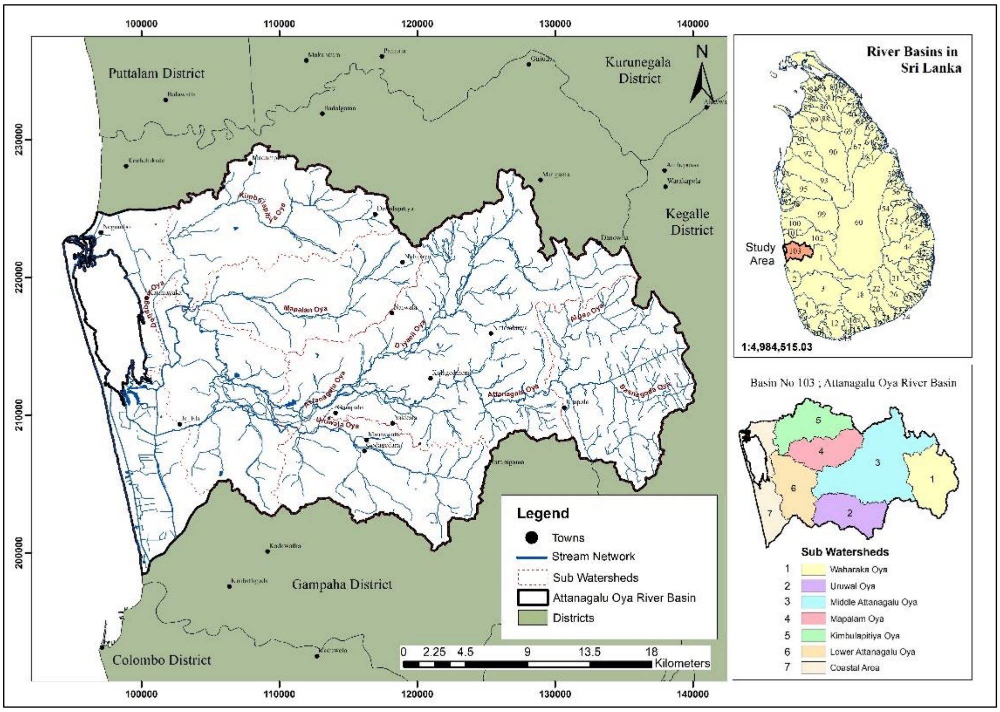

Figure 1: The Study Area: Atthanagalu River basin in Sri Lanka
Source: Prepared by author, 2023

The Normalized Difference Vegetation Index (NDVI) for the year 2022 of the Attanagalu Oya River basin was calculated using the Land Sat 8 satellite data downloaded from the USGS GloVis Website (https://glovis.usgs.gov/). The following equation was used to calculate the Normalized Difference Vegetation Index (Equation 1). Band 5 is the near-infrared (NIR) and Band 4 is Red Band.

$$NDVI = (Band\ 5 - Band\ 4) / (Band\ 5 + Band\ 4)$$ *Equation*

Classification of selected criteria: The selected six parameters; elevation, distance from the river, drainage density, rainfall, slope, soil type and Normalized Difference Vegetation Index (NDVI) have been classified into new categorized classes into five risk levels, namely very low, low, medium, high and very high-risk zones for flooding. The reclassify tool in Arc GIS 10.8 was used for that. In the next step of data processing, all factors were defined as raster datasets (30m resolution) and the AHP technique was used to calculate the factor weights. Table 1 shows the marginal values of the classification according to the risk level of flooding.

Table 1: The Marginal values of the criteria classification

Parameters /Unit	Class	Risk Level	Rating
Elevation (m)	0 – 10	Very high-risk	5
	10 – 20	High	4
	20 – 50	Medium	3
	50 – 150	Low	2
	150 - 400	Very low	1
Distance from river (m)	< 100	Very high-risk	5
	100 – 200	High	4
	200 – 300	Medium	3
	300 – 500	Low	2
	500 - 1000	Very low	1
Drainage Density (sum of the channel lengths /km^2)	< 0.5	Very low	1
	0.5 – 1	Low	2
	1 – 1.5	Medium	3
	1.5 – 3	High	4
	3 - 5	Very high-risk	5
Rainfall (mm)	< 1710	Very low	1
	1710 – 1740	Low	2
	1740 – 1770	Medium	3
	1770 – 1790	High	4
	1790 <	Very high-risk	5
Slope (%)	0 – 2	Very high-risk	5
	2 – 5	High	4
	5 – 15	Medium	3
	15 – 35	Low	2
	35 <	Very low	1
Soil type (Permeability of the soil type)	Worst	Very high-risk	5
	Bad	High	4
	Medium	Medium	3
	Good	Low	2
	Very Good	Very low	1
NDVI	-0.064 – 0.13	Very high-risk	5
	0.14 – 0.2	High	4
	0.21 – 0.24	Medium	3
	0.25 – 0.28	Low	2
	0.29 – 0.43	Very low	1

Source: Prepared by author, 2023

The pairwise comparison matrix: The importance of the selected parameters is assigned values on a scale ranging from 1 to 9 as rating scores. The Pairwise Comparison Matrix is shown in table 2 using a 7 x 7 matrix. The values of each row are compared with each column to define the relative importance to obtain a rating score. For example, elevation is significantly more important than NDVI and therefore assigned the value 8. The rows describe the importance of NDVI. Therefore, the rows have the inverse value of the pairwise comparison (e.g., 1/8 for elevation)

Table 2: Pair-wise comparison matrix

Criteria	Elevation	Distance from river	Drainage Density	Rainfall	Slope	Soil type	NDVI
Elevation	1	4	5	5	6	7	8
Distance from river	1/4	1	4	4	7	7	8
Drainage Density	1/5	1/4	1	2	3	3	3
Rainfall	1/5	1/4	1/2	1	3	3	4
Slope	1/6	1/7	1/3	1/3	1	2	2
Soil type	1/7	1/7	1/3	1/3	1/2	1	2
NDVI	1/8	1/8	1/3	1/4	1/2	1/2	1

Source: Prepared by author, 2023

In the next step, normalized factor weights for each parameter were calculated using the Pair-wise comparison matrix. Further Consistency Ratio (CR) was calculated to assess the significance of the calculated weight values. CR was calculated using the following equation (Equation 2) where CI is the consistency index and RI is the random index.

$$CR = CI/RI \qquad \textit{Equation 2}$$

Finally, the weighted overlay method in ArcGIS was used to create the final flood susceptibility map for the study area and it was classified into five classes based on the risk of flooding. Such as very high risk, high risk, moderate risk, low risk and very low risk. The findings were interpreted using maps and data tables.

3. Results and Discussion

Based on a literature survey regarding the flood assessment of the Attanagalu Oya river basin, seven flood conditioning factors were selected in the catchment scale: elevation, distance from the river, drainage density, rainfall, slope, soil type and normalized difference vegetation index (NDVI).

3.1 Spatial characteristics of the river basin

The elevation of the Attanagalu Oya river basin ranged between 0 - 400m from mean sea level. Elevation of 82% river basin area below 50m and 9% area below 100m of the study area. Only 2.3% of the area is above 300m elevation. With these elevation differences, it can identify 15< slope areas in the eastern part of the basin. The drainage density of the river basin ranged between 0 – 4.21 and high drainage density can be identified in the middle and lower sub-basin areas. The average annual rainfall of the study area ranged between 1684 -1881 mm and an increase can be detected in the north-south direction. There are main soil types, namely alluvial soils, bog and half-bog soils, latosols and regosols on old red and yellow sands, red-yellow podzolic soils and regosols on recent beach and dune sands are distributed in the study area. The Normalized Difference Vegetation Index of the river basin ranged between -0.06 and 0.43. High NDVI values can be detected in the eastern part of the Attanagalu Oya river basin and low values can be detected in the western urbanized areas. The spatial distribution of the selected criteria is shown in Figure 2.

3.2 Analytical Hierarchy Process

As the initial step of the AHP process, the relative significance of each criterion and their corresponding weights were defined based on empirical knowledge and recent studies (Mokhtari et al., 2023; Seejata et al., 2018; Swain et al., 2020; Vojtek & Vojteková, 2019). It ranges from 7 (highest importance) to 1 (lowest importance). They are elevation, distance from the river, drainage density, rainfall, slope, soil type and Normalized Difference Vegetation Index (NDVI). Using expert judgment and the literature review, the rating of criteria was estimated according to the nine-point continuous scale in the AHP method. Finally, the normalized pairwise comparison matrix (Table 2) and the final weights were calculated (Table 3).

Table 3: Normalized factor weights and final weights

	Elevation	**Distance from river**	**Drainage Density**	**Rainfall**	**Slope**	**Soil type**	**NDVI**	**Weights**
Elevation	0.480	0.677	0.435	0.387	0.286	0.298	0.286	**0.41**
Distance from river	0.120	0.169	0.348	0.310	0.333	0.298	0.286	**0.27**
Drainage Density	0.096	0.042	0.087	0.155	0.143	0.128	0.107	**0.11**
Rainfall	0.096	0.042	0.043	0.077	0.143	0.128	0.143	**0.10**
Slope	0.080	0.024	0.029	0.026	0.048	0.085	0.071	**0.05**
Soil type	0.069	0.024	0.029	0.026	0.024	0.043	0.071	**0.04**
NDVI	0.060	0.021	0.029	0.019	0.024	0.021	0.036	**0.03**

Source: Prepared by author, 2023

According to the AHP calculations, CI is equal to 0.07 and RI value for the 7 factors are 1.32. So, the calculated CR value is equal to 0.06 and this value is less than 0.10 (standard value). Therefore, we can assume that the calculated matrix was reasonably consistence and calculated weights values can be significant for the selected purpose.

In the next step, all factors were defined as raster datasets (30m resolution) and reclassified into new categorized classes into five risk levels, namely very low, low, medium, high and very high-risk zones for flooding. Figure 3 shows the reclassified parameters according to the table 1.

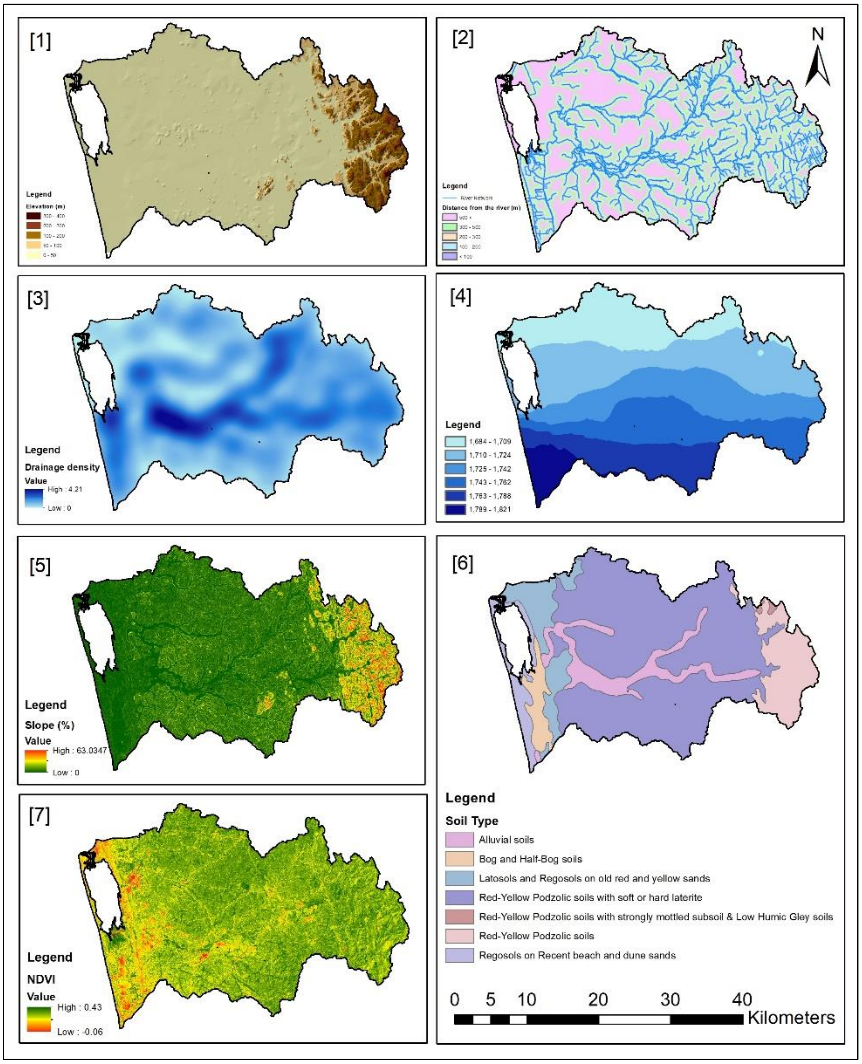

Figure 2: The spatial distribution of the selected criteria within the Aththanagalu river basin; [1] elevation, [2] distance from the river, [3] drainage density, [4] rainfall, [5] slope, [6] soil type and [7] Normalized Difference Vegetation Index
Source: Prepared by author, 2023

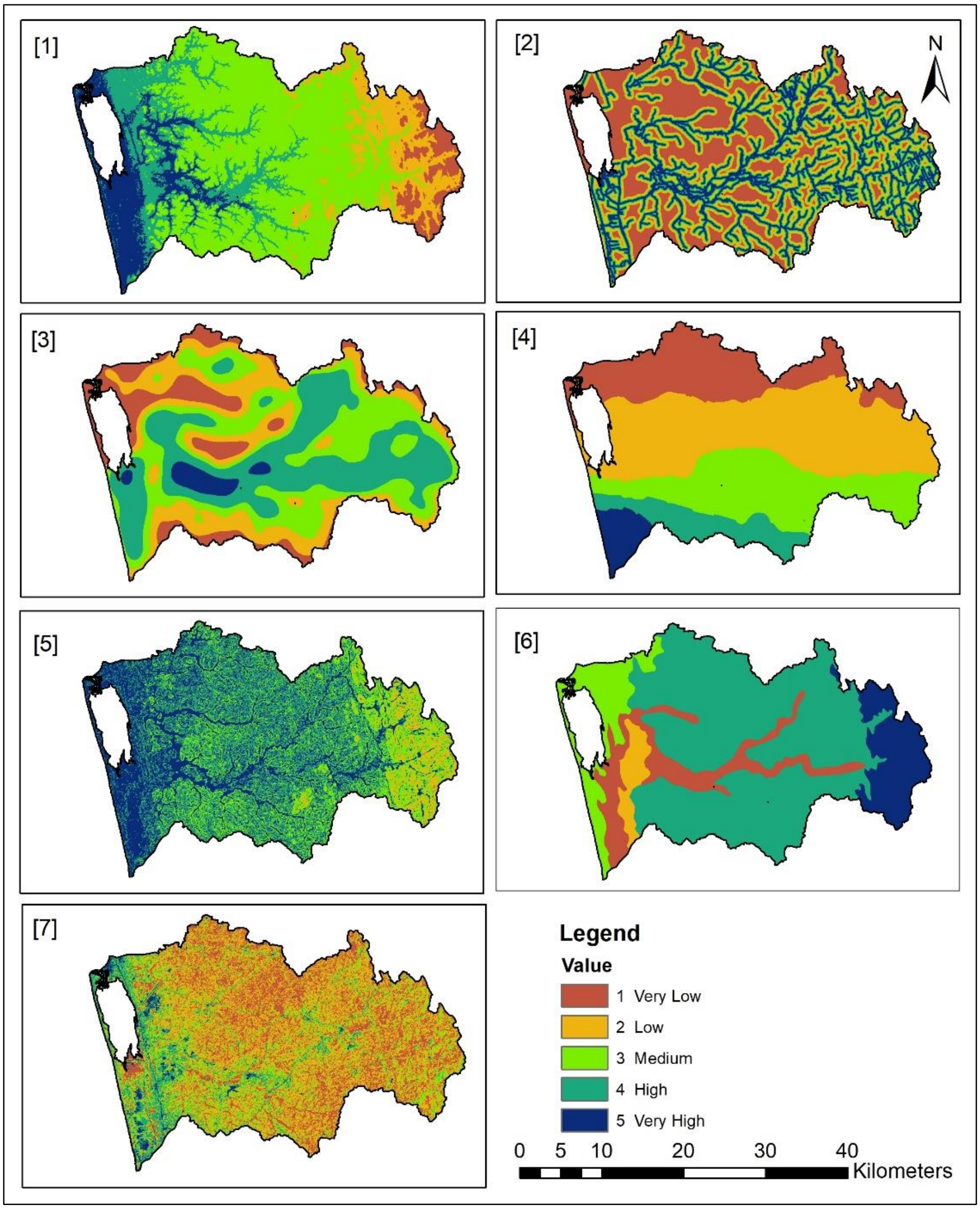

Figure 3: The reclassified parameters according to the risk of flooding in the study area; [1] elevation, [2] distance from the river, [3] drainage density, [4] rainfall, [5] slope, [6] soil type and [7] Normalized Difference Vegetation Index (NDVI)
Source: Prepared by author, 2023

3.3 Flood Susceptibility Levels or Zones of Attanagalu Oya River Basin

The weighted overlay method was used to create the final flood susceptibility map using the weights that were calculated in the previous step. Flood susceptibility of the area was classified into five classes based on the risk of flooding such as very high risk, high risk, moderate risk, low risk and very low risk. The total area of these classes is equal to 21.71 km^2 (very high risk), 172.99 km^2 (high risk), 440.73 km^2 (moderate risk), 194.40 km^2 (low risk) and 2.38 km^2 (very low risk). It has been found that the southwest area of the river basin is vulnerable to very high-risk flooding. The flood susceptibility map of the Attanagalu Oya river basin area is shown in Figure 4.

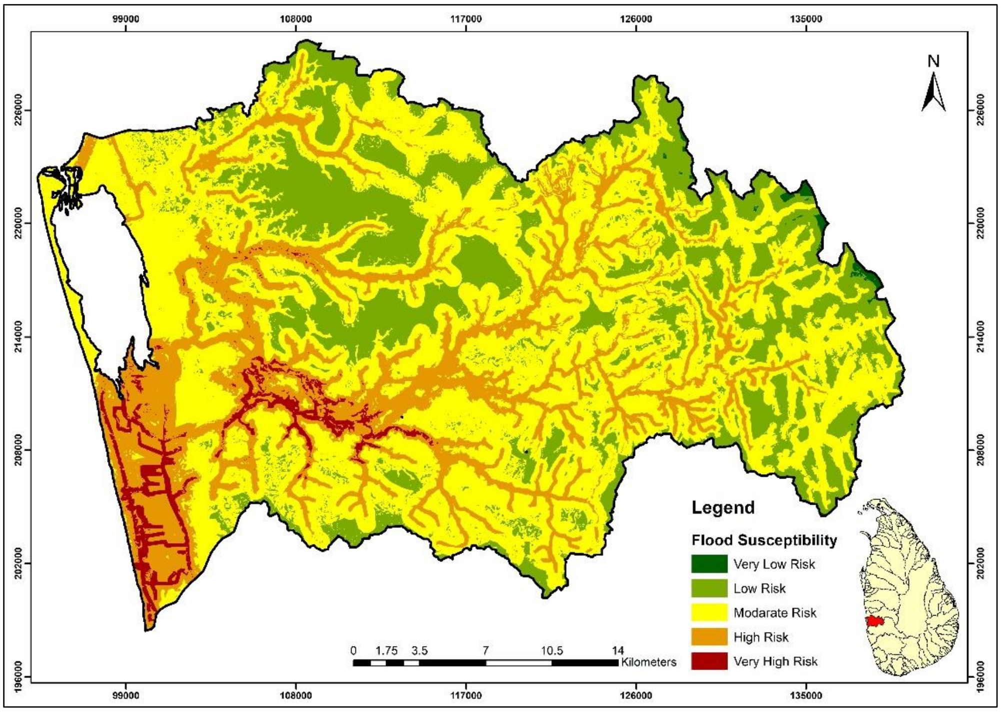

Figure 4: The flood susceptibility map of the Attanagalu Oya river basin
Source: Prepared by author, 2023

When comparing the flood assessment that has been done regarding this area, the use of different kinds of analytical methods for flood assessment can be recognized. Some of those researchers have focused on flood management to prevent its adverse impact on the environment. Moreover, those researchers used different methodologies in the identification of flooding areas and vulnerability (Wijesekera and Rajapakse, 2013b; Igshana, Jeevadacksha and Fathima Rishna, 2017; Chathurani *et al.*, 2022a). Therefore, the findings of the recent study have been compared with those of researchers. Some of those studies have focused on the identification of risk and vulnerable areas of flooding in the Attanagalu Oya river basin (Chathurani *et al.*, 2022a). While the current study selected seven flood conditioning factors other researchers had focused on to different factors. Thus, depending on the differences in the selected factors, some differences can be identified in the study results. But, most of the geographical areas were identified as high-risk zones for flood vulnerability.

The flood that occurred in the year 2016 can be identified as the most severe incident in the Attanagalu Oya river basin in the past few decades. Therefore, the research regarding 2016 flood event enables further validation of the results (International Water Management Institute (IWMI), 2016; Pushpakumara and Achala Isuru, 2018; Chathurani *et al.*, 2022a). Those studies have estimated that there are around 200 km^2 flood inundated areas during the incident. In this study, 21.71 km^2 of very high risk and 172.99 km^2 of high-risk areas were found in the Attanagalu Oya river basin. When considering the spatial distribution of the 2016 flood event and the recent results it can be observed that there are similarities in the spatial distribution. Hence, the significance of the current study findings can be confirmed.

There are a number of reasons for the differences between the findings of previous studies and this study. This study has selected only seven flood conditioning factors specially focusing on to the physical characteristics of the river basin. However, there are a number of flood conditioning factors observed in past literature surveys such as basin morphometric characteristics, runoff, land use and land cover (LULC) and human factors. Moreover, this research has used the satiate estimated data due to the lack of availability of real-time data for the entire basin area. Hence, it may have caused the changes in the findings.

4. Conclusions

The findings of this study identified the high-risk area for flooding in the Attanagalu Oya river basin using AHP and GIS weighted overlay methods. The study found 21.71 km2 of very high-risk areas and 172.99 km2 of high-risk areas in the river basin. It has been found that the southwest area of the river basin is vulnerable to very high-risk flooding. The AHP technique provides useful insights for flood susceptibility mapping when a higher number of parameters are used.

In order to make decisions about sustainable development, plan and design essential interventions and allocate funding for flood risk reduction, it is crucial to understand the flood risk of low-lying terrain. It is possible to establish strategies to lessen catastrophes and mitigate hazards while raising living standards by analyzing disaster risks and how they might be expressed throughout society at large. Flood susceptibility mapping and assessment is essential for identifying flood risk zones and flood prevention and mitigation strategies because it identifies the most vulnerable areas based on the physical factors that determine susceptibility to flooding. Therefore, such studies will open new avenues for flood risk management, prevention and mitigation in Sri Lanka.

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