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FLOOD RISK ASSESSMENT IN THE VULNERABLE ECONOMIC ZONES: A CASE STUDY IN THE KELANI RIVER BASIN

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ABSTRACT

This research presents a comprehensive framework for managing flood risk in the Kelani River basin, employing the Analytic Hierarchy Process (AHP) and spatial analysis to enhance flood risk comprehension, support informed decision-making, and facilitate effective flood management. Initially, the framework identifies key parameters influencing flood risk, which are then used to create flood hazard and vulnerability indexes through AHP. The hazard index indicates the likelihood of a flood event, while the vulnerability index assesses potential impacts. These two indexes are combined to form an overall flood risk index. Subsequently, this index is utilized to develop a web-based spatial decision support system (SDSS), enabling businesses and stakeholders to visualize and analyze flood risk information, aiding them in making well-informed decisions regarding flood mitigation and adaptation measures. This research offers valuable insights for policymakers and authorities in the Kelani River basin, fostering resilience and sustainable development in the region. Though the study acknowledges limitations related to data availability and generalization to other regions, it serves as a valuable foundation for the development of more comprehensive and effective flood risk management frameworks in the Kelani River basin and beyond.

Keywords: Analytic Hierarchy Process (AHP), Flood Risk Index, Spatial Analysis, Spatial Decision Support System, Susceptibility Mapping

1. Introduction

Floods are recognized as one of the major natural hazards with significant economic and social impacts, as well as one of the most common natural disasters worldwide (Hemmati et al., 2020). According to the Vision of Humanity Organization (dlewis, 2020) in 2019, floods accounted for 42% of all weather-related disasters in the world and the CRED international disaster database (CRED, n.d) shows that floods have been the most common natural disaster in the recent years. Countries that are in tropical regions with severe monsoonal influences commonly face frequent flood events that result in significant property damage and loss of human life. As a tropical country experiencing a significant impact of monsoons, Sri Lanka is particularly susceptible to flood hazards (Nuska, 2021). A study conducted by the Environmental Ministry of Sri Lanka on the national climate change adaptation strategy between 2011 and 2016 reveals that the wet-zone region is expected to experience an increase in rainfall intensity due to the effect of the monsoon season and topography of the region (National Adaptation Plan for Climate Change Impacts in Sri Lanka Climate Change Secretariat Ministry of Mahaweli Development and Environment 2016, n.d.). This increase in rainfall intensity is expected to increase the likelihood of flooding in flood-prone rivers.

The Kelani River, which is located in the wet zone of Sri Lanka, stands out as a river that has experienced the highest frequency of flooding, leading to substantial damages (Samarasinghe et al., 2022). The importance of studying the Kelani River basin emerges from the need to comprehensively understand and effectively address the risks and impacts associated with flood events (Mawilmada, 2010). By gaining insight into the dynamics of the Kelani River basin, researchers and policymakers can develop informed decisions and strategies to mitigate the adverse effects of flooding and enhance overall resilience in the region. Hence, this study aims to create a web-based spatial decision support system that empowers stakeholders to make well-informed decisions supported by reliable information.

This research represents a crucial step in addressing and mitigating the persistent flood risks faced by the Kelani River basin in Sri Lanka. By employing advanced spatial analytics and a comprehensive framework, it strives to provide a robust understanding of flood hazards and vulnerabilities in the region. The development of a web-based spatial decision support system empowers stakeholders to make informed choices, allocate resources efficiently, and ultimately enhance the basin's resilience in the face of increasingly intense rainfall and flood events. This endeavor not only benefits the local communities but also contributes valuable insights and methodologies that can be applied to other flood-prone regions, fostering a more proactive and adaptive approach to managing one of the world's most common and impactful natural disasters.

2. Literature Review

The importance of studying the Kelani River basin emerges from the need to comprehensively understand and effectively address the risks and impacts associated with flood events (Perera, 2021).

A flood risk assessing and forecasting model requires the efficient management of extensive spatial and temporal datasets. This involves various tasks such as data acquisition, storage, processing, manipulation, reporting, and displaying results. Due to the complexity of flood forecasting, it can be challenging for individual organizations to effectively handle the decision-making process (Wang & Cheng, 2007). One of the challenges in developing a real-time decision support system is the difficulty in linking data, analysis tools, and models. This integration barrier hinders the seamless flow of information and knowledge exchange among different organizations involved in flood management. According to Wang and Cheng, a web-based Spatial Decision Support System (SDSS) that aims to facilitate information exchange, knowledge sharing, and model integration among diverse stakeholders through web-based platforms needs to be implemented (Wang & Cheng, 2007). The SDSS allows for the integration of various data sources, including real-time monitoring data, historical records, and spatial data layers, into a unified platform (Wang & Cheng, 2007). It provides users with access to interactive maps, visualization tools, and analytical capabilities to analyze and interpret flood-related information. Furthermore, it enables the sharing and dissemination of research findings, best practices, and decision-support models across different organizations (Horita et al., 2015). Wang and Cheng (2007) have identified the multitier architecture as a widely used and effective approach for enhancing the quality and performance of SDSS. This architecture is designed to optimize the functionality and efficiency of the SDSS by organizing it into multiple tiers or layers. In the multitier architecture, the SDSS is divided into distinct layers, each serving a specific purpose and carrying out specific tasks. The architecture typically consists of three tiers: the presentation tier, the application tier, and the data tier (Wang & Cheng, 2007).

According to the study conducted by Horita et al. (2015), the integration of volunteered geographic information and remote sensing data can be used to monitor water-related vegetation stress. SDSS plays a crucial role in enhancing the effectiveness of flood risk management. By integrating various data sources and flood assessment models, an SDSS can facilitate informed decision-making processes (Horita et al., 2015). However, in the Sri Lankan context, there is currently a gap in the availability of a proper SDSS for making informed decisions regarding floods. Limited research has been conducted in this specific area within the Sri Lankan context. An SDSS has the potential to integrate multiple flood assessment models, diverse data sources, and analytical tools (Wang & Cheng, 2007). By bringing these components together, decision-makers can gain comprehensive insights into flood risks and make informed choices regarding flood management strategies.

3. Methodology

The study employed the Analytic Hierarchy Process (AHP) to calculate the flood index for the basin while also investigating and analyzing various factors related to flood hazard and vulnerability. These factors will be identified and comprehensively explained in the subsequent sections. This process incorporated various parameters, including susceptibility mapping to assess the vulnerability of different areas to flooding. Furthermore, the framework aims to develop a web-based spatial decision support system that empowers stakeholders, including businesses, to make well-informed decisions supported by reliable information. By integrating the collected data, flood index calculations, and spatial analysis results, the decision support system will provide users with a user-friendly interface to visualize and analyze flood risks in the Kelani River Basin.

3.1. Study area

The Kelani River in Sri Lanka is not only the second-largest watershed in the country, but it also is the fourth-longest river (Perera & Nakamura, 2023). Originating from Adams Peak and the Kirigalpotta areas, which are situated at an elevation of 2,200 meters above the mean sea level in the Central Hills, the Kelani River flows entirely within the wet zone of Sri Lanka (Perera & Nakamura, 2023). The Kelani River basin receives a substantial average annual rainfall of 3,450 mm, resulting in a voluminous water flow of approximately 7,860 million cubic meters (Perera, 2021). During the monsoon period, the river experiences a remarkable peak flow ranging from about 800 to 1500 cubic meters per second as it reaches the sea (Samarasinghe et al., 2022). Administratively, the Kelani River spans across three provinces, namely, Western, Sabaragamuwa, and Central. This vast and vital river system plays a crucial role in the ecology, economy, and livelihoods of the regions it traverses (Alberta. et al., 2010).

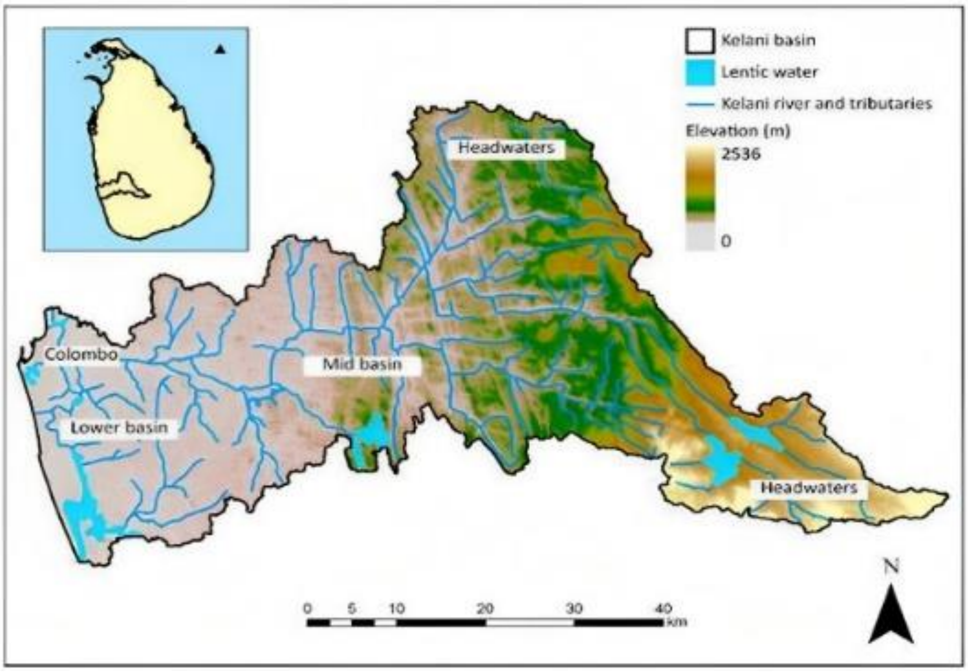

Figure 1. Topographic map of the Kelani River basin.

3.2. Data collection

This study utilized a combination of primary and secondary data sources. The primary data collection involved gathering insights and opinions from experts regarding the flood factors specific to the study area. The secondary data were publicly available from the official websites of several government departments. The specific data sources used for each flood factor are summarized in Table 1.

3.3. Data analysis

This study aimed to investigate and analyze a range of factors associated with flood hazard and vulnerability. The identification and comprehensive explanation of these factors are included in the following subsections. To determine the relative contributions of flood causative factors and assign appropriate weights to them, the study utilized the AHP, which consisted of four main steps. Firstly, a decision hierarchy was constructed to organize the attributes and sub-attributes. Secondly, the relative importance of these attributes and sub-attributes was determined. Thirdly, each alternative was evaluated and its overall weight for each attribute was calculated. Finally, a consistency check was conducted to ensure the reliability of the subjective evaluations (Malgwi et al., 2021).

Table 1. Data factors and data sources.

Data Factor	Data Source
Slope	Shuttle Radar Topography Mission (SRTM) digital elevation model
Elevation	SRTM digital elevation model
Lithology	Sri Lanka National Spatial Data Infrastructure (NSDI) Geoportal Retrieved September 15, 2022, from https://geoportal.nsdi.gov.lk/
Hydrology	Sri Lankan Rivers shapefile from the United Nations Office for the Coordination of Humanitarian Affairs Regional Office for Asia and the Pacific (OCHA's ROAP) Retrieved September 01, 2022, from https://data.humdata.org/dataset/sri-lanka-water-bodies-0-0
Roads	Sri Lankan roads shapefile from the United Nations OCHA's ROAP. Retrieved September 15, 2022, from https://data.humdata.org/dataset/hotosm Ika roads
Structure	Sri Lanka NSDI Geoportal Retrieved September 15, 2022, from https://geoportal.nsdi.gov.lk/
Normalized Difference Vegetation Index (NDVI)	Calculation using United States Geological Survey (USGS) Earth Explorer Landsat 9 satellite images Retrieved September 15, 2022, from https://www.usgs.gov/landsat-missions/landsat-9
Land Use and Land Cover (LULC)	Calculation using USGS Earth Explorer Landsat 9 satellite images Retrieved September 15, 2022, from https://earthexplorer.usgs.gov/
Rainfall	Website of the Disaster Management Center, Sri Lanka (DMC) Retrieved September 15, 2022, from https://www.dmc.gov.lk/index.php?option=com_dmcreports&view=reports&Itemid=277&report_type_id=6&lang=en
River water level	Website of the DMC Retrieved September 15, 2022, from https://www.dmc.gov.lk/index.php?option=com_dmcreports&view=reports&Itemid=277&report_type_id=6&lang=en
Soil Permeability	World Soil Map Retrieved September 15, 2022, from https://data.isric.org/geonetwork/srv/eng/catalog.search#/home
Population Density	OCHA's ROAP Retrieved September 15, 2022, from https://data.humdata.org/group/lka?organization=ocha-roap
Gender ratio	Department of Census and Statistics, Sri Lanka (DCS) Retrieved September 15, 2022, from http://www.statistics.gov.lk/GenderStatistics/StaticalInformation/Population

These steps allowed for a systematic assessment of the criteria, evaluation of alternatives, and generation of overall weights, while also ensuring the consistency of the subjective evaluations. The opinions of experts from academia and authorities played a crucial role in this process. Their insights, along with conclusions drawn from existing literature, were considered to ensure the validity and accuracy of the AHP evaluations conducted in this study.

In the pairwise comparisons conducted to assess the relative importance of the factors, the study utilized the nine-point pairwise comparison scale, also known as the Saaty scale (Saaty, 1987). By employing this scale, the study ensured a structured and consistent approach to comparing and weighing the factors involved in the assessment (Bendijo & Morales, 2022).

Table 2. Pairwise comparisons scale (Saaty, 1987).

Intensity	Definition	Explanation
1	Equal	Two elements contribute equally
3	Moderate	Slight favoring of one element
5	Strong	Strong favoring of one element
7	Very strong	Very strong favoring of one element
9	Extreme	Highest extreme importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed

To facilitate the pairwise comparison process within the AHP framework, expert opinions were sought by distributing a questionnaire to individuals with relevant expertise and knowledge of flood hazards and related factors. The questionnaire was distributed to subject matter experts, academic specialists, as well as professionals with experience in disaster management and other relevant authorities. By gathering insights and perspectives from these experts, the study aimed to ensure the inclusion of diverse viewpoints and expertise in the assessment of the flood hazard and flood vulnerability factors involved in the AHP analysis.

3.4. Flood hazard factors

Flood hazard identification is a complex process that involves considering multiple factors, which can vary from one study area to another. The selection of criteria depends on the specific characteristics and context of the study (Baykal et al., 2023). The selected flood hazard factors in this study included rainfall intensity, river density, soil permeability, Land Use and Land Cover (LULC), slope, and elevation. These factors were chosen based on their relevance and potential influence on flood occurrence and severity in the Kelani River basin.

3.5. Flood vulnerability factors

Flood vulnerability in an area depends on environmental, economic, social, and even political factors, which affect measuring the vulnerability. That means vulnerability is influenced by several factors including human settlement conditions, infrastructure, regulations and policies, and economic patterns (Sangati et al., 2009). Flood vulnerability differs for people in different circumstances (Mbow et al., n.d.). The population density, gender ratio, and road density were considered for assessing flood vulnerability in this study, as there is a lack of statistical data on factors such as property, infrastructure, and other crucial criteria.

3.6. Flood risk assessment

By systematically analyzing data factors, decision-makers can gain valuable insights into the level of flood risk and develop effective strategies for mitigation and preparedness.

The assessment process typically involves three stages, each focusing on different aspects of flood risk. In this study, the following calculations were conducted based on selected factors derived from expert opinions and existing literature:

Flood hazard index: This stage aimed to develop a flood hazard index by considering factors such as rainfall intensity, river density, elevation, slope, LULC, and soil permeability. A pairwise comparison of these factors was performed according to expert opinions gathered previously. Subsequently, the consistency ratio was calculated to ensure the reliability of the comparisons. The study area was then classified using the flood hazard index generated based on the calculated weights for the decision criteria and criteria values.

Flood vulnerability index: In this stage, a flood vulnerability index was developed by considering factors such as road density, population density, and gender ratio. Similar to the previous stage, a pairwise comparison was conducted based on expert opinions. The consistency ratio was calculated to validate the comparisons, and the area of study was classified using the resulting vulnerability index generated based on the calculated weights for the decision criteria and criteria values.

Risk index calculation: The flood hazard index and flood vulnerability index were combined to create an overall risk index, providing an assessment of flood-associated risk in the study area. Thus, from Buta et al. (2020)

$$\boldsymbol{Flood\ risk\ index} = \boldsymbol{Flood\ hazard\ index} \times \boldsymbol{Flood\ vulnerability\ index}$$

3.7. Mapping and visualization

Depending on data availability, data types, and computational constraints, various methods can be employed to generate flood risk maps. In this study, the calculated flood assessing indexes and data were utilized in Geographic Information System (GIS) applications, specifically using tools like ArcGIS. This allowed for the generation of different types of flood maps, including flood hazard maps, flood vulnerability maps, flood inundation maps, and flood risk maps.

To assess past flood events and analyze their characteristics, historical data maps were created for comparison with the generated maps. Additionally, hydraulic models and computer simulations were employed within the GIS framework to create maps that predict water flow patterns and identify areas at risk of flood inundation. To ensure a comprehensive assessment, multiple data sources were integrated into the generation of the flood risk map. This included incorporating topographical data, land use information, and historical flood records. By combining these various data sources and utilizing advanced GIS techniques, a comprehensive flood risk map was generated, providing valuable insights for decision-making and risk management strategies. The methodology process, depicted in Figure 2, outlines the steps involved in generating flood maps. It provides an overview of the process leading up to the generation of flood maps.

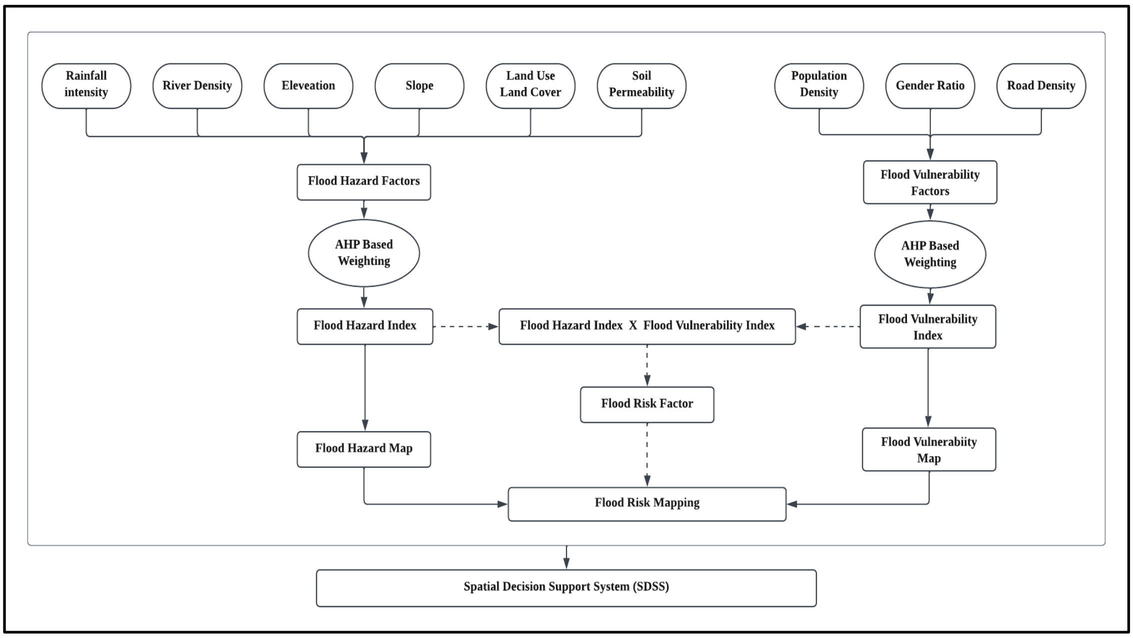

Figure 2. The framework of the methodology process.

3.8. Spatial Decision Support System (SDSS)

Utilizing advanced spatial analysis and modeling techniques, the SDSS enables the processing and interpretation of the collected data systematically. By performing calculations, comparisons, and modelling of various flood factors, the system generates meaningful insights that aid in understanding the dynamics of flood risk. The integration of these factors within a comprehensive framework enables a holistic assessment of flood hazards, accounting for their complex interrelationships and spatial patterns. This approach enables the identification of high-risk areas and the prioritization of mitigation efforts.

4. Results/Analysis and Discussion

Through the utilization of the identified parameters for flood hazard and flood vulnerability, the maps shown in Figures 3 and 4 were constructed to unravel the distinctive characteristics and gather profound insights concerning the Kelani River basin. (Samarasinghe et al., 2022). These maps were developed based on variables such as rainfall intensity, river density, elevation, slope, and soil permeability. These cartographic representations serve as powerful tools for policymakers and decision-makers, enabling them to discern geographical and spatial insights.

In particular, the maps in Figure 3 are designed for rainfall intensity, river density, elevation, slope, and soil permeability and offer a comprehensive visual representation of the basin's intricate landscape. By overlaying these layers of information, decision-makers can discern patterns and relationships that might not be immediately apparent through isolated data points. For instance, the maps bring forth noteworthy insights, such as the equitable dispersion of elevated regions across various elevation categories throughout the river basin. Moreover, areas characterized by high soil permeability in conjunction with steep slopes might experience rapid surface runoff during heavy rainfall, potentially leading to flash floods (Douinot et al., 2022).

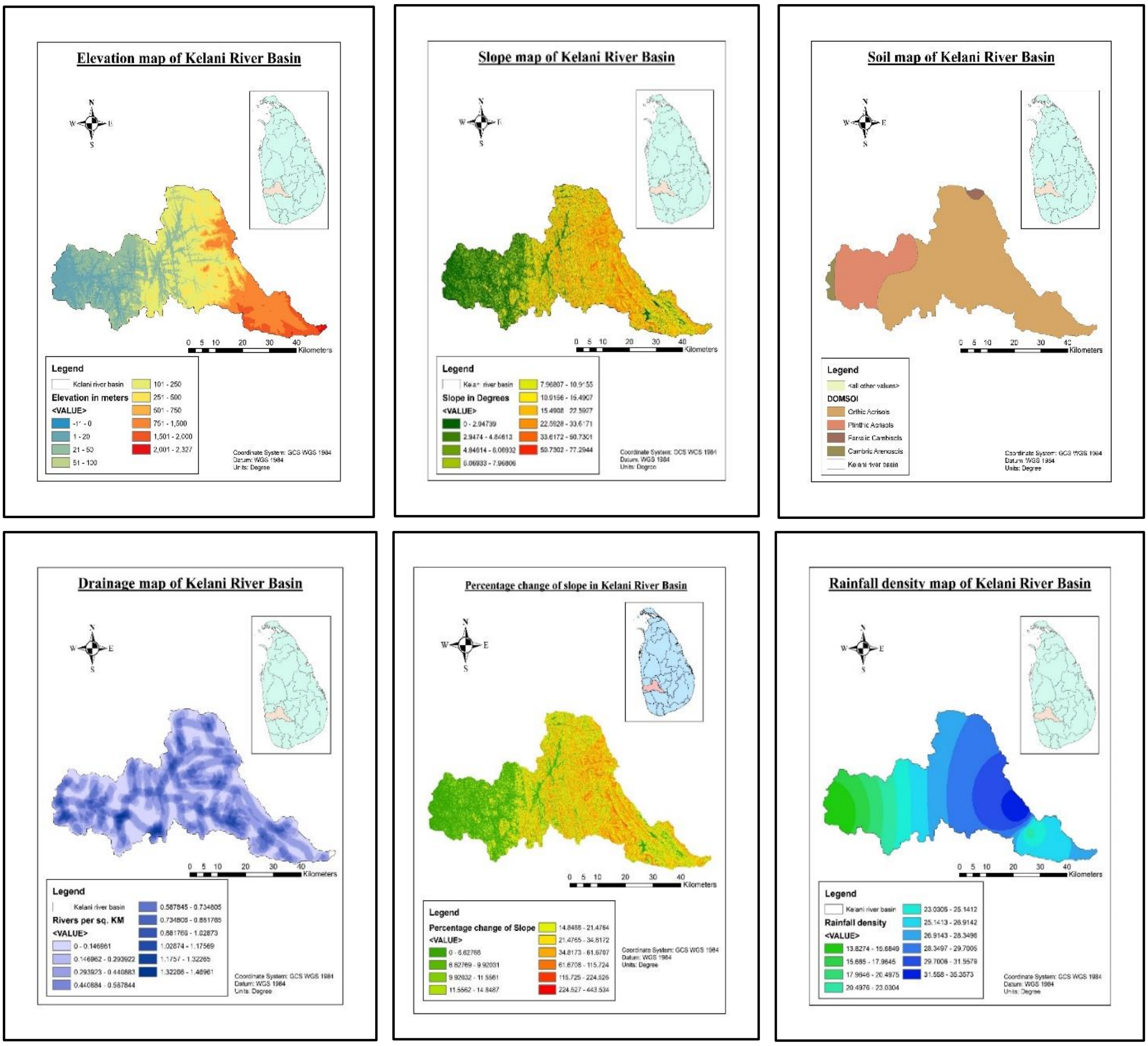

Figure 3. (a) Elevation map, (b) Slope map, (c) Soil map, (d) Drainage map, (e) Percentage Change slope Map, (f) Rainfall density map.

Maps developed on vulnerability factors shown in Figure 4, which are road density, population density, and gender ratio, bring an additional layer of analysis for the decision-makers. These maps serve not only to unveil the vulnerability of the area's livelihood to natural calamities but also to highlight broader social vulnerabilities. By considering elements such as accessibility, demographic distribution, and gender balance, policymakers can identify regions particularly susceptible to flooding (Rimba et al., 2017).

For instance, the map representing road density facilitates the identification of road networks and their distribution, which in turn aids decision-makers in assessing accessibility and planning evacuation routes. The population density and gender ratio maps provide insights into demographic variations, helping policymakers pinpoint areas with high concentrations of vulnerable groups, such as the elderly or young.

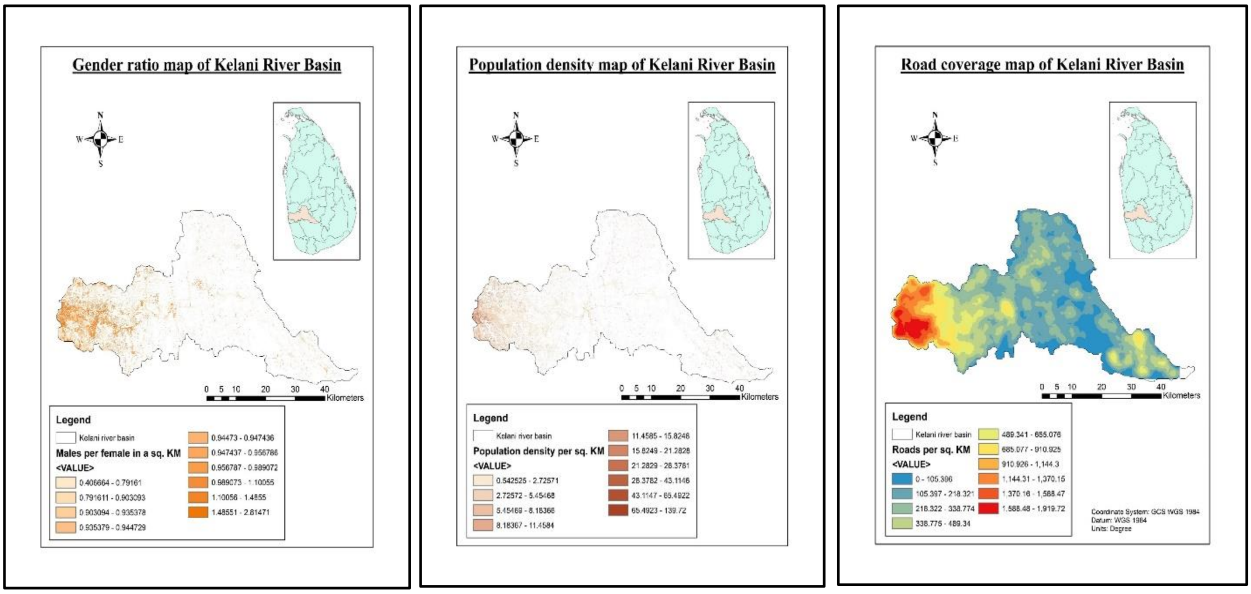

Figure 4. (a) Population density map, (b) Genderratio map, (c) Road coverage map.

These cartographic aids, coupled with demographic insights, play a crucial role in guiding policy and decision-makers. By leveraging the information embedded in these maps, authorities can effectively plan and respond to flood events (Wang, Zhu, & Yu, 2022, p. 16595). The insights generated from the maps facilitate an informed understanding of the factors that underlie the emergence of flood hazards and vulnerability. Consequently, policymakers can strategize and execute actions that effectively address these causes, enhance flood resilience, and ensure the safety and well-being of the populace. Moreover, the integration of AHP into these maps offers an additional layer of analysis. This integration empowers the determination of risk areas based on a comprehensive flood risk index tailored to the Kelani River basin. Consequently, when confronted with hazardous situations, decision-makers gain the capability to make well-informed choices. Furthermore, this risk index exerts a significant tangible influence on decisions concerning new construction within the region. By factoring in potential risks, future buildings can be designed to proactively address challenges and mitigate potential issues, thereby enhancing the overall preparedness of the basin.

4.1. Development of dashboard and SDSS

In addition to the generated maps, a dashboard was developed utilizing the collected rainfall and water level data sourced from the DMC website. This dashboard is designed to offer detailed insights based on the recorded rainfall and water levels. It effectively signals instances where the water level rises, surpassing the predetermined safe or threshold levels corresponding to each gauging centre. This determination is grounded in the unique geographical characteristics encompassing the respective gauging centers. As such, the dashboard provides a classification into normal, alert, or high-risk levels. Figure 5 presents an image showcasing the visual representation of this dashboard.

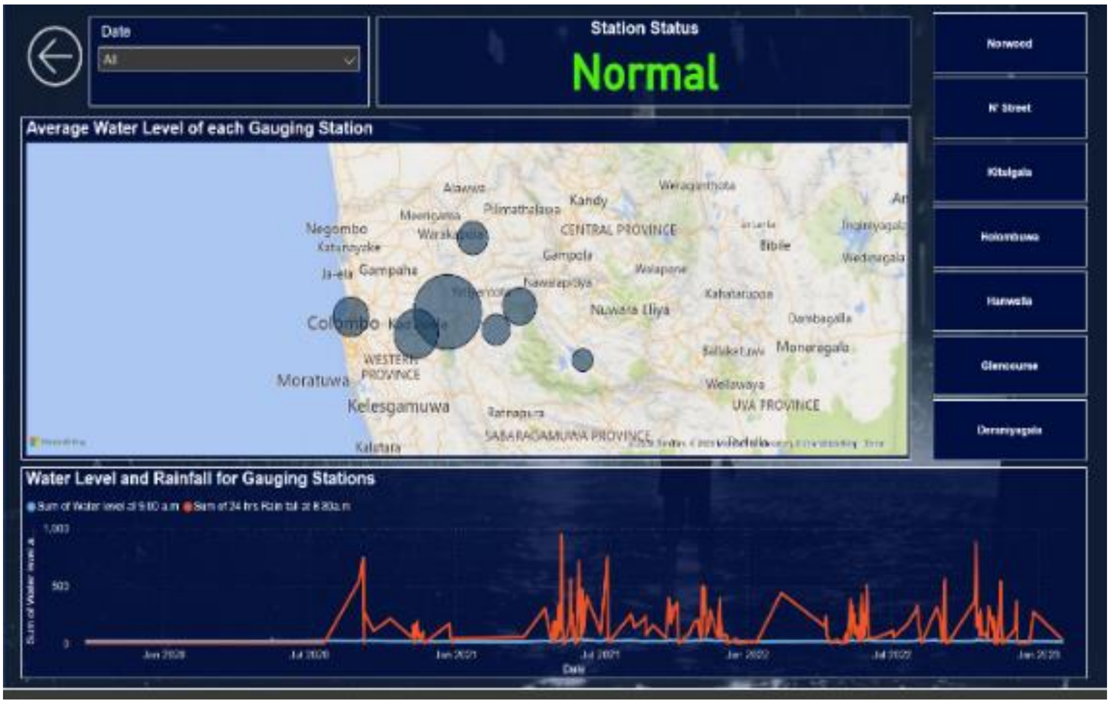

Figure 5. Flood data dashboard.

To further enhance the decision-making capabilities of policymakers and stakeholders, a web-based SDSS was developed. This system integrates the above-mentioned data, maps, and dashboard visualizations. The primary objective of the SDSS is to enhance decision-making processes related to flood risk assessment. It provides decision-makers with a user-friendly interface and tools to explore different scenarios, evaluate the potential impacts of various interventions, and assess the effectiveness of different flood mitigation strategies. The SDSS incorporates sensitivity analysis, scenario comparison, and optimization features to support evidence-based decision-making. By facilitating the exploration of alternative options and their associated risks, the SDSS empowers decision-makers to make informed choices regarding flood mitigation and preparedness strategies (Hsu & Gourbesville, 2023). Moreover, as a tangible outcome of this research, a dedicated web page has been established, showcasing the generated findings. Figure 6 offers a glimpse into the visual content presented on this web page.

4.2. Data limitations

The availability and quality of data used for the assessment were subject to limitations. While efforts were made to gather primary and secondary data from various sources, data coverage, resolution, and consistency may vary. Additionally, certain factors such as property and infrastructure conditions might not have comprehensive and up-to-date data, leading to uncertainties in the assessment (Yi & Zhang, 2013, p. 1709). An example of a scenario impacted by this limitation is the integration of the dashboard created to indicate water levels and the status of a particular area. If the dashboard could be integrated with a live data source, it would enable real-time status updates, providing decision-makers and stakeholders with timely information.

Figure 6. Webpage.

5. Conclusion

This study is dedicated to assessing flood impacts and associated risks within the Kelani River basin in Sri Lanka. The primary objective is to equip stakeholders with the necessary tools for informed decision-making. The methodology involves the comprehensive collection of data from primary and secondary sources, encompassing factors such as slope, elevation, hydrology, roads, lithology, structures, NDVI, LULC, rainfall, river water level, soil permeability, population density, and gender ratio.

Data analysis involves the evaluation of flood hazard and vulnerability factors, employing the AHP. The outcome of this framework is the generation of flood hazard and vulnerability indexes on timely available data, subsequently synthesized to calculate a comprehensive risk index. The indexes are presented using mapping techniques and dashboard visualizations, seamlessly integrated into a SDSS to facilitate effective decision-making. Despite some data limitations, this study lays a solid foundation for flood mitigation and preparedness strategies. It provides a valuable framework for policymakers to navigate flood risk scenarios, ultimately ensuring the resilience of the basin against future flood events.

It is worth noting that the findings of this study are specific to the Kelani River basin and might not be directly applicable to other regions or river basins. Factors such as topography, climate patterns, and land use practices can vary, leading to variations in flood risk. Thus, caution should be exercised when generalizing the results, and further studies are necessary to assess flood risk in different regions.

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