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REMOTE SENSING AND GIS-DRIVEN MODEL FOR FLOOD SUSCEPTIBILITY ASSESSMENT IN THE UPPER SOLO RIVER WATERSHED

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ABSTRACT:

This study aims to develop an expedited flood susceptibility model with remote sensing data that can be effectively utilized for a large catchment area. We apply the model to the Upper Solo River Watershed in Indonesia. The model incorporates the hydrological attributes of the watershed obtained from remote sensing data, including elevation, slope, flow accumulation, proximity to rivers, rainfall, drainage density, topographic wetness index, land use land cover, normalized difference vegetation index, soil moisture, and land surface curvature. The flood susceptibility criteria are generated using remote sensing datasets such as The Shuttle Radar Topography Mission (SRTM), Sentinel 2 Multispectral Instrument, Global Precipitation Measurement (GPM) v6, and NASA-USDA Enhanced SMAP Global Soil Moisture Data. Through utilizing remote sensing data and GIS analytic tools, this study has discovered that it is possible to create a flood susceptibility model for large catchment regions cost-efficiently. Our study indicates that areas in the surrounding of Surakarta City, the most populated city in this watershed, are the most susceptible. Therefore, the government and community should increase their capacity to cope with this potential disaster.

Key-words: *GIS, Remote sensing, Flood susceptibility, Watershed characteristics.*

1. INTRODUCTION

Natural catastrophes are observed to escalate due to natural phenomena and human actions, resulting in substantial casualties, damage to property, and destruction of resources. Human actions such as deforestation, land clearance on mountain slopes, and cultivation in places with steep slopes might contribute to the occurrence of natural catastrophes. Indonesia is susceptible to natural disasters because it is situated in a region of active tectonics and volcanism resulting from the convergence of three tectonic plates: India-Australia, Pacific and Eurasia. Flooding is the most common natural disaster that we often suffer from in Indonesia (Susetyo, 2008). Moreover, compared to other Southeast Asian states, Indonesia had the largest number of flood disasters for the years 1980 to 2018 (Samphantharak, 2019).

The Upper Solo River Watershed is located in the Indonesian province of Jawa Tengah (South Central Java). This area has had long records of flood events for years. During flood events, the amount of water in this area forms due to the combination of different factors like much rain, high tides and failures to drain the water. The flooding damaged infrastructures and caused the loss of lives, including the collapse of bridges and roads. For example, the most colossal floods in over 50 years in 2007, were caused by extreme precipitation and insufficient drainage. The flood inundation is high, affecting more than 11,000 houses (Zein, 2010). There are thousands of people displaced from their houses, living in tents or temporary houses, which led to various health problems. Afterwards, the local municipal authorities strengthened the drainage system to mitigate the disaster. Although

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attempts have been made, the Upper Solo River Watershed is still highly prone to flooding, especially in the rainy season. Over the past few years, there has been a rise in the occurrence and intensity of extreme weather events, including heavy rainfall, leading to increasingly regular instances of flooding in the area. Therefore, it is necessary to continuously monitor and implement measures to decrease the adverse effects of flooding on the populations in the region.

A flood is defined as the occurrence of abnormally large volumes or elevations of water in rivers, lakes, ponds, reservoirs, and other bodies of water, which leads to land flooding beyond the normal boundaries of these water bodies (Marfai, 2003). Flooding is a frequent occurrence, as it is widespread across the entire earth. Flooding can arise from intense precipitation, glacial melting, tsunamis, hurricanes, and other oceanic occurrences. At the same time, flood hazard refers to the likelihood of a flood occurring of a specific size in a particular area during a specific period (Alkema and Middelkoop, 2005).

The floods may result from natural processes that affect the socio-economic system (Falguni and Singh, 2020; Komolafe et al., 2020). Several factors, such as climate, rainfall, land structure, vegetation, slope, human activities, and land use change, can also increase the intensity of flooding (Curebal et al., 2016; Chagas et al., 2022). In some areas, floods may have been a natural process in the past, but due to urbanization and land use change, they become disasters that lead to loss of lives, disturb livelihood, and devastate infrastructure (Rincón et al., 2018). In addition, forest and urban clearing decreases water absorption and increases the amount of runoff (Sugianto et al., 2022). As a sequent, this raises the level of floods and their intensity. Therefore, such geographical factors can be used to model flood susceptibility.

The utilization of the current dataset and technology will be the key to successfully building a cheaper and faster model. The integration of GIS and Remote Sensing technology will allow for the assessment of flood hazards on a large scale (Pradhan et al., 2009). Several studies have demonstrated different GIS and remote sensing technology approaches in mapping flood-prone areas across the globe (Elkhrachy, 2015; Islam and Sado, 2000). The investigations were carried out with different methods such as spatial multi-criteria analysis (Zhou et al., 2021), cell automata (Ghimire et al., 2013), and Analytic Hierarchical Processes (Negese et al., 2022; Sarmah et al., 2020); but application with widely accessible data that can be used to model large catchment with low-cost is limited. Furthermore, such studies in the Solo River Watershed are limited and need a more comprehensive approach. Farid et al. (2020) initiated their flood study in the region, more specifically, but not comprehensively covering the whole region. Therefore, this study aims to develop an expedited flood susceptibility model with remote sensing data that can be effectively utilized for a large catchment area, especially for the Upper Solo River Watershed.

The remainder of this paper is organized as follows. The second section provides a detailed description of the study area, highlighting its geographical characteristics. The third section outlines the data collection and methodology, detailing the types of remote sensing data used, the processing techniques, and the model development process. In the fourth section, the results of the model are presented. The fifth section discusses the implications of the findings, comparing them with existing models and highlighting the advantages of the proposed approach. The paper concludes with a summary of the key findings, potential applications, and suggestions for future research.

2. STUDY AREA

The Solo River water system is mainly drained by an extensive water system positioned between 6.48-8.07 S latitude and 110.26-112.41 E longitude (**Fig.1**). The area under consideration, which is designated as watershed, has a length of 12 districts from the province of Central Java to the province of East Java. It is also bounded by a range of mountains that clearly differentiate it from adjacent river basins. The regression is very surprising; it goes from zero meters above the seawater in the Madur Strait to 3,265 meters above sea level at Mount Lawu's peak. This watershed covers an area of 6,072 km^2 only. In this area, the diversity of the relief is striking. That goes from flatlands to mountains with gentle slopes to steep ones, which, in turn, cause lots of changes in the climates and rain patterns.

A thorough analysis is carried out, which deals with the urban area of the most developed city in Surakarta, which lies immediately upstream. The lithological characteristics of the erupted materials varied through time, as volcanic complexes like Merapi, Merbabu, and Lawu defined the region. Pumice, conglomerates, breccias, and tuff are among the volcanic materials abundant in the larger area, which are often mixed with andesitic ones. The creations of these volcanic formations are catalysts of the watershed's fertile soils, which support a diversity of land cover types. However, there has been a decrease in specific land cover categories like sub-aerial acidic clastic deposits in recent years. Hydrologically, the Solo River and its tributaries constitute an intricate network that plays an important role in the area's water resource management, with the river's flow originating from the eastern slopes of these prominent volcanic mountains. The watershed's unique topography and geological characteristics facilitate many ecosystems and present challenges and opportunities regarding water resource management, land use, and conservation efforts within this vital river basin area.

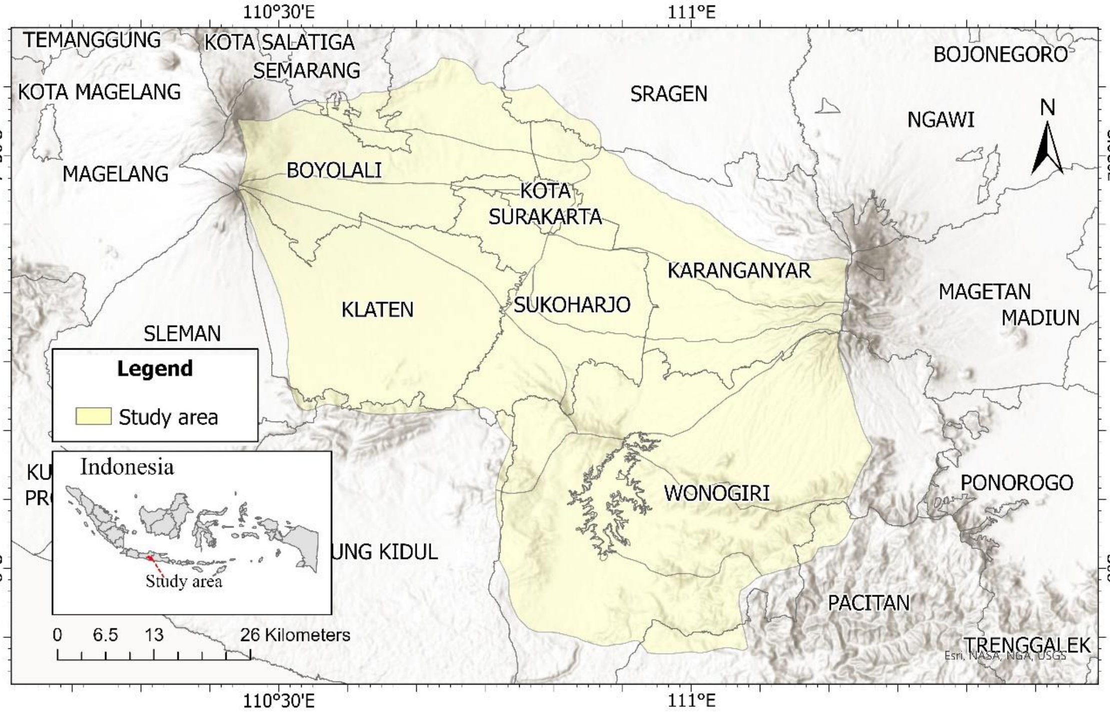

Fig. 1. Location of Upper Watershed of Solo River.

3. DATA AND METHODS

The model utilizes a range of physical characteristics derived from remote sensing datasets **(Table 1**), including elevation, slope, flow accumulation, distance to rivers, rainfall, drainage density, topographic wetness index, land cover, Normalized Difference Vegetation Index, soil moisture, and curvature. These parameters allow for a thorough assessment of flood susceptibility in the region. Floods have been broadly investigated, and many contributing factors have been tallied (Negese et al., 2022; Wanders et al., 2014). Local and wide-scale water flows are largely a function of topography, which causes more water concentration in low-lying areas and level lands due to the lack of movement (low velocity), which induces flooding. The flood risk linked to height and river distance is another factor. Lowlands are more susceptible to flooding mainly because of the higher high water and smaller river velocity. The occurrence of floods decisively depends on the velocity and the extent of the water stream and the capacity of drainage systems as well. When the amount of flowing water and the traffic volume of drainage channels are over the capacity, there will be more possibility of flooding. Land use/Land cover (LULC) affects the amount of runoff, therefore directly affecting the flooding potential. Soil moisture expresses the ability to infiltrate water. Higher moisture represents that the soil has a lower ability to infiltrate water.

Additionally, areas with flat curvature are more prone to flooding than other topographic features. Finally, it is crucial to consider precipitation and topographic wetness index as significant factors, as heavy precipitation leads to more water build-up, while the topographic wetness index helps identify areas with possibly saturated land surfaces. Both of these factors contribute to an increased susceptibility to flooding.

Therefore, we derived eleven parameters from four datasets (**Table 1**). The parameters include elevation, slope, flow accumulation, distance to rivers, drainage density, topographic wetness index, curvature, land cover, Normalized Difference Vegetation Index, Rainfall, and soil moisture. DEM was derived into elevation, slope, flow accumulation, distance to rivers, drainage density, topographic wetness index, and curvature. On the other hand, land cover and Normalized Difference Vegetation Index were derived from Sentinel 2 MSI Image. Lastly, Global Precipitation Measurement (GPM) v6 and NASA-USDA Enhanced SMAP Global Soil Moisture Data produce rainfall and soil moisture data, respectively.

Table 1.

The source of datasets.

No	Data	Description	Source	Derived Data
1	DEM	The Shuttle Radar Topography Mission (SRTM).	USGS (Earth Resources Observation And Science (EROS) Center, 2017)	elevation, slope, flow accumulation, distance to rivers, drainage density, topographic wetness index, curvature
2	Images	Sentinel 2 Multispectral Instrument	ESA ("User Guides - Sentinel-2 MSI - Level-2 Processing - Sentinel Online," n.d.)	land cover, Normalized Difference Vegetation Index
3	Rainfall data	Global Precipitation Measurement (GPM) v6.	NASA ("GES DISC Dataset: GPM IMERG Final Precipitation L3 Half Hourly 0.1 degree x 0.1 degree V06 (GPM_3IMERGHH 06)," n.d.)	Rainfall
4	Soil Moisture Data	NASA-USDA Enhanced SMAP Global Soil Moisture Data.	NASA (Entekhabi et al., 2010)	soil moisture

The development of the flood susceptibility model consisted of two processes for the flood-controlling parameters (**Fig. 2**). The parameters were initially transformed into a raster format to facilitate analysis. The characteristics were subsequently standardized to a consistent geographic resolution through resampling. **Fig. 2** illustrates the division of the resampled parameters into five distinct measurement scales, ranging from 1 (indicating a minimal susceptibility to flooding) to 5 (indicating a significant susceptibility to flooding). Applying the weighted overlay technique achieved the integration of all the factors. This methodology enables the incorporation of numerous spatial datasets by allocating weights to each parameter. The weights allocated to the parameters were based on scoring and weighting by Negese et al. (2022).

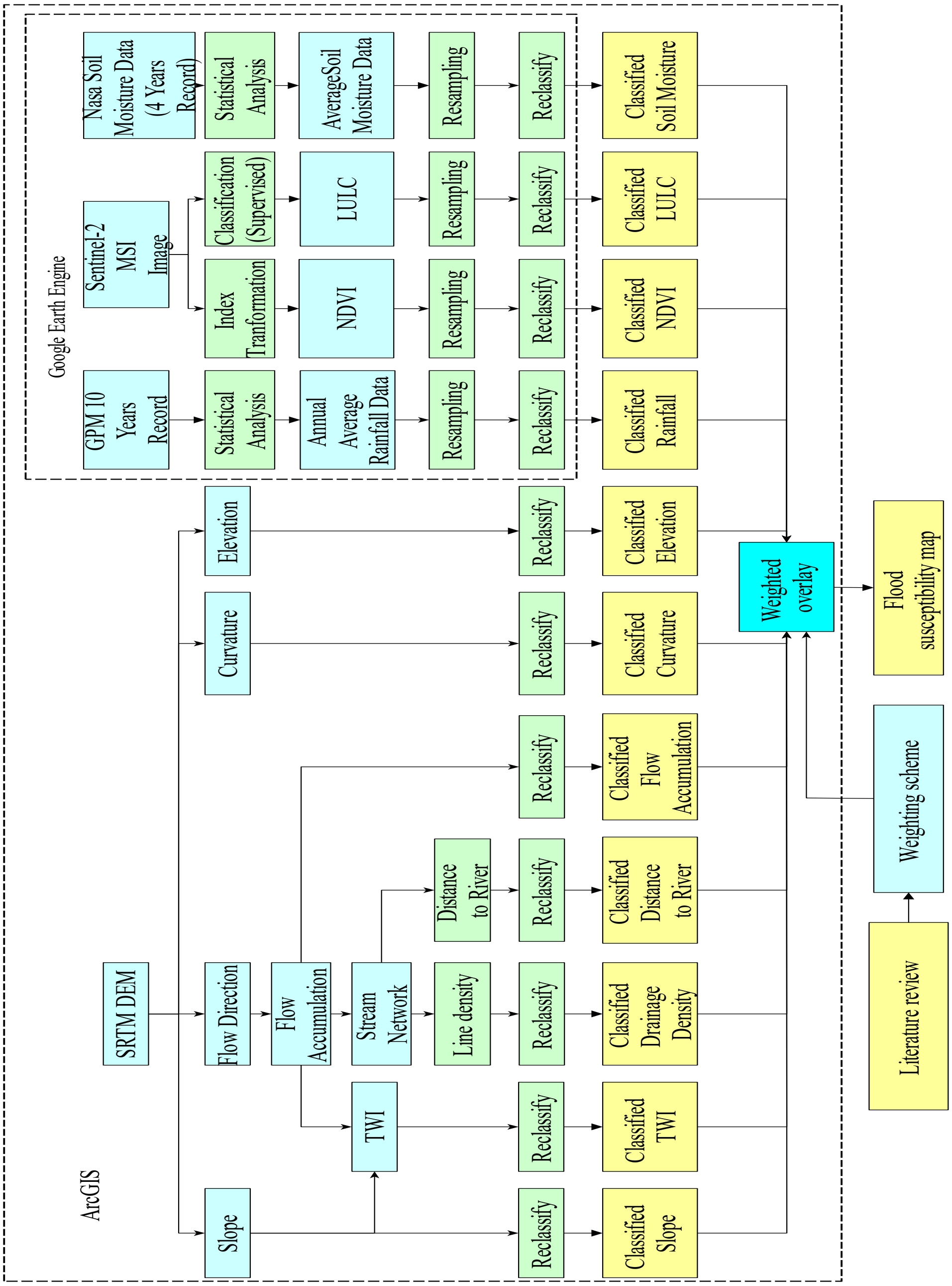

Fig. 2. The research framework.

4. RESULTS

The Flood susceptibility map for the Upper Solo River basin was generated using remote sensing data and GIS modelling. The flood susceptibility criteria were determined after a thorough analysis of the existing literature, which revealed information about the research area's topography, hydrology, meteorology, and anthropology. The flood susceptibility characteristics, as illustrated in **Fig. 3**, have simplified the ranking of flood susceptibility criteria based on their respective contributions to the susceptibility of flood occurrence.

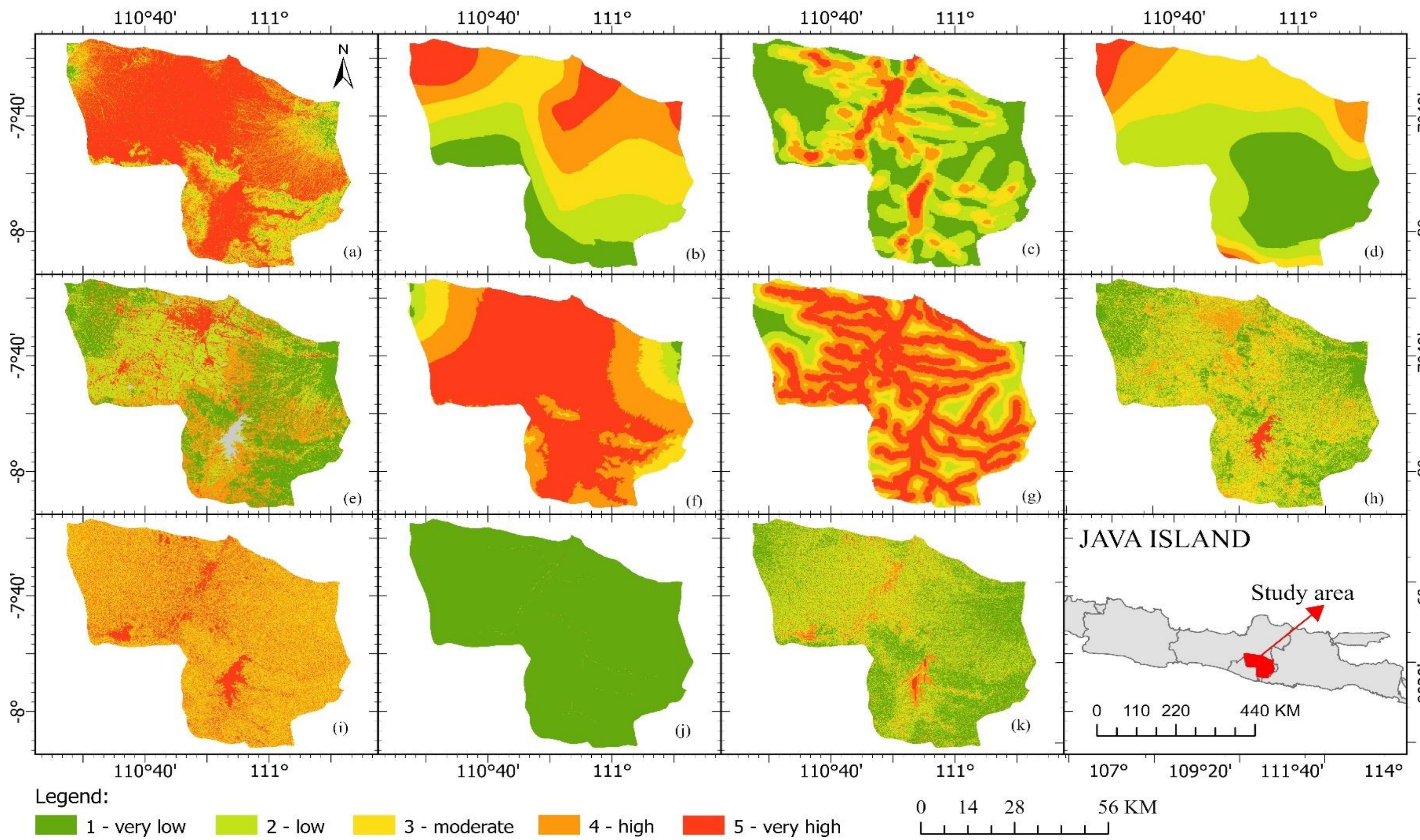

Fig. 3. Remote sensing datasets used to derive classified flood susceptibility parameters. Note: (a) Slope, (b) Relief, (c) Digital Elevation Model (DEM) Derived Drainage, (d) Soil Moisture, (e) Land Cover, (f) Elevation, (g) Digital Raster, (h) Normalized Difference Vegetation Index, (i) Curvature, (j) Flow Accumulation, (k) Topographic Wetness Index.

According to the data in **Fig. 3** and **Table 2**, the areas with a very low likelihood of floods (shown by the blue hue on the map) are Wonogiri, which covers 596.45 square kilometers (42.60% of the total area), Karanganyar, which covers 154.08 square kilometers (27.37% of the total area), and Boyolali, which covers 110.71 square kilometers (26.36% of the total area), (**Fig.4**). The places with the least susceptibility to flooding, represented by the dark green tint on the map, are Wonogiri (444.15 square kilometers, 31.72%), Klaten (268.63 square kilometers, 41.15%), and Karanganyar (146.26 square kilometers, 25.98%). The locations with significant flood vulnerability, indicated by the green-cyan color on the map, include Wonogiri (15.29%), Klaten (29.33%), and Sukoharjo (18.45%). Flood-prone areas, indicated by the light green color on the map, include Sukoharjo, which covers 281.29 square kilometers (57.46%), Boyolali, which covers 133.59 square kilometers (31.81%), and Karanganyar, which covers 29.18 square kilometers (19.98%). The locations with a high risk of flooding, shown by the yellow hue on the map, include Sukoharjo, which covers 50.08 square kilometers (10.20%), Surakarta, which covers 18.46 square kilometers (39.89%), and Karanganyar, which covers 19.98 square kilometers (3.5%). The existence of high and very high conditions may be a cause for concern, particularly when the wet season falls between October and March, when rainfall exceeds 200 mm.

The findings indicate that the Upper Solo River Watershed faces a substantial danger of flooding (**Fig. 4**), particularly in the center and northern sections (in the surrounding of Surakarta City). Water buildup in these areas is impacted by variables such as proximity to the Bengawan Solo River, the river's V-shaped cross-section, and the presence of steep terrain. Wonogiri, Karanganyar, and Boyolali are relatively less susceptible to floods than the other locations studied, but Sukoharjo, Surakarta, and specific sections of Karanganyar are more susceptible. These findings highlight the significance of caution, especially during the rainy season, because all enterprises within the extended watershed are vulnerable to the harmful consequences of flooding.

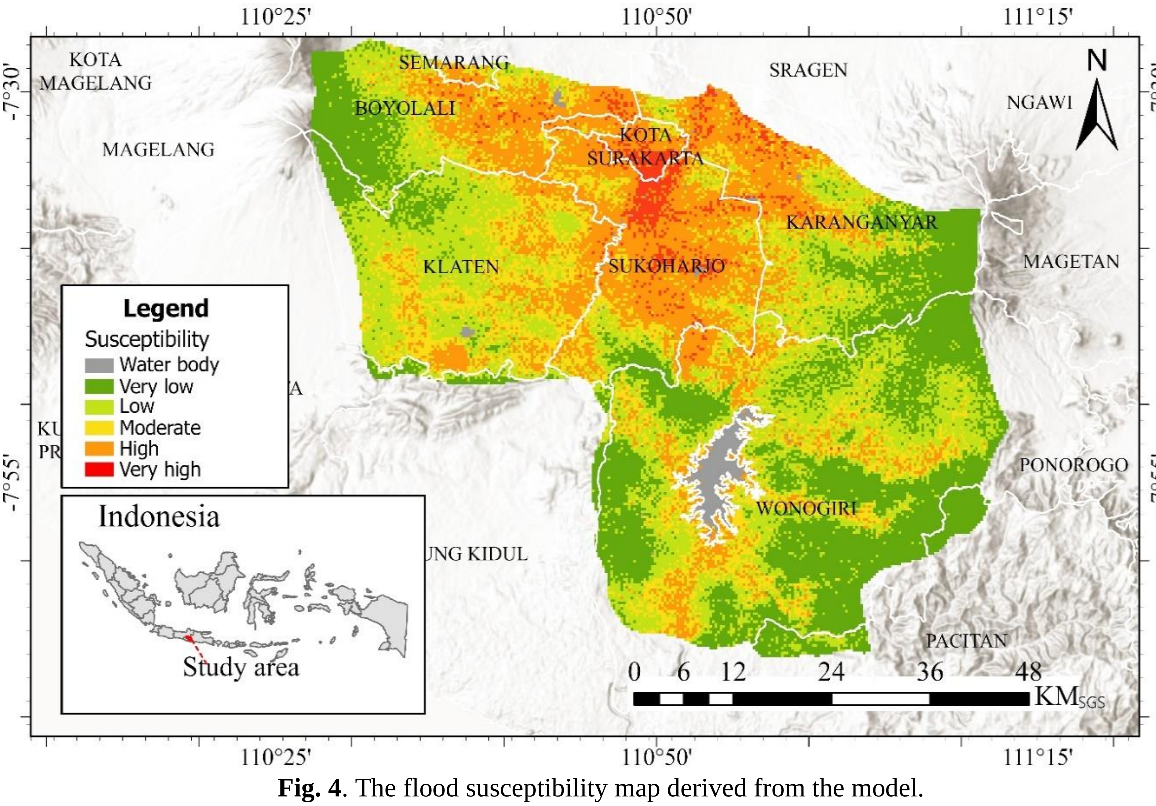

Fig. 4. The flood susceptibility map derived from the model.

5. DISCUSSION

The current investigation uncovers a wide range of flood susceptibility across the Upper Solo River Watershed, highlighting areas of notable susceptibility and the need for tailored flood prevention policies informed by data analysis. The analysis reveals a complex and varied flood-susceptibility environment, with significant differences in flood susceptibility among different cities/regencies within the watershed (Anna et al., 2021). Model of flood susceptibility also shows that Surakarta has the largest part of the whole area in 'High' level of potential threat. Historical records from spilled-over flood events each year backs this finding up. Surakarta City and its surrounding areas are the most densely populated areas in this watershed and have the highest potential for flood disasters. This condition requires the government and the community to be active in order to strengthen their ability to deal with and prevent the negative effects of such disasters. The objectives of disaster preparedness and response, the infrastructure which is resilient to disasters, and the community which is awareness of the community are the core points in the construction of disaster preparedness and response. The increased resilience to flood can to minimize flood impact to lives, properties and socio-economic stability.These findings give key insights for the state-and-impact analysis concerning flood mitigation and resilience measures. For a strategic allocation of resources and application of adapted flood measures across the regions of the watershed, decision-makers should know the distinct ground of flood susceptibility for diverse regions (Smith et al,2010; Xiang et al,2020). The use of GIS and RS in acquiring the related data precisely identifies the flood-subjected sections of a given location. This method will make it possible to identify Scanning more critical cities that lie in vulnerable locations, including Surakarta (Dinge et al.,2020; Hussain et al.,2021).

The studies emphasized the importance of taking precautions during the wet season to reduce the adverse effects of floods on activities within the watershed, especially due to climate changes (Damayanti, 2011; Musiyam et al., 2020; Mustikaningrum et al., 2023; Nada et al., 2023; Nurkhaida and Rejekiningrum, 2021; Purwanto et al., 2023; Saputra et al., 2022; Zein, 2010). Based on the climate forecast, it is estimated that the upper section of the Solo River Water Basin will see negative influences from the ongoing climate changes as well as impacts of future changes in earth's climate on the incidence of floods (Anna et al., 2016; Sipayung et al., 2018). Solo Upper River Watershed has recorded the growth of flood-affected rainfall that resulted from climate change, urbanization, and redevelopment of land uses. Given the course of events, flood management strategies should be flexible to tackle insightful situations (Janicka and Kanclerz, 2023; Kemp and Kemp, 2023).

Furthermore, the expected deviation from the current climate condition, characterized by a massive prevalence of heavy rains as well as the hike in temperatures brought by climate change, is undoubtedly an element that will contribute greatly to the intensification of flooding in the area. Apart from being high in volume and area, flood events, which are exacerbated by climate change and changes in moisture content and hydrological mechanisms, fail to yield the desired flood mitigation results (Modi et al., 2021). Besides that, the rise of the river flow may cause flood frequency (Tahmasebi Nasab et al., 2022; Yamamoto et al., 2021). Compared to recent studies by Mansour et al. (2024), Shakoor et al. (2024), Damayanti et al. (2024), Sari et al. (2024), Sahid (2024) and Shah & Ai (2024), this study offers a more cost-effective approach to flood analysis, primarily because it utilizes widely accessible data that can be applied across various regions. While the other studies may rely on specialized, localized, or expensive data sources and methodologies, this study's reliance on universally available data ensures broader applicability and reduces the financial barriers to conducting flood studies, making it a more practical option for researchers and policymakers in diverse geographic and economic contexts. Future studies need to identify the variable side of flood risk by focusing on environmental factors such as climate change, and urbanization and their potential to transform the frequency and severity of flood events. It is imperative to equip predictive models with meteorological scenarios and land-use patterns. With these models, we can understand the dynamics of the flood risk across seasons and space over time and develop comprehensive flood mitigation strategies that could adapt to various future scenarios. Striving at community interaction in the analysis of flood risk and contrivances of mitigation plans leads to social justice and cultural suitability as well as political solutions for poor and composed people issues along the flood-line.

Table 2. Susceptibility classification of the watershed.

Regency/city	Area of Classes												Total
	%	VH	%	H	%	M	%	L	%	VL	%	WB	
Boyolali	2.39	10	31.8	133.6	15.6	65.33	23.4	98.34	26.4	110.7	0.5	1.9	419.92
Gunung kidul	0		0.84	0.33	4.64	1.81	36.8	14.37	57.7	22.5	0		39.01
Karanganyar	3.55	20	29.2	164.3	13.7	77.08	26	146.3	27.4	154.1	0.2	1.3	563
Klaten	0.21	1.38	19.3	125.8	29.3	191.4	41.2	268.6	9.75	63.63	0.3	1.9	652.79
Surakarta	39.9	18.5	49	22.68	6.96	3.22	3.66	1.69	0		0.5	0.2	46.27
Magetan	0		0		0		0		100	0	0		0
Pacitan	0		0		0.86	0.6	13.6	9.47	85.5	59.38	0		69.44
Semarang	2.63	0.44	51.2	8.52	26.8	4.47	19.1	3.17	0.23	0.04	0		16.64
Sleman	0		0		0		18.8	0.86	81.2	3.73	0		4.59
Sragen	0		100	0.01	0		0		0		0		0.01
Sukoharjo	10.2	50.1	57.5	281.3	18.5	90.33	9.66	47.28	3.85	18.85	0.4	1.7	489.53
Wonogiri	0.14	2.01	9.95	139.3	15.3	214	31.7	444.2	42.6	596.5	0.3	4.2	1400.1

Note: WB represents the area of a water body in square kilometers. VL stands for very low susceptibility, L for low susceptibility, M for moderate susceptibility, H for high susceptibility, and VH for very high susceptibility, all measured in square kilometers.

6. CONCLUSIONS

The combination of remote sensing data with GIS modelling developed the Flood Susceptibility Map of the Upstream Solo River Basin. The driving factors for this model stemmed from the integral analysis of topography, hydrology, meteorology, and anthropology. The inundation concerns pertaining to the central and the northern sections of Surakarta City, particularly for areas adjacent to the Bengawan Solo River and the ones having high-sloped terrains, are critically mentioned. Inversely, Wonogiri, Karanganyar, and Boyolali seem to reveal very little vulnerability. The lowest areas with more flood susceptibility, like Sukoharjo and Surakarta, respectively, need additional attention, especially during the wet periods, when the whole catchment is vulnerable to flood hazards' contribution to downstream flooding.

Flood mapping of areas identified through Geographic Information System (GIS) and remote sensing can be used as the basis for developing plans in flood-prone cities, such as Surakarta. Future studies should serve to discover the dynamic nature of flood risk by setting up environmental factors such as climate change and urbanization, which will ultimately result in the alteration of the frequency and intensity of floods.

Using predictive models, including meteorological scenarios and land-use patterns, reduces uncertainties, thereby helping to develop holistic flood mitigation solutions. Engaging the community in flood risk analysis and mitigation planning ensures social justice, cultural suitability, and political solutions for affected populations in flood-prone areas. Moreover, the government and society should strengthen their ability to deal with this possible disaster.

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