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RAPID GIS-BASED FLOOD SUSCEPTIBILITY MODEL BASED ON REMOTE SENSING DATA IN THE UPPER OF SOLO RIVER WATERSHED

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ABSTRACT

This study aims to create a rapid flood susceptibility model using remote sensing data that can be applied for wide catchment area. We implement the model to the Upper Solo River Watershed in Indonesia. The model takes into account the physical characteristics of the watershed that were derived from remote sensing data, such as elevation, slope, flow accumulation, distance to rivers, rainfall, drainage density, topographic wetness index, land use land cover, normalized difference vegetation index, soil moisture, and curvature of the land surface. The remote sensing datasets involved to generate the flood susceptibility criteria include The Shuttle Radar Topography Mission (SRTM), Sentinel 2 Multispectral Instrument, Global Precipitation Measurement (GPM) v6, NASA-USDA Enhanced SMAP Global Soil Moisture Data. This study found that by leveraging such remote sensing data and GIS analysis techniques, we can develop a cost-effective flood susceptibility model for wide catchment areas.
Keywords: GIS, remote sensing, flood, susceptibility, watershed

INTRODUCTION

Natural disasters appear to increase due to natural processes and human activity, causing significant loss of lives, property, and materials. Natural disasters can be caused by human activities such as deforestation, land clearing on mountain slopes, and cultivation in areas with steep slopes. Indonesia is prone to natural disasters due to its location in an area of active tectonics and volcanism caused by the convergence of three tectonic plates: the Indian-Australian Plate, the Pacific Plate, and the Eurasia Plate. Flood is one of the natural disasters that become catastrophic in Indonesia [1]. In addition, compared to other South East Asian countries, Indonesia experienced the most frequent of flood disasters between 1980 and 2018 [2].

The Upper Solo River Watershed is located in the Indonesian province of Central Java. The area has a documented history of inundation dating back many years. This region's flooding is caused by a combination of factors, including excessive rainfall, high tides, and inadequate drainage. According to historical records, the Upper Solo River Watershed has experienced several significant floods. In 1966, heavy rainfall caused extensive flooding in the region, resulting in one of the most notable flood events. Significant infrastructure damage, including roads and bridges, and fatalities were caused by the inundation. In 2007, the region again experienced significant flooding, regarded as the largest flood fifty years later, due to excessive rainfall and inadequate drainage. This catastrophe inundated over 11,000 homes [3]. Again, significant infrastructure damage, including residences, roads, and bridges, was caused by the flooding, which also claimed lives. Since then, the local government has worked to strengthen the drainage systems in the region to mitigate the effects of flooding. Despite these efforts, the Upper Solo River Watershed remains susceptible to inundation, particularly during the wet season. In recent years, the frequency and severity of extreme weather events, such as excessive rainfall, have increased, resulting in more frequent flooding in the region. Consequently, sustained monitoring and mitigation efforts are required to reduce the impact of flooding on the region's communities.

A flood is characterized by exceptionally high flows or levels of rivers, lakes, ponds, reservoirs, and other water bodies, resulting in the inundation of land outside the water bodies' area [4]. Flooding is not uncommon, as it occurs everywhere on the planet. Flooding may occur due to heavy precipitation, melting glaciers, tsunamis, hurricanes, and other ocean phenomena. Consequently, flood hazard is the probability that a flood event of a given magnitude will occur in a given location within a given time frame [5].

Floods are also caused by complex hydrological, geological, and geomorphological conditions, deforestation, and urbanization, causing significant social, economic, and environmental damage [6], [7]. For example, floods can affect the loss of human life and negatively affect populations, infrastructure damage, damage to crops and livestock, loss of ecosystem services, the spread of disease, and contamination of water supplies [8]. In addition, other factors such as climate, land structure, vegetation, and slope, humanity, and land-use change (such as deforestation and urbanization) also contribute to flooding [9].

A combination of complex hydrological, geological, and geomorphological conditions and human activities such as deforestation and urbanization can cause floods. Floods significantly affect social, economic, and environmental impacts [7]. Floods can result in the loss of human life, displacement of populations, damage to infrastructure, crops, and livestock, loss of ecosystem services, the spread of disease, and contamination of water supplies [8]. Apart from natural factors such as climate, land structure, vegetation, and slope, human activities also contribute to flooding [9]. For example, deforestation and urbanization increase the amount of impermeable surfaces, reducing the soil's capacity to absorb water and increasing the speed and volume of runoff [10]. This, in turn, leads to more frequent and severe floods. Additionally, changes in land use can alter the water cycle and affect river flow, exacerbating the risk of flooding [11].

The current available dataset and technology provide opportunity on developing rapid and low-cost model. The integration of information extracted through Geographical Information Systems (GIS) and Remote Sensing (RS) technology offers tremendous potential for identification, monitoring, and assessment of flood disaster [12].

Many studies have demonstrated the use of GIS and remote sensing technologies to map the spatial variability of flood hazards [13]–[18]. Those studies used various approach including: spatial multi-criteria [19], Cellular Automata [20], Analytical Hierarchical Processes has also been developed [21], [22]. However, comprehensive studies to analyses the susceptibility, especially in the upper Solo River Watershed, are limited. Farid et al. [23] has conducted a study on the flood risk in this area but limited to a small part, i.e. Sragen regency. Meanwhile, the Upper Solo River Watershed covers at least five regencies that are out of the study. This study aims on the development of a rapid flood susceptibility model utilizing remote sensing data, specifically targeting wide catchment areas.

RESEARCH SIGNIFICANCE

This study represents a significant advancement in flood susceptibility assessment through the development of a cost-effective and comprehensive model based on remote sensing data. The model allows for the creation of flood susceptibility maps using affordable data collection methods, making it suitable for wide catchment areas. By improving our understanding of floods and their impact, this approach offers an effective solution for flood modeling, enabling better mitigation strategies in the region.

MATERIAL AND METHODS

The model's implementation is demonstrated in the Upper Solo River Watershed of Indonesia. Incorporating various physical characteristics that are generated from remote sensing datasets (Table 1), such as: elevation (El), slope (Sl), flow accumulation (FA), distance to rivers (DR), rainfall (Rf), drainage density (DD), topographic wetness index (TWI), land use land cover (LULC), Normalized Difference Vegetation Index (NDVI), soil moisture (SM), and curvature (Cu), the model provides a comprehensive understanding of flood susceptibility in the region.

All those factors have been studied contributing the flood occurrences [22], [24]. The slope of the terrain governs the pace of surface water flow, with lowlands and flatlands being more susceptible to flooding due to increased water accumulation and decreased water flow speed. Elevation and distance to the river are significant determinants, with lower elevated locations and areas closer to rivers having a greater likelihood of inundation due to their relatively greater river discharge and slower water flow. Flood occurrence is influenced by flow accumulation and drainage density, with greater flow accumulation and drainage density increasing the likelihood of flooding. LULC plays a crucial role in determining flood risk, with densely vegetated areas being less susceptible to flooding due to delayed water flow and greater infiltration. The soil type is also crucial, with fine soil texture increasing surface runoff and decreasing infiltration, thereby increasing the likelihood of inundation in these areas. NDVI and curvature are additional parameters contributing to flooding susceptibility, with increased vegetation density delaying runoff and flat curvature being the most susceptible to flooding. Lastly, precipitation and TWI are important determinants, with excessive precipitation increasing water accumulation and TWI indicating locations with potentially saturated land surfaces, both increasing the likelihood of flooding.

The method of developing the flood susceptibility model involved two steps for the flood-controlling parameters (Fig. 1). The parameters were initially converted into a raster format to aid in analysis. The parameters were then standardized to a constant geographic resolution using a resampling technique. As shown in Fig. 2, the resampled parameters were then divided into five unique measurement scales, ranging from 1 (representing a very low susceptibility to flooding) to 5 (representing a high susceptibility to flooding). The process of combining all the parameters was accomplished through the utilization of the weighted overlay technique. This approach allows for the integration of multiple spatial datasets by assigning weights to each parameter. The weights assigned to the parameters were determined based on an AHP model developed by Negese et al [22].

Table 1 Data sources

No	Data	Description	Source	Derived Data
1	DEM	The Shuttle Radar Topography Mission (SRTM).	USGS [25]	El, Sl, FA, DR, Cu , DD, TWI
2	Images	Sentinel 2 Multispectral Instrument	ESA[26]	LULC, NDVI
3	Rainfall data	Global Precipitation Measurement (GPM) v6.	NASA [27]	RF
4	Soil Moisture Data	NASA-USDA Enhanced SMAP Global Soil Moisture Data.	NASA [28]	SM

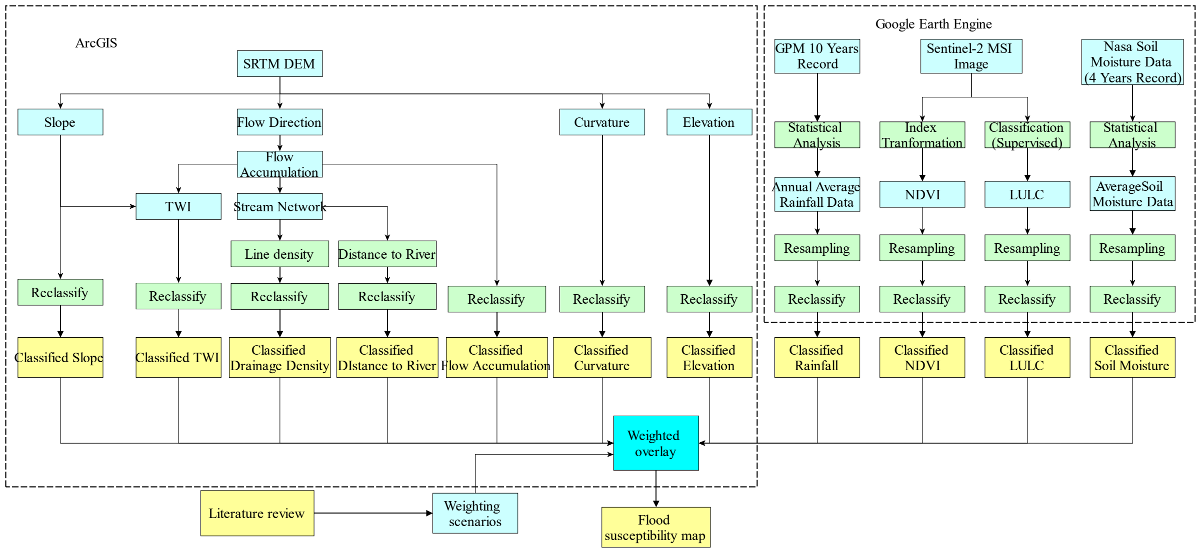

Fig.1 Research framework

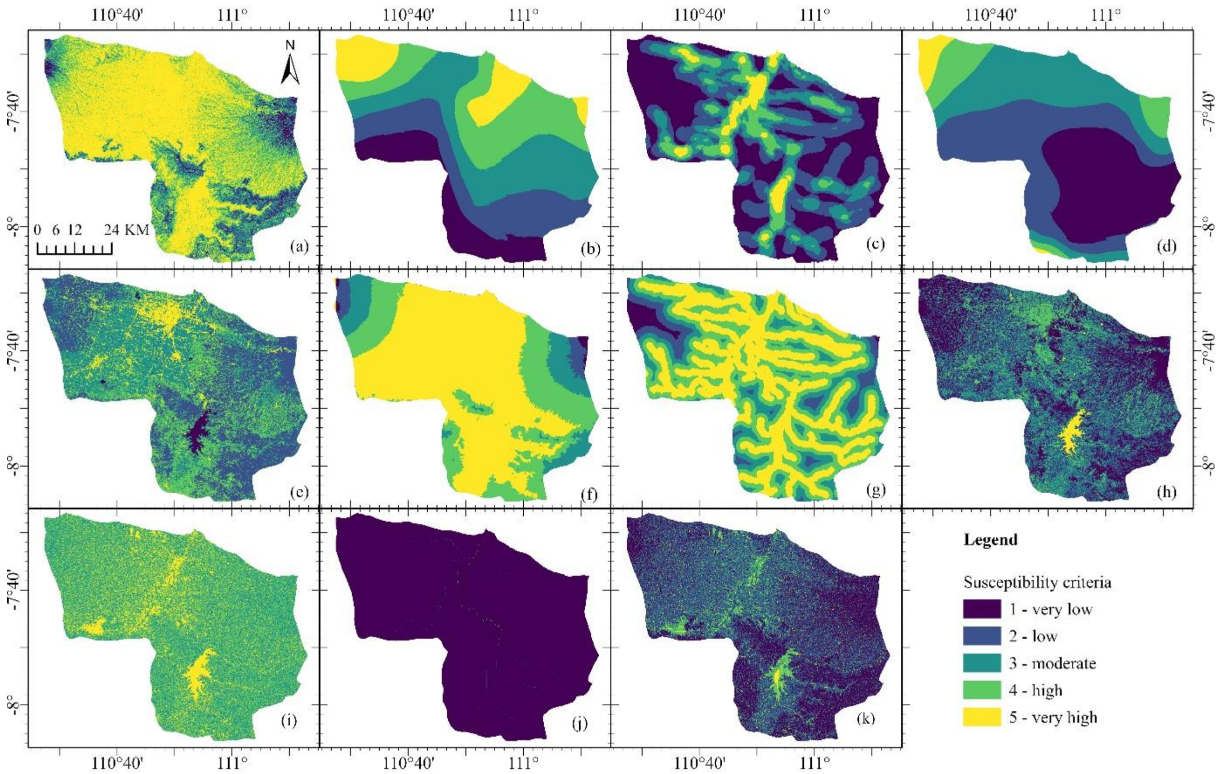

Fig.2 Classified flood susceptibility parameters derived from remote sensing datasets. Note: (a) Sl, (b) Rf, (c) DD, (d) SM, (e) LULC, (f) El, (g) DR, (h) NDVI, (i) Cu, (j) FA, (k) TWI

RESULTS AND DISCUSSION

The Flood susceptibility map was made based on the remote sensing data modelling in the Upper of Solo River. The flood susceptibility parameters selected based on a familiarity of the study area with the topographic, hydrologic, climatic, and anthropic settings from an extensive literature survey. The AHP (Fig.2) has helped in ranking the flood susceptibility in order of their contribution to the flood occurrence probability.

The findings indicate that the Upper of Solo River Watershed exhibits a high flood susceptibility hazard index, primarily concentrated in the middle and northern regions. Factors such as proximity to the Bengawan Solo River, the V-shaped cross-section of the river, and mountainous boundaries contribute to water accumulation in these areas. Among the studied locations, Wonogiri, Karanganyar, and Boyolali show relatively lower flood susceptibility, while Sukoharjo, Surakarta, and parts of Karanganyar demonstrate higher vulnerability. These findings highlight the need for caution, especially during the wet season, as all activities within the elongated watershed can be at risk of flood impacts.

Based on Fig. 3 and Table 2, the locations that have very low flood susceptibility (colored blue on the map) are Wonogiri 596.45 sq km (42.60%), Karanganyar 154.08 sq km (27.37%), and Boyolali 110.71 sq km (26.36%). The locations that have low flood susceptibility (colored dark green on the map) are Wonogiri 444.15 sq km (31.72%), Klaten 268.63 sq km (41.15%), and Karanganyar 146.26 sq km (25.98%). The locations that have moderate flood susceptibility (colored green-cyan on the map) are Wonogiri 214.01 sq km (15.29%), Klaten 191.44 sq km (29.33%), and Sukoharjo 90.33 sq km (18.45%). The locations that have high flood vulnerability (light green on the map) are parts of Sukoharjo 281.29 sq km (57.46%), Boyolali 133.59 sq km (31.81%), and Karanganyar 29.18 sq km (19.98%). The locations that have very high flood vulnerability (colored yellow on the map) include Sukoharjo 50.08 sq km (10.20%), Surakarta 18.46 sq km (39.89%), and Karanganyar 19.98 sq km (3.55%). The high and very high conditions should be a concern, mainly when the wet season occurs between October and March with >200 mm of rainfall.

The study identified key factors contributing to higher flood susceptibility in the middle and northern parts of the watershed, including proximity to the Bengawan Solo River and the V-shaped cross-section of the river. Specific areas, such as Wonogiri, Karanganyar, and Boyolali, have lower susceptibility, while Sukoharjo, Surakarta, and parts of Karanganyar exhibit higher susceptibility. These findings underscore the need for precautions during the wet season to mitigate flood impacts on activities within the watershed [3], [29], [30].

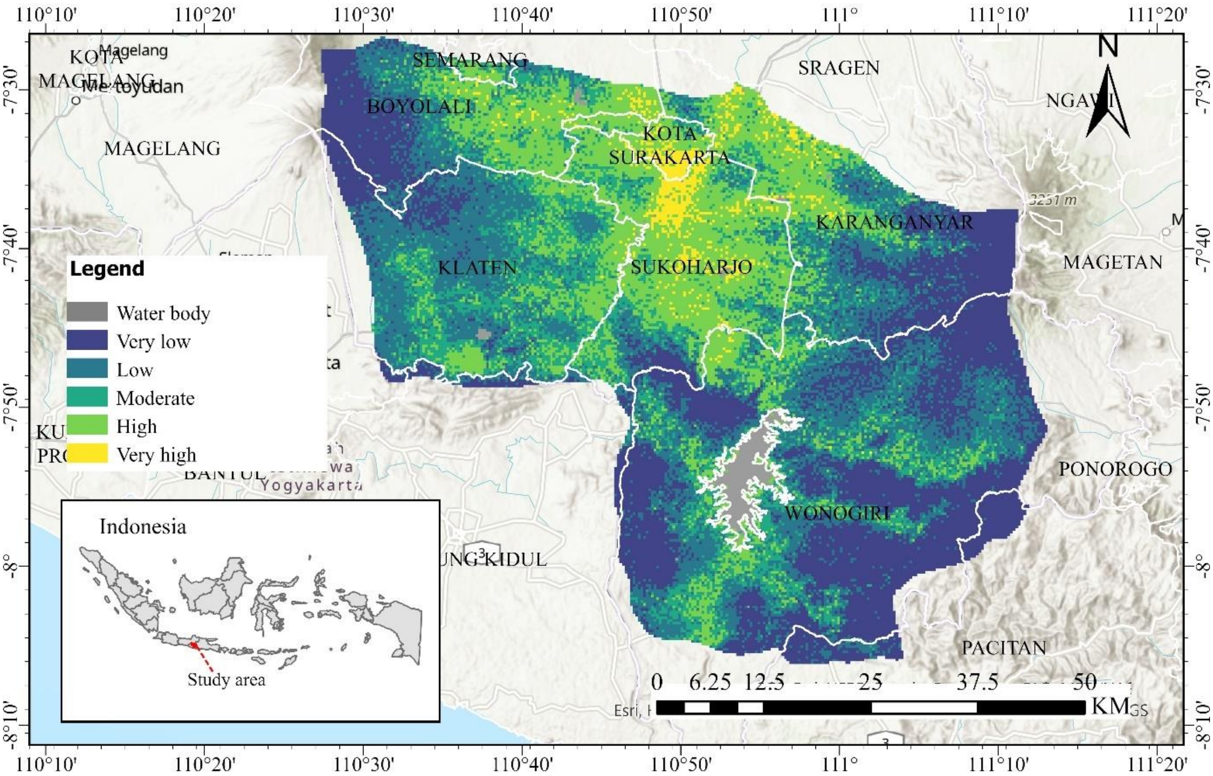

Fig.3 Flood susceptibility map resulted from the model

Table 2. Area of susceptibility class for each region

	Area of Classes												Total
Regency/city	WB	%	VL	%	L	%	M	%	H	%	VH	%	
Boyolali	1.90	0.45	110.71	26.36	98.34	23.42	65.33	15.56	133.59	31.81	10.04	2.39	419.92
Gunung kidul		0.00	22.50	57.68	14.37	36.83	1.81	4.64	0.33	0.84		0.00	39.01
Karanganyar	1.32	0.23	154.08	27.37	146.26	25.98	77.08	13.69	164.28	29.18	19.98	3.55	563.00
Klaten	1.90	0.29	63.63	9.75	268.63	41.15	191.44	29.33	125.81	19.27	1.38	0.21	652.79
surakarta	0.21	0.45		0.00	1.69	3.66	3.22	6.96	22.68	49.03	18.46	39.89	46.27
Magetan		0.00	0.00	100.00		0.00		0.00		0.00		0.00	0.00
Pacitan		0.00	59.38	85.50	9.47	13.63	0.60	0.86		0.00		0.00	69.44
Semarang		0.00	0.04	0.23	3.17	19.08	4.47	26.84	8.52	51.23	0.44	2.63	16.64
Sleman		0.00	3.73	81.23	0.86	18.77		0.00		0.00		0.00	4.59
Sragen		0.00		0.00		0.00		0.00	0.01	100.00		0.00	0.01
Sukoharjo	1.71	0.35	18.85	3.85	47.28	9.66	90.33	18.45	281.29	57.46	50.08	10.23	489.53
Wonogiri	4.18	0.30	596.45	42.60	444.15	31.72	214.01	15.29	139.30	9.95	2.01	0.14	1400.11

Note: WB – water body (sq km), VL – very low susceptibility (sq km), L – low susceptibility (sq km), M – moderate susceptibility (sq km), H – high susceptibility (sq km), VH – very high susceptibility (sq km).

CONCLUSIONS

This study successfully employed a comprehensive flood susceptibility model using remote sensing data, highlighting the high flood susceptibility in the Upper of Solo River Watershed, particularly in the middle and northern regions. Factors such as proximity to the Bengawan Solo River and the V-shaped cross-section of the river contribute to water accumulation. Precautions should be taken during the wet season to mitigate flood impacts in vulnerable areas like Sukoharjo, Surakarta, and parts of Karanganyar.

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REFERENCES

[1] C. Susetyo, "Urban flood management in Surabaya City: anticipating changes in the Brantas River system," ITC, 2008.

[2] K. Samphantharak, "Natural Disaster and Economic Development in Southeast Asia." Rochester, NY, May 14, 2019. doi: 10.2139/ssrn.3388396.

[3] M. Zein, "A community-based approach to flood hazard and vulnerability assessment in flood prone areas; A case study in Kelurahan Sewu, Surakarta City-Indonesia," Master's Thesis, University of Twente, 2010.

[4] M. A. Marfai, "GIS Modelling of river and tidal flood hazards in a waterfront city," *Case Study: Semarang City, Central Java, Indonesia*, 2003.

[5] D. Alkema and H. Middelkoop, "The influence of floodplain compartmentalization on flood risk within the Rhine–Meuse Delta," *Natural Hazards*, vol. 36, pp. 125–145, 2005.

[6] A. A. Komolafe, B. S. Awe, I. E. Olorunfemi, and P. G. Oguntunde, "Modelling flood-prone area and vulnerability using integration of multi-criteria analysis and HAND model in the Ogun River Basin, Nigeria," *Hydrological Sciences Journal*, vol. 65, no. 10, pp. 1766–1783, 2020.

[7] M. Falguni and D. Singh, "Detecting flood prone areas in Harris County: A GIS based analysis," *GeoJournal*, vol. 85, no. 3, pp. 647–663, 2020.

[8] D. Rincón, U. T. Khan, and C. Armenakis, "Flood risk mapping using GIS and multi-criteria analysis: A greater Toronto area case study," *Geosciences*, vol. 8, no. 8, p. 275, 2018.

[9] I. Curebal, R. Efe, H. Ozdemir, A. Soykan, and S. Sönmez, "GIS-based approach for flood analysis: case study of Keçidere flash flood event (Turkey)," *Geocarto International*, vol. 31, no. 4, pp. 355–366, 2016.

[10] S. Sugianto, A. Deli, E. Miswar, M. Rusdi, and M. Irham, "The effect of land use and land cover changes on flood occurrence in Teunom

Watershed, Aceh Jaya," *Land*, vol. 11, no. 8, p. 1271, 2022.

[11] V. B. Chagas, P. L. Chaffe, and G. Blöschl, "Climate and land management accelerate the Brazilian water cycle," *Nature Communications*, vol. 13, no. 1, p. 5136, 2022.

[12] B. Pradhan, M. Shafiee, and S. Pirasteh, "Maximum flood prone area mapping using RADARSAT images and GIS: Kelantan river basin.," *International Journal of Geoinformatics*, vol. 5, no. 2, 2009.

[13] M. Shafapour Tehrany, F. Shabani, M. Neamah Jebur, H. Hong, W. Chen, and X. Xie, "GIS-based spatial prediction of flood prone areas using standalone frequency ratio, logistic regression, weight of evidence and their ensemble techniques," *Geomatics, Natural Hazards and Risk*, vol. 8, no. 2, pp. 1538–1561, 2017.

[14] R. G. Greene and J. F. Cruise, "Urban watershed modeling using geographic information system," *Journal of water resources planning and management*, vol. 121, no. 4, pp. 318–325, 1995.

[15] G. N. Paudyal, "An integrated GIS-numerical modelling system for advanced flood management," in *Proceeding of the International Conference on Water Resources and Environment Research: Towards the 21st Century, Kyoto University, Japan*, 1996, pp. 555–562.

[16] M. M. Islam and K. Sado, "Development of flood hazard maps of Bangladesh using NOAA-AVHRR images with GIS," *Hydrological Sciences Journal*, vol. 45, no. 3, pp. 337–355, 2000.

[17] I. Elkhrachy, "Flash flood hazard mapping using satellite images and GIS tools: a case study of Najran City, Kingdom of Saudi Arabia (KSA)," *The Egyptian Journal of Remote Sensing and Space Science*, vol. 18, no. 2, pp. 261–278, 2015.

[18] S. P. Ozkan and C. Tarhan, "Detection of flood hazard in urban areas using GIS: Izmir case," *Procedia Technology*, vol. 22, pp. 373–381, 2016.

[19] Q. Zhou *et al.*, "A GIS-Based Hydrological Modeling Approach for Rapid Urban Flood Hazard Assessment," *Water*, vol. 13, no. 11, p. 1483, 2021.

[20] B. Ghimire, A. S. Chen, M. Guidolin, E. C. Keedwell, S. Djordjević, and D. A. Savić, "Formulation of a fast 2D urban pluvial flood model using a cellular automata approach," *Journal of Hydroinformatics*, vol. 15, no. 3, pp. 676–686, 2013.

[21] T. Sarmah, S. Das, A. Narendr, and B. H. Aithal, "Assessing human vulnerability to urban flood hazard using the analytic hierarchy process and geographic information system," *International Journal of Disaster Risk Reduction*, vol. 50, p. 101659, 2020.

[22] A. Negese, D. Worku, A. Shitaye, and H. Getnet, "Potential flood-prone area identification and mapping using GIS-based multi-criteria decision-making and analytical hierarchy process in Dega Damot district, northwestern Ethiopia," *Appl Water Sci*, vol. 12, no. 12, p. 255, Oct. 2022, doi: 10.1007/s13201-022-01772-7.

[23] M. Farid, B. Gunawan, M. S. B. Kusuma, S. A. Habibi, and A. Yahya, "Assessment of flood risk reduction in Bengawan Solo River: A case study of Sragen Regency," *GEOMATE Journal*, vol. 18, no. 70, pp. 229–234, 2020.

[24] N. Wanders, D. Karssenberg, A. de Roo, S. M. de Jong, and M. F. P. Bierkens, "The suitability of remotely sensed soil moisture for improving operational flood forecasting," *Hydrology and Earth System Sciences*, vol. 18, no. 6, pp. 2343–2357, Jun. 2014, doi: 10.5194/hess-18-2343-2014.

[25] Earth Resources Observation And Science (EROS) Center, "Shuttle Radar Topography Mission (SRTM) Non-Void Filled." U.S. Geological Survey, 2017. doi: 10.5066/F7K072R7.

[26] "User Guides - Sentinel-2 MSI - Level-2 Processing - Sentinel Online." Accessed: Jun. 14, 2023. [Online]. Available: https://copernicus.eu/user-guides/sentinel-2-msi/processing-levels/level-2

[27] "GES DISC Dataset: GPM IMERG Final Precipitation L3 Half Hourly 0.1 degree x 0.1 degree V06 (GPM_3IMERGHH 06)." doi: 10.5067/GPM/IMERG/3B-HH/06.

[28] D. Entekhabi *et al.*, "The Soil Moisture Active Passive (SMAP) Mission," *Proceedings of the IEEE*, vol. 98, no. 5, pp. 704–716, May 2010, doi: 10.1109/JPROC.2010.2043918.

[29] R. Nurkhaida and P. Rejekiningrum, "Trend analysis of agricultural water supply and demand for water conservation and climate change anticipation," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 2021, p. 012102.

[30] S. Damayanti, "Resilience for the 2007 flood event, using community knowledge: A Case in Part of Sukoharjo Regency, Indonesia," Master's Thesis, University of Twente, 2011.