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Mapping the Levels of Physical Vulnerability to Floods in Sragen Regency Using the E-S-A Framework

Andita Aghatia[1], Isti Andini[1,2], Paramita Rahayu[1]
[1]Urban and Regional Planning program, Faculty of Engineering, Universitas Sebelas Maret, Surakarta, Indonesia
[2]Pusat Informasi Pembangunan Wilayah (PIPW), Universitas Sebelas Maret, Surakarta, Indonesia
*_e-mail_: anditaaghatia@student.uns.ac.id

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Abstract

Floods have historically been a frequent natural disaster in Sragen Regency, primarily caused by the overflow of Bengawan Solo River. The river poses a significant threat and increases the vulnerability scale of the region. This study focuses on mapping the levels of physical vulnerability to floods in Sragen Regency using the E-S-A (Exposure – Sensitivity - Adaptive Capacity) framework. The research employs scoring and spatial overlay methods for three components: exposure, sensitivity, and adaptive capacity. Results reveal that physical vulnerability to floods in Sragen Regency is classified into three levels: low, medium, and high. Most of the area, covering 607.78 km², falls under medium vulnerability, followed by low vulnerability covering 355.70 km², and high vulnerability covering 9.96 km². Despite the relatively well-developed adaptive capacity in the region, the region has not significantly mitigated the high exposure, while sensitivity levels remain moderate. The mapping of physical vulnerability to flooding in Sragen Regency using the E-S-A Framework is a reference to knowledge about the comprehensive vulnerability approach used and the basis for disaster mitigation and adaptation policies in spatial planning, including the improvement of the Spatial Plan so that there is no development direction in areas with high levels of vulnerability.

Keywords: E-S-A framework; physical flood vulnerability; spatial analysis; Sragen Regency

1. INTRODUCTION

The development of urban areas has led to the increase of hazard threats and vulnerability (Fitria et al., 2019). When a system's vulnerability is high, climate change exacerbates the impacts significantly. Climate change triggers extreme weather conditions, potentially increasing the frequency and intensity of natural disasters, particularly hydrological disasters such as landslides, coastal erosion, and floods (Pujiono et al., 2021). Flooding occurs when an area or landmass is inundated with water due to rising water volumes (Qiu et al., 2019; Setiawati et al., 2020; Zywiec et al., 2024). Regional vulnerability to floods generally increases due to significant growth in development activities. Vulnerability, as defined by National Agency for Disaster Management or BNPB (2012), refers to a system's condition when facing a hazard or disaster, often characterized by its inability to cope. Vulnerability can be measured through the Exposure – Sensitivity - Adaptive Capacity or E-S-A Framework, which evaluates exposure, sensitivity, and adaptive capacity as components of response (IPCC, 2001). Physical vulnerability specifically refers to the susceptibility of infrastructure, buildings, and physical structures to damage or destruction during a disaster.

In Sragen Regency, Central Java province, 18 subdistricts have experienced flooding over the past five years, with some areas reporting up to 15 flood events. The primary cause of these floods is the overflow of the Bengawan Solo River. It has affected 65 villages across 11 subdistricts, which are categorized as flood-prone areas within the Bengawan Solo watershed (Permadani & Susilowati, 2022). Consequently, the Bengawan Solo River poses a significant threat, amplifying the vulnerability of Sragen Regency. Subdistricts significantly affected by flooding, such as Masaran, Sidoharjo, Ngrampal, and Sragen, are located close to the Bengawan Solo River. This proximity influences the exposure component, defined as the extent to which a system interacts with or is located near a hazard. Additionally, the number of substandard housing units (*Rumah Tidak Layak Huni* or RTLH) in rural areas far exceeds those in urban areas, reaching 78% of total buildings in Jenar subdistrict, thereby affecting the sensitivity component. Sensitivity is defined as the internal state of a system that can be positively or negatively impacted by exposure to a disaster (Rancak et al., 2023). Adaptive capacity, defined as the system's ability to adapt to hazards by reducing the risk of damage, is influenced by the availability of evacuation spaces.

In Sragen Regency, evacuation points have been mapped and included in the Sragen Regency Geoportal to support disaster response during floods.

These conditions underscore the need for a comprehensive mapping of vulnerability levels in Sragen Regency. This study aims to address the research question: "How can the levels of physical vulnerability to floods in Sragen Regency be mapped?" The E-S-A (Exposure-Sensitivity-Adaptive Capacity) Framework developed by the Intergovernmental Panel on Climate Change or IPCC (2001) serves as an appropriate and comprehensive approach to assess vulnerability based on exposure, sensitivity, and adaptive capacity. This method has yet to be widely implemented, particularly in Sragen Regency.

This research focuses on mapping the level of physical vulnerability to flood disasters in Sragen Regency using the E-S-A Framework. Results of this research are expected to contribute to the understanding of a comprehensive vulnerability approach to represent vulnerability not only from the potential of the area to occur (exposure), but also from how an infrastructure can reduce the impact of larger floods or support (sensitivity) and how the readiness of the area in facing and mitigating disasters (adaptive capacity), which in this case is flood disaster. This study also offers practical contributions to Sragen Regency by providing a basis for minimizing activities in areas with high flood vulnerability. The findings serve as a foundation for improved spatial planning, particularly in disaster mitigation, land-use regulation, and as an input for the development of spatial planning strategies in Sragen Regency.

2. LITERATURE REVIEW

2.1. VULNERABILITY

Vulnerability theory seeks to explain why some systems (regions/places and people/groups) are more susceptible to the adverse impacts of disasters than others. The theory or approach to vulnerability is essential because the concept of vulnerability is recognized as a critical aspect in reducing disaster-related losses (Siagian & Parwanto, 2017). According to Guillaumont & Wagner (2021) in the Multidimensional Vulnerability Index Report, vulnerability is defined as a condition that makes individuals, communities, assets, or systems more susceptible to the impacts of hazards due to influences from physical, social, economic, and environmental factors or specific processes. In this context, environmental vulnerability encompasses ecosystem conditions such as water, air, soil, plants, and animals; physical vulnerability relates to the physical structures of the environment, building conditions, and infrastructure; economic vulnerability pertains to financial conditions, investments, and potential losses; and social vulnerability includes community perceptions of risk as well as cultural and demographic factors.

According to the United Nations Office for Disaster Risk Reduction or UNISDR (2009), vulnerability refers to the characteristics and conditions of an entity, system, or asset that make it susceptible to the adverse impacts of a hazard. This concept highlights that vulnerability consists of two main components: exposure and adaptive capacity, which are interconnected and interact with each other. The mathematical approach to vulnerability, as formulated by UNISDR (2009), is represented in Equation 1.

$$V = f(E, AC) \quad \text{.....(1)}$$

where: *V* = Vulnerability, *E* = Exposure, *AC* = Adaptive Capacity

Meanwhile, BNPB (2012) defines vulnerability as the condition of a system when facing disaster or hazard threats, which generally refers to a state of incapacity. Simply put, if a system (community or society) is unable to cope with potential hazards or disaster threats, it can be categorized as vulnerable. The components of this approach are exposure and sensitivity. In more detail, the exposure component is represented by the sum of the indices of residential property loss, public facility loss, and temporary critical facility loss. Meanwhile, sensitivity is expressed through the weighting of each variable. Mathematically, the concept of vulnerability as outlined in BNPB Regulation Nomor 2 of 2012 is formulated in Equation 2.

$$V = E \; x \; S \quad \text{.....(2)}$$

where: *V* = Vulnerability, *E* = Exposure, *S* = Sensitivity

IPCC (2001) offers a more comprehensive approach, defining vulnerability as the inability of a system to withstand the impacts of climate change or extreme events. This approach measures vulnerability as a system comprising exposure, sensitivity, and adaptive capacity, which together form a response. This is mathematically expressed in Equation 3.

$$V = AC - (E + S) \quad \text{.....(3)}$$

where: *V* = Vulnerability, *AC* = Adaptive Capacity, *S* = Sensitivity, *E* = Exposure

Compared to the approaches of UNISDR (2009) and BNPB (2012), the IPCC (2001) model is considered superior as it incorporates all three components, making it more comprehensive. This aligns with Blaikie et al. (2014), who argue that vulnerability is directly caused by unsafe conditions, including hazardous locations, unprotected infrastructure, and a lack of disaster preparedness. These characteristics are well-represented by the components of vulnerability outlined in IPCC (2001). Sensitivity is particularly important as it determines a system's response to hazards, while adaptive capacity reflects a system's ability to anticipate or manage threats. Additionally, exposure includes factors that are difficult to modify, such as geomorphology and rainfall patterns, which are closely related to flood risk.

Ultimately, the assessment of vulnerability requires a comprehensive approach that considers all relevant components. Ignoring or omitting one of these components risks introducing bias into the analysis and providing an inaccurate representation of the vulnerability level of a given region.

2.2 PHYSICAL VULNERABILITY COMPONENTS

Physically, vulnerability typically refers to the observation of geographical and man-made environmental conditions when facing disasters. Abbasov (2018) explains that the physical vulnerability of an area depends on its proximity to the source of the disaster. From these various definitions, it can be concluded that physical vulnerability refers to the susceptibility of infrastructure, buildings, and physical structures of an area's environment to damage or destruction during a disaster. It is also related to the potential impacts of the existing physical environment, particularly if the area is located near the source of the disaster. The process of synthesizing theories from the operational definitions of each component of physical vulnerability is presented in Table 1 below.

Tabel 1. Theoretical Synthesis Vulnerability Component

Component	Theory	Theoretical Synthesis
Exposure	The extent and frequency with which a system is exposed to significant weather changes. The physical conditions of an agropolitan system that are vulnerable to the impacts of hazards.	The physical condition of a system is characterized by how closely or frequently it is exposed to hazards.
Sensitivity	Conditions within the system that indicate its susceptibility to disturbances. The degree to which a system is influenced by or responsive to hazards.	The degree to which a system responds and is vulnerable or sensitive to hazards or disturbances.
Adaptive Capacity	The ability of a system to adjust to climate change, including variability and extreme climatic events, to reduce potential damage, take advantage of opportunities, or address the consequences The system's ability to adapt to hazards by reducing the risk of damage.	The capability of a system to manage hazards, adapt, or take anticipatory measures to address them.

Source: (ICCTF, 2017; IPCC, 2001; Kumalasari & Soetomo, 2014)

2.3 PHYSICAL VULNERABILITY TO FLOODING

The interaction between vulnerability and hazards creates disaster risk, and when additional triggering factors are present, it can lead to disasters (Nurjanah et al., 2011, cited in Aji, 2015). Thus, vulnerability can be simply understood as one of the components that contribute to the occurrence of disasters. Flood vulnerability refers to the degree of susceptibility of an area to flooding disasters. Studies on flood disaster vulnerability and its mapping are essential to mitigate the impacts of flooding, provide early warnings regarding flood hazards and risks, and assist governments in formulating disaster protection policies (Aisyah, 2021).

Tabel 2. Variables of Physical Vulnerability to Flooding

Component	Variables
Exposure	Environment Physical Structure (slope, land use, river distance, rainfall, soil type) & Flooding (Flood frequency, Flood depth)
Sensitivity	Building Condition (building density & building type), Utilities (water supply, drainage density and waste management)
Adaptive Capacity	Critical Facilities (medical facilities & emergency shelter)

Good adaptive capacity helps reduce the effects of exposure and sensitivity, thereby lowering vulnerability and resulting in areas with low vulnerability levels (Thomas et al., 2018). Essentially, all areas are vulnerable to flooding, although they vary in their levels of vulnerability. According to Utami et al. (2021), high vulnerability refers to areas with significant potential, impact, and recovery time from flooding. In contrast, moderate vulnerability implies a lower potential, impact, and recovery time compared to high vulnerability. Low vulnerability, on the other hand, characterizes areas considered relatively safer with minimal potential, impact, and recovery time from flooding. The use of variables for each component of physical vulnerability to flooding is presented in Table 2 below

3. RESEARCH METHODS

3.1. STUDI AREA

The study area of this research is Sragen Regency, Central Java province, which consists of 20 districts. The selection of this study area is based on the accumulation of historical flood disaster calculations in the last decade (2021-2031) based on data from Central Statistics Bureau or BPS of Central Java Province. Based on the data, Sragen Regency has the highest number of events in Greater Solo area: 15 flood events. Meanwhile, the other regions such as Boyolali Regency and Karanganyar Regency had 5 flood events, Sukoharjo Regency had 7 flood events, Surakarta City had 12 flood events, Wonogiri Regency had 13 flood events and Klaten Regency had 14 flood events.

The high frequency of flooding events in Sragen Regency area justifies the selection of the study location. In addition, it is evidence that a less-than-optimal spatial arrangement in the area coupled with the presence of the Bengawan Solo River poses a threat and increases the scale of vulnerability in the area. A map of the study area of Sragen Regency is presented in Figure 1.



Figure 1. Map of Sragen Regency Study Area

3.2. RESEARCH APPROACH AND DATA COLLECTION METHOD

This research adopts a quantitative descriptive approach with a deductive method and is grounded in a positivistic paradigm. The study is conducted within the spatial scope of Sragen Regency and focuses on the temporal scope of 2023 or the most recent conditions of the variables utilized. Data for this research is obtained through secondary data surveys conducted via literature reviews and institutional studies. The collected data are subsequently analyzed using scoring techniques and interpreted into maps. Each variable map is then subjected to overlay analysis to produce a composite

map of physical vulnerability to floods. The variables, parameters, and scoring analysis employed in this study are detailed in Table 3 below.

Tabel 3. Variables, Parameters, and Research Scores

Component	Variable	Subvariable	Parameter	Score
Exposure	Environment physical structure	Slope	>40% (very steep)	1
			15%-40% (steep)	2
			5% - 15% (undulating)	3
			2% - 5% (gently sloping)	4
			0 - 2% (Flat)	5
		Land use	Forest, Secondary Mangrove Forest, Industrial Plantation Forest, Rocky Land, Coastal Sand, Road Networks, Paved Surfaces	1
			Dry Fields, Gardens, Plantations	2
			Shrubs, Grasslands, Savannah	3
			Settlements/Buildings, Industrial Areas, Yards, Coconut Plantations, Rice Fields, Dryland Agriculture	4
			Rivers, Open Land, Reservoirs, Swamps, Ponds, Water Bodies	5
		River distance	>500 m	1
			>250-500 m	2
			>100-250 m	3
			>50-100 m	4
			0-50 m	5
		Rainfall	< 1500 mm/year (very low)	1
			1500 - 2000 mm/year (low)	2
			2000 - 2500 mm/year (moderate)	3
			2500 - 3000 mm/year (high)	4
			> 3000 mm/year (very high)	5
Sensivity	Flooding	Soil type	Regosol, Lithosol, Organosol, Rendzina, Lithosol-Grumosol Association, Lithosol-Mediterranean-Rendzina Complex, Regosol-Grumosol Complex	1
			Andosol, Laterite, Grumosol, Podsol, Podsolic, Grumosol-Mediterranean Association	2
			Brown Forest Soil, Mediterranean Soil	3
			Latosol	4
			Alluvial, Planosol, Grey Hydromorphic, Groundwater Lattice	5
		Flood frequency	No flood events/year	1
			Only 1 flood event/year	2
			2-3 flood events/year	3
			4-5 flood events/year	4
			More than 6 flood events/year	5
		Flood depth	Not inundated by floods	1
			≤ 50 cm	2
			> 50 - 100 cm	3
			> 100 - 150 cm	4
			> 150 cm	5
	Building condition	Building density	0–200 buildings/km² (very low)	1
			200–400 buildings/km² (low)	2
			400–700 buildings/km² (moderate)	3
			700–1000 buildings/km² (high)	4
			> 1000 buildings/km² (very high)	5
		Building type	0% – 20% uninhabitable housing	1
			> 20% – 40% uninhabitable housing	2
			> 40% – 60% uninhabitable housing	3
			> 60% – 80% uninhabitable housing	4
			> 80% – 100% uninhabitable housing	5
Adaptive Capacity	Utilities	Water supply	PDAM, Pamsimas, Bore Wells	1
			Reservoirs	2

Component	Variable	Subvariable	Parameter	Score
			Springs	3
			Rainwater	4
			Rivers/Lakes	5
		Drainage density	> 3.11 (very dense)	1
			2.28 - 3.10 (dense)	2
			1.45 - 2.27 (moderate dense)	3
			0.63 - 1.44 (light dense)	4
			< 0.62 (least dense)	5
		Waste management	Areas within ≤ 4 km range	1
			Areas within > 4-8 km range	2
			Areas within > 8-12 km range	3
			Areas within > 12-15 km range	4
			> 15 km (beyond waste management facility range)	5
	Critical facilities	Medical facilities	Areas within ≤ 3.5 km range	1
			Areas within > 3.5-5.5 km range	2
			Areas within > 5.5-7.5 km range	3
			Areas within > 7.5-10 km range	4
			> 10 km (beyond healthcare facility range)	5
		Emergency shelter	Areas within ≤ 1.4 km range	1
			Areas within > 1.4 - 2.8 km range	2
			Areas within > 2.8 - 4.2 km range	3
			Areas within > 4.2 - 5.4 km range	4
			Areas within > 5.4 km (beyond evacuation space range)	5

The scoring analysis in this study was conducted on a scale of 1 to 5, where higher scores indicate a greater influence on the level of physical vulnerability to flooding, as determined by parameters established through a literature review. The assigned scores were subsequently input into the attribute table within GIS software for overlay analysis. The overlay analysis specifically utilized the intersect tool.

The intersect tool is a method within overlay analysis used to examine the merging of map layers. This method combines all the attribute table contents corresponding to overlapping polygons between input layers, resulting in a new map layer (Arridha, 2019). Following the overlay analysis, the total physical vulnerability level was calculated across the three components: exposure, sensitivity, and adaptive capacity using the formula provided by the IPCC (2001), as presented in Equation 4.

$$V = AC - (S + E) \quad (4)$$

where: *V* = Vulnerability, *AC* = Adaptive Capacity, *S* = Sensitivity, *E* = Exposure

Based on the results of the formula, a total vulnerability value for each class is obtained. These values are then classified into intervals corresponding to low, medium and high levels of vulnerability. Thus, it is necessary to know the width of the class for each vulnerability level classification, which is calculated as described in Equation 5.

$$Ki = \frac{Xt - Xr}{k} \quad (5)$$

where: *Ki* = class interval, *Xt* = highest data value, *Xr* = lowest data value, *k* = desired number of classes

4. RESULTS AND DISCUSSION

4.1. THE GENERAL OVERVIEW OF THE REGION OF SRAGEN REGENCY

Sragen Regency is geographically located between 110°45'E and 111°10'E longitude, and 7°15'S and 7°30'S latitude, encompassing a total area of 994.57 km² divided into 20 districts. The regency is traversed by the Bengawan Solo River, which flows from east to southwest, bisecting the region. The presence of this river significantly increases Sragen Regency's vulnerability to flooding, as river overflows frequently inundate the area. Based on data from the Central Statistics Agency (BPS) of Sragen Regency from 2019 to 2023, 18 out of the 20 districts in Sragen Regency have experienced flooding. The frequency of flood events in Sidoharjo and Ngrampal districts reached 11-15 occurrences, while

other areas predominantly experienced 1-5 occurrences. Notably, Tangen and Miri districts did not report any flooding incidents in the last five years, as depicted in Figure 2.



Figure 2. Historical Flood Event Map of Sragen Regency 2019-2023

4.2. THE CHARACTERISTICS OF THE EXPOSURE COMPONENT IN SRAGEN REGENCY

The exposure components of Sragen Regency are assessed based on slope, land use, river distance, rainfall, soil type, flood frequency, and flood depth. In Sragen Regency, 69.41% of the area features undulating slopes with gradients of 5-15%. Areas with undulating slopes tend to have scattered locations in the Sragen Regency area. Regions with flatter slopes tend to exhibit higher levels of physical vulnerability. This is because rainfall runoff naturally flows towards lower contour areas, often resulting in water accumulation or slower drainage in flatter regions (Budiharso & Momongan, 2023).

Regarding land use, 53.75% of Sragen Regency is dominated by rice fields, including those cultivated continuously or intermittently with other crops. These areas tend to be in the districts of Miri, Sumberlawang, Mondokan, Sukodono, Tangen, Jenar, Kalijambe, Pelupuh, Kedawung, Karangmalang, Sambirejo, Gondang, Tanon, Sidoharjo, Sragen, Ngrampal, and Sambungmacan. Furthermore, 25.75% of the region is dedicated to built-up land, primarily for residential purposes. Areas characterized by water bodies or built-up land tend to have higher physical vulnerability. This is attributed to the reduced water infiltration capacity and increased surface runoff in these areas, which heighten flood risk compared to natural or vegetated land that allows for greater rainwater infiltration (Fitrotunnisa et al., 2024). The maps of slope and land use in Sragen Regency are presented in Figure 3.

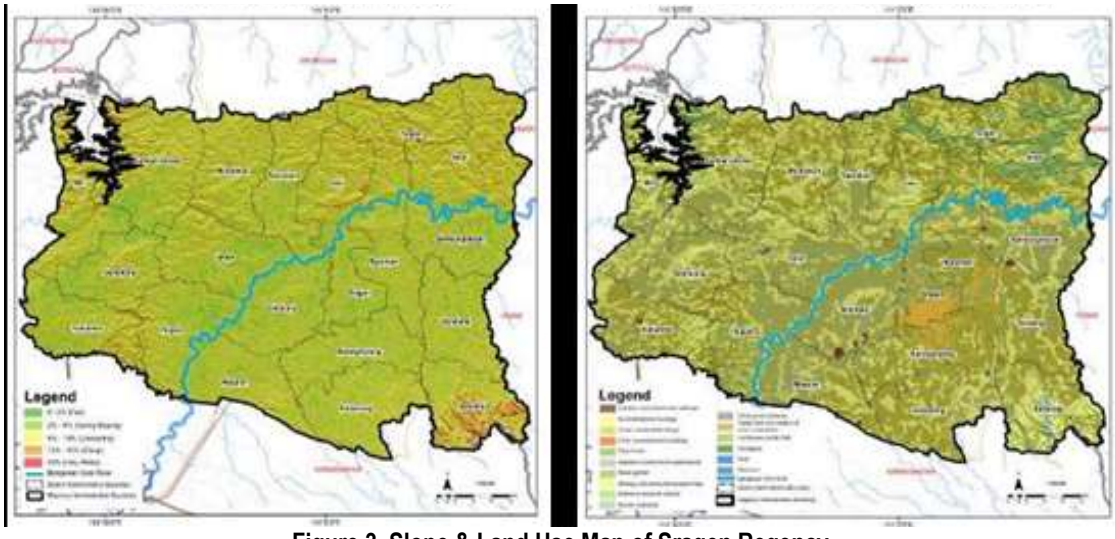


Figure 3. Slope & Land Use Map of Sragen Regency

In terms of river distance, 94.71% of the area is located more than 500 meters away from rivers, while 0.58% of the area is within 0-50 meters of a river and most areas (94.71%) are located at a distance of more than 500 meters from the river. Regions closer to rivers tend to have higher levels of physical vulnerability. This is because areas near rivers are more prone to direct impacts from water flow and overflow, particularly during periods of heavy rainfall or major flooding (Natannael et al., 2024).

Regarding rainfall, 62.27% of the area receives annual precipitation of 1,500-2,000 mm, while 36.99% of the area experiences rainfall exceeding 2,000 mm annually. Areas with low rainfall are spread throughout Sragen Regency, except in most sub-districts; Sumberlawang, Mondokan, Gemolong, Tanon, Plupuh, Masaran, and Kedawung. Areas with higher rainfall tend to exhibit greater physical vulnerability. This is due to the fact that one of the primary causes of flooding is high-intensity rainfall, which significantly contributes to surface runoff, especially when the soil becomes saturated (Afdhalia & Oktariza, 2019). The maps of river distance & rainfall in Sragen are presented in Figure 4.

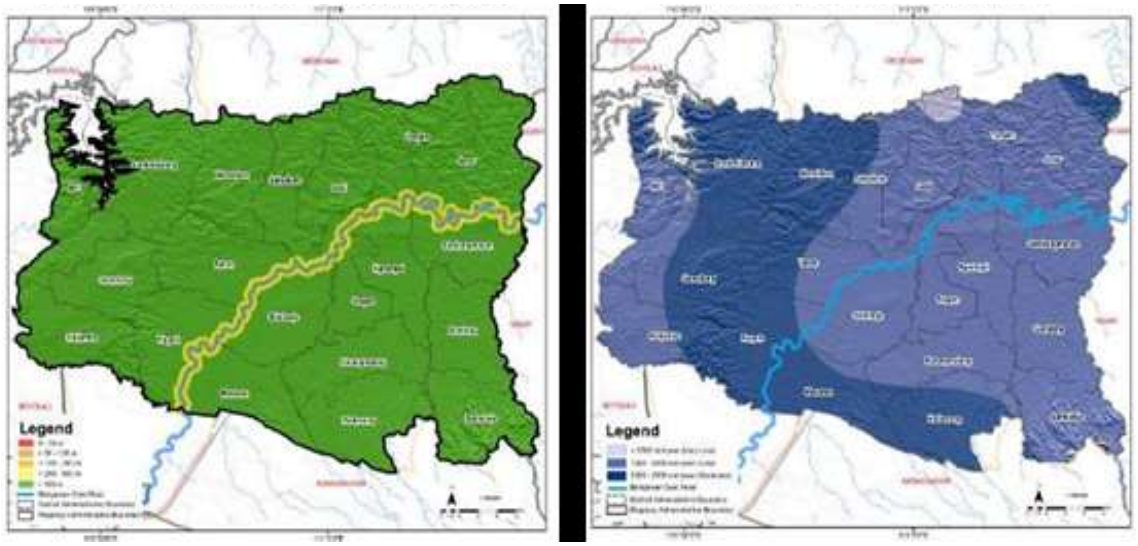


Figure 4. River Distance & Rainfall Map of Sragen Regency

In terms of soil type, 35.22% of the area consists of a complex of lithosol, mediterranean, and rendzina soils while 8.59% comprises alluvial soils, ranging from brownish gray to dark gray alluvial types. The soil type is a type of soil tha easily absorbs water with the dominance spread in the subdistricts; Mondokan, Sukodono, Gesi, Tangen, Jenar, and some subdistricts of Sumberlawang, Tanon and Plupuh. Alluvial soils tend to have higher vulnerability levels. This is because their high infiltration capacity allows for greater absorption of rainwater into the soil layers, reducing surface runoff and mitigating flood risks (Natannael et al., 2024).

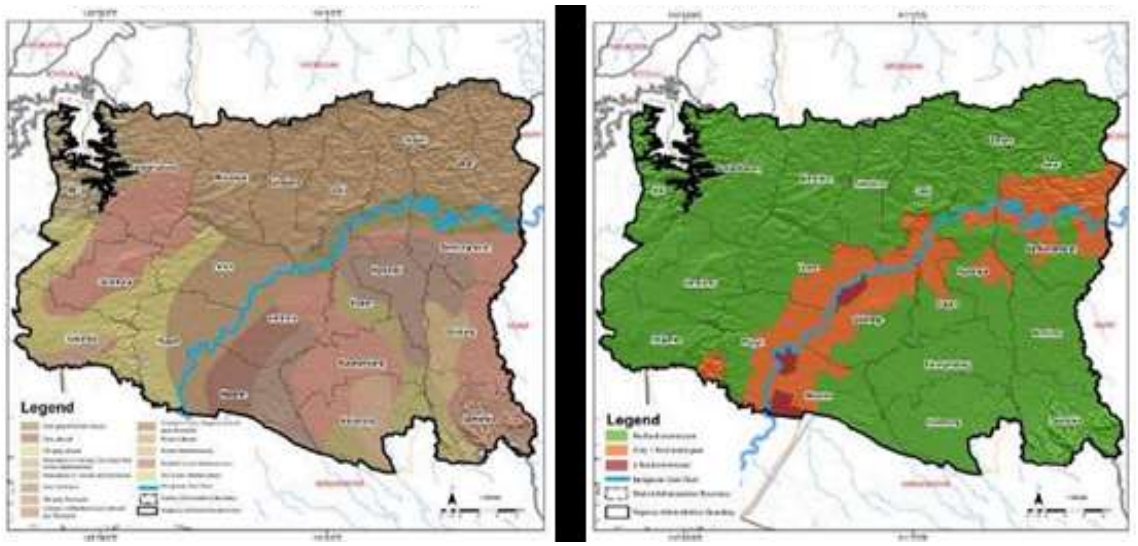


Figure 5. Soil Type & Flood Frequency Map of Sragen Regency

Regarding flood frequency, 17.15% of Sragen Regency experienced one flood event in 2023, while 1.12% experienced two flood events. The frequency of flooding in Sragen Regency is dominated by one flood event in one year, in 39 villages located in Masaran, Plupuh, Sidoharjo, Tanon, Sragen, Sukodono, Sambungmacan, Ngrampal, Gesi, Jenar, and Kalijambe subdistricts. Areas with higher flood frequency tend to exhibit greater physical vulnerability. This is because recurring flood events exacerbate environmental and infrastructure conditions. High flood frequency increases the exposure of physical components such as settlements, infrastructure, and agricultural land to damage risks (Nita et al., 2022). The maps of soil type & flood frequency in Sragen Regency are presented in Figure 5.

In terms of flood depth, 8% of Sragen Regency has recorded flood depths of 50 cm, 7.5% has depths ranging from >50 cm to 100 cm, and 1.67% has depths reaching >100 cm to 150 cm. The highest flood depth was in Sidokerto and Jabung villages in Plupuh subdistrict, Sragen Regency with the highest depth reaching 1.5 meters. Areas with greater flood depths tend to have higher physical vulnerability. This is because higher floodwaters increase the community's vulnerability to physical damage, heightening the risk of damage to buildings, infrastructure, and public facilities caused by corrosion (Rukmana et al., 2020). The map of flood depth in Sragen Regency is presented in Figure 6.



Figure 6. Flood Depth Map of Sragen Regency

4.3. THE CHARACTERISTICS OF THE SENSITIVITY COMPONENT IN SRAGEN REGENCY

The sensitivity components of Sragen Regency are assessed based on building density, building type, water supply, drainage density, and the coverage of waste management facilities. In terms of building density, the region is predominantly characterized by low-density areas, with a range of 201–400 buildings/km², while urban areas tend to have higher densities. The highest building density in Sragen Regency is in Sragen and Karangmalang districts. Areas with very high building density tend to exhibit greater vulnerability. This is because densely built-up land exacerbates the reduction of water infiltration capacity (Gusfira et al., 2023).

Regarding building type, most areas have less than 20% of houses categorized as uninhabitable (*Rumah Tidak Layak Huni* or RTLH) within each subdistrict. However, Jenar and Sambungmacan subdistricts have the highest proportion of RTLH, reaching 60-80%. Areas with a very high percentage of RTLH are more vulnerable, as these houses typically have nonpermanent structures, making them less capable of withstanding or mitigating the impacts of disaster (Rif'ati & Pamungkas, 2023). The maps of building density & building type in Sragen Regency are presented in Figure 7.

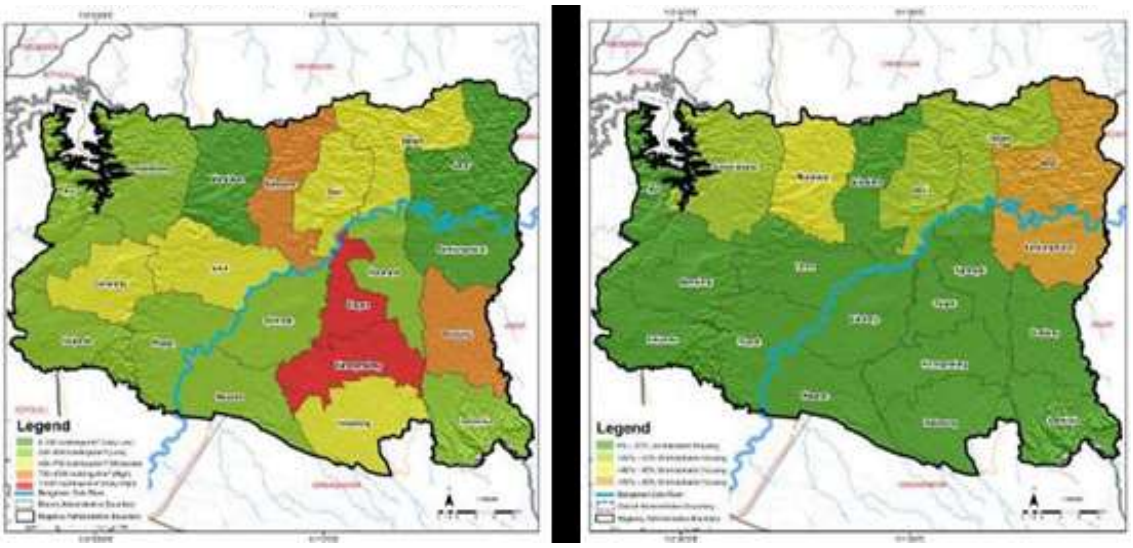


Figure 7. Building Density & Building Type Map of Sragen Regency

In terms of water supply, most of the region relies on PDAM and community-based water supply systems (Pamsimas), while northern Sragen Regency primarily depends on reservoirs. The reservoir is still utilized as the main source of clean water in Mondokan, Sukodono, Gesi, Tangen, and Jenar subdistricts. Areas relying on reservoir-based water sources tend to have higher vulnerability. This finding aligns with Jamshed et al. (2019) who argued that the lack of necessities, such as access to clean water both during and after floods, exacerbates vulnerability to flooding. This is because protected water sources can provide a consistent supply, unaffected by contamination or infrastructure damage caused by floods.

For drainage density, 10 subdistricts have poorly connected drainage systems with densities ranging from 0.63–1.44 km/km², while 9 subdistricts have very sparse drainage systems (< 0.62 km/km²). The highest drainage density is in Sragen district with a density of 4.87 km/km² in the classification (>3.11 km/km²), which is very dense. In line with Wandra's research (2022), an area becomes susceptible to flooding if there is insufficient drainage infrastructure to accommodate surface runoff. This occurs because the drainage system is unable to efficiently convey water, leading to increased water ponding and exacerbating the risk of flooding. The maps of water supply & drainage density in Sragen Regency are presented in Figure 8.

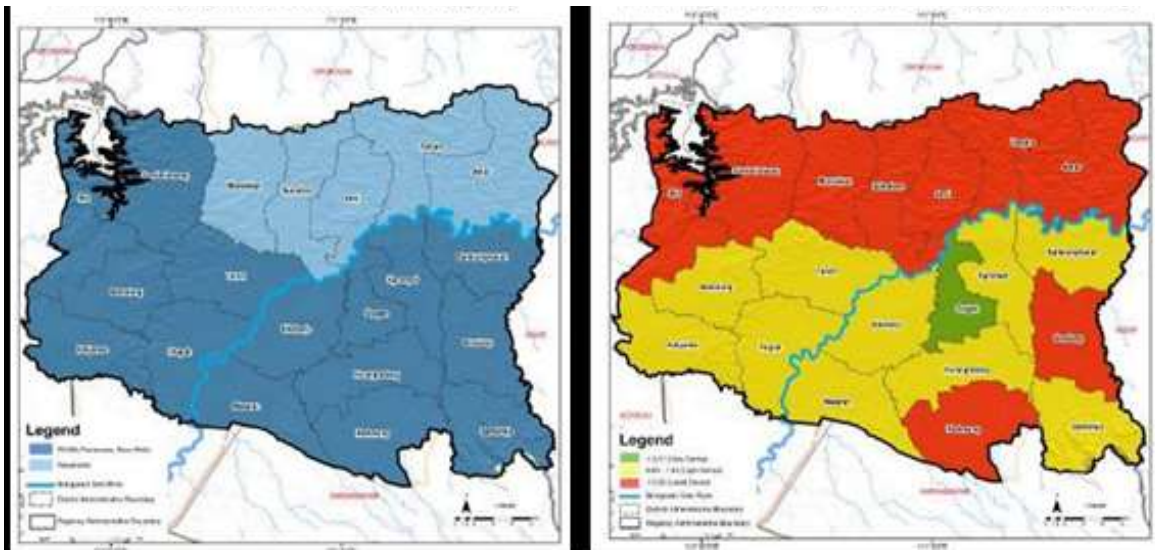


Figure 8. Water Supply & Drainage Density Map of Sragen Regency

Areas without access to waste management facilities tend to exhibit higher flood vulnerability. This is due to the potential for unmanaged waste to clog drainage systems, further increasing flood risks in areas with limited waste management coverage. Regarding waste management facility coverage, 36.56% (357.26 km²) of Sragen Regency is not served by waste management facilities such as landfills (*Tempat Pemrosesan Akhir* or TPA), temporary waste storage (*Tempat Pembuangan Sementara* or TPS), or reduce-reuse-recycle temporary waste storage (TPS 3R) facilities. While

the dominance of 63.44% of the area is already within the reach of waste management with varying distance of reach (Subiyanto et al., 2020). The map of waste management in Sragen Regency is presented in Figure 9.



Figure 9. Waste Management Map of Sragen Regency

4.4. THE CHARACTERISTICS OF THE ADAPTIVE CAPACITY COMPONENT IN SRAGEN REGENCY

The adaptive capacity components of Sragen Regency are assessed based on the accessibility of medical facilities and emergency shelter. In Sragen Regency, 69.68% of the area, covering 680.79 km² is within a range of less than 3.5 km from healthcare facilities, including medical practices, community health centers (Puskesmas), and hospitals. Areas outside the reach of healthcare facilities tend to exhibit higher physical vulnerability, as the lack of access to healthcare facilities reduces the ability to address and mitigate the impacts of flooding effectively (Murbana & Handayani, 2021).

Regarding evacuation spaces, in Sragen Regency, there are 24 scattered evacuation centers, including fields, green open spaces, and multipurpose buildings that have been designated by the Sragen Regency Government as evacuation centers in the event of a disaster. 61.85% of Sragen Regency is already within the evacuation area. The other 38.15% (372.68 km²) of the district is beyond the reach of evacuation spaces. Areas outside the coverage of evacuation spaces tend to have higher physical vulnerability due to limited access and prolonged evacuation times during disasters (Hasddin & Tamburaka, 2021). The maps of medical facilities and emergency shelter in Sragen Regency are presented in Figure 10.

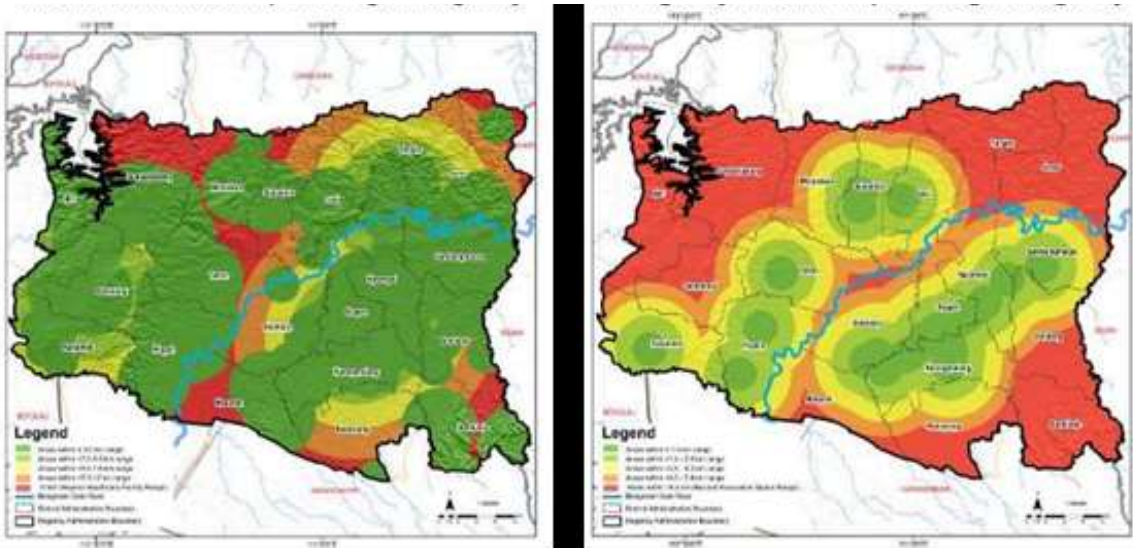


Figure 10. Medical Facilities & Emergency Shelter Type Map of Sragen Regency

4.5. THE LEVELS OF PHYSICAL VULNERABILITY TO FLOODS IN SRAGEN REGENCY

After the scoring analysis was conducted for each research variable, an overlay analysis was conducted, which was divided into four segments, namely exposure, sensitivity, and adaptive capacity, and a comprehensive overlay of all variables and sub-variables was also conducted. The results of this map are divided into three levels of vulnerability, namely low, medium, and high vulnerability. This resulted in a map illustrating the level of physical vulnerability to flooding in Sragen Regency, as shown in Figure 11.

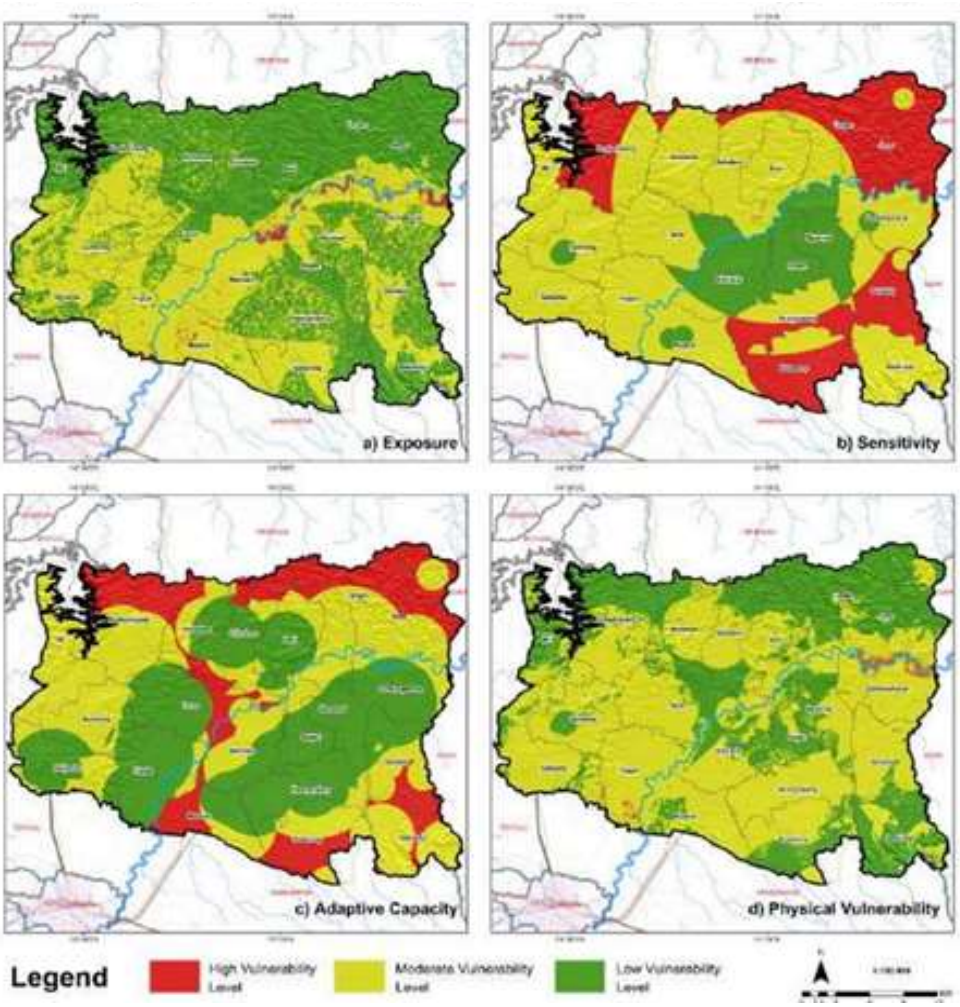


Figure 11. Physical Vulnerabilty Levels to Floods Map of Sragen Regency

The mapping results were used to calculate the area of each vulnerability level, as presented in Table 4

Tabel 4. The Area of Physical Flood Vulnerability Levels in Sragen Regency

Component	Classification	Area (km^2)	Percentage (%)
Exposure	low vulnerability level	506.12	51.99
	medium vulnerability level	454.34	46.67
	high vulnerability level	12.97	1.33
Sensitivity	low vulnerability level	136.01	13.97
	medium vulnerability level	585.32	60.13
	high vulnerability level	252.11	25.90
Adaptive Capacity	low vulnerability level	383.03	39.35
	medium vulnerability level	402.60	41.36
	high vulnerability level	187.80	19.29
Physical Vulnerability	low vulnerability level	355.70	36.54
	medium vulnerability level	607.78	62.44
	high vulnerability level	9.96	1.02

The physical flood vulnerability in Sragen Regency is generally classified into three levels: low, medium, and high vulnerability. Areas with high vulnerability based on exposure cover an area of 12.97 km², primarily located along the Bengawan Solo River. Consistent with the findings of Utami et al. (2021), areas with high vulnerability have the greatest potential for flood disasters. If a flood occurs, these areas are likely to experience severe impacts, requiring the longest recovery time due to significant damage and disruption. Meanwhile, medium vulnerability areas surround these high-vulnerability zones and low vulnerability areas are typically found in the peri-urban regions of Sragen Regency. For sensitivity, areas with high vulnerability encompass 252.11 km², mostly located in peri-urban districts, while medium vulnerability dominates the surrounding regions. Areas near the center of Sragen Regency generally exhibit low vulnerability levels. Regarding adaptive capacity, areas with high vulnerability span 187.80 km². High vulnerability is predominantly observed in peri-urban areas, while urban areas tend to have lower vulnerability, indicating better adaptive capacity.

Based on the overall assessment of physical flood vulnerability across all components, the majority of Sragen Regency's area 62.44%, or 607.78 km² is classified as having medium vulnerability. This is followed by low vulnerability, accounting for 36.54% or 355.70 km². High vulnerability accounts for only 1.02% of the area or 9.96 km². Areas with high flood vulnerability face the greatest risk and potentially devastating impacts, requiring the longest recovery periods. Moderately vulnerable areas still experience flood risk, but the potential impact and recovery time are less severe. Low vulnerability areas are considered the safest from both the potential and impacts of flooding.

Areas with high physical vulnerability indicate a greater susceptibility to flood impacts compared to other regions. These areas are characterized by high exposure to flood risks. Topographically, they are located on undulating slopes (5%-15%), which hinder water flow. The land use is predominantly rice fields with continuous cropping patterns, reducing the land's water absorption capacity. Proximity to rivers (<250 meters) significantly increases flood risk, particularly under rainfall intensity ranging from 1,500 to 2,000 mm/year. The presence of gray-brown alluvial soil with low permeability exacerbates the area's susceptibility. Additionally, the frequency of annual flooding and flood depths reaching 50 cm highlight the vulnerability of these regions.

From a sensitivity perspective, areas with high vulnerability often have very low building density, but are dominated by substandard housing (RTLH), comprising 60%-80% of existing structures, increasing the risk of damage during floods. The primary water source for these areas is reservoirs, which are prone to contamination during floods. Furthermore, low drainage density (<0.62 km/km²) indicates insufficient water management systems and long distances to waste management facilities (>8-12 km) exacerbate sanitation issues during flooding.

In terms of adaptive capacity, areas with high vulnerability show relatively good accessibility to healthcare facilities within 3.5 km. However, evacuation spaces are located at considerable distances (4.2-5.4 km), which may impede rapid responses during emergencies. Although these high-vulnerability areas exhibit good adaptive capacity regarding access to healthcare and evacuation facilities, they have moderate sensitivity. Infrastructure and building conditions in these areas are not yet sufficient to minimize the impact of severe floods. The high exposure to flood risks, including environmental factors such as slope gradient, land use, river proximity, soil type, rainfall intensity, flood frequency, and flood depth are the primary contributors to the elevated vulnerability levels.

This study aligns with the findings of Blaikie et al. (2014), which state that vulnerability is most directly caused by unsafe conditions. These unsafe conditions include hazardous locations, unprotected infrastructure, and a lack of disaster preparedness, all of which are effectively represented by the E-S-A framework proposed by the IPCC (2001). This research is also in line with Thomas et al. (2018), who emphasizes the importance of the interaction of adaptive capacity, sensitivity and exposure in reducing system vulnerability. Therefore, it does not only focus on improving adaptive capacity, but also on reducing the level of exposure and sensitivity of the region.

5. CONCLUSION

The analysis of physical flood vulnerability in Sragen Regency, conducted using the E-S-A Framework approach, reveals variations in vulnerability levels across the region. The majority of the area, covering 607.78 km², is classified as having medium vulnerability, while a smaller area of 9.96 km², predominantly located in the southern part of Jenar district, exhibits high vulnerability. Using the E-S-A Framework approach, it is evident that although some areas possess good adaptive capacity, high exposure remains the primary factor dominating vulnerability levels. The established adaptive capacity is insufficient to significantly counterbalance the high potential risks (exposure). Meanwhile, the moderate

sensitivity level indicates that the condition of buildings and infrastructure in these areas is not yet optimal in minimizing the impact of more severe flood disasters.

This study is expected to provide insights into the use of vulnerability-based approaches and offer practical contributions to stakeholders, emphasizing not only the need to enhance adaptive capacity but also the importance of reducing exposure and sensitivity levels. Given that highly vulnerable areas constitute only a small portion of the region, greater attention should be directed toward the moderately vulnerable areas, which dominate the landscape. Therefore, future spatial planning should aim to minimize land development in highly vulnerable areas while focusing on enhancing adaptive capacity both structurally and non-structurally in moderately vulnerable areas. Additionally, maximizing infrastructure development is crucial to mitigating the impacts of flooding and improving overall disaster resilience.

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