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Multi-Hazard Analysis in Gunungkidul Regency Using Spatial Multi-Criteria Evaluation

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Abstract

This study has two aims: to determine the spatial distribution of multi-hazard levels and to discover the interactions, interdependencies, and effects that cascade among hazards in Gunungkidul Regency, Special Region of Yogyakarta. A multi-hazard map was created with a scale of 1:250,000 and modelled using SMCE (Spatial Multi-Criteria Evaluation). The conditioning factors used included slope, rainfall, historical data, river distance, geomorphology, land cover, lithology, and fault distance. The selected conditioning factors for each hazard were then weighted using weighted overlay analysis. The results showed that the area of Gunungkidul can be included in the high-risk category for floods, since the probability of flooding is 56.72%, the probability of landslides is 9.14%, that of drought is 48.86%, and that of seismic disturbance is 20.83%. (Multi-hazard maps are created by overlaying flood, landslide, seismic, and drought hazard maps.) After these risk factors were calculated, the regions on the multi-hazard map were re-categorized into five hazard classes. All areas in Gunungkidul Regency have multiple hazards, with risk factors of different magnitudes. The interaction between hazards can generate new hazards that are called cascading hazards. The cascading hazards in the study area are most likely to occur in the north of Gunungkidul Regency with its very high seismic and landslide hazard risk factors, due to the geological and geomorphological conditions of the Baturagung Structural Hills.

Keywords: Multi-Hazard, Spatial Multi-Criteria Evaluation (SMCE), Weighted Overlay, Cascading Effects.

1. Introduction

Due to its geography, Gunungkidul Regency is prone to several disasters such as earthquakes, tsunamis, floods, droughts, and landslides (Gunungkidul Regency Regional Regulation No. 22 Concerning Establishment, Organizational Structure, Position and Duties of the Regional Disaster Management Agency, 2011). Hydrometeorological factors, such as floods and droughts mostly cause disasters that often occur yearly in this area. It was recorded that 14 districts experienced drought in 2019 (BPBD Gunungkidul, 2019). In addition, there were floods, landslides, and strong winds caused by the Cempaka Tropical Cyclone in 2017. According to data from the Regional Disaster Management Agency (BPBD Gunungkidul, 2017), landslides were recorded at several points in Gedangsari District; flooding was recorded in Nglipar District and several other districts, resulting in many bridges being damaged. Many disaster events occur every year. This fact highlights the importance of preparing hazard maps in Gunungkidul Regency as one of the region's disaster mitigation efforts.

The use of a single hazard map for each type of natural disaster will be insufficient, and disaster management may not function well in certain areas (López-Saavedra *et al.*, 2022). These areas are typically not affected by just one type of natural hazard but have the potential for two or more types of natural disasters to occur at the same time or in succession, often leading to multiple simultaneous tragedies (Bender, 1991 ; De Angeli *et al.*, 2022). The requirements for each disaster risk must be assessed using an appropriate model, and a comprehensive overview must be created; this can be achieved by simulating a multi-hazard assessment. One could argue that this modelling approach is crucial for implementing strategies meant to lessen the effects of future calamities (Skilodimou *et al.*, 2019). In the previous multi-hazard research, the AHP method assisted by GIS technology was used to perform consistent data processing (Skilodimou *et al.*, 2019).

Potential hazards in a certain area tend to be diverse and can be related to one another. According to Sanderson (1996) in Nurafiah *et al.* (2019), the multi-hazard approach explains the potential hazards that may cause other hazards in the same area. According to Van Westen & Greiving, (2017), the term 'multi-hazard' denotes all relevant hazards and their interactions in a given area. The multi-hazard approach is a way of planning and designing an area by taking into account the main hazards and other potential hazards by mapping each hazard type in that area.

The interaction between hazards can generate new hazards beyond the primary hazard. This is known as cascading hazards (Zhang *et al.*, 2023). For example, an earthquake with a magnitude of Mw 7.4 in Palu, Central Sulawesi, Indonesia, in 2018 created cascading secondary hazards, including tsunamis, liquefaction, and landslides (Triyanti *et al.*, 2022). The 2018 Palu disaster shows that under certain physical conditions, the interaction of several types of hazards can create new hazards with greater destructive power resulting in extensive damage and great losses of life and property. Hence, multi-hazard mapping must be undertaken to anticipate cascading hazards, especially in areas with typical geological characteristics.

The geology of the Gunungkidul Regency area is dominated by Miocene limestone from the Wonosari Formation, including the Wonosari Basin area (central part) and the Gunungsewu Karst Hills (southern part). In the northern part of Gunungkidul Regency one finds the Baturagung Structural Hill Complex, composed of old volcanic rocks, has many fracture and fault structures, and has experienced substantial weathering (Santosa, 2005). The variations in physical characteristics Gunungkidul Regency and the disasters which have occurred there mean that it is crucial to carry out a multi-hazard study to anticipate cascading hazards. In addition, the number of people at risk is constantly growing; the population growth in Gunungkidul is 1.97% annually (BPS-Statistics of Gunungkidul Regency, 2022a). Thus, multi-hazard mapping is very important as a way to reduce the number of losses when a disaster occurs.

The research in multi-hazard assessment in Gunung Kidul Regency, combining flood, landslide, drought, and seismic hazard, is novel, as indicated by the lack of prior studies addressing these specific combinations of multi-hazards in the region (Pourghasemi *et al*., 2020; Koks *et al*., 2019; Bera *et al*., 2023; Youssef *et al*., 2023). The map will show the geographic distribution in Gunungkidul Regency based on the type of disaster and the degree of hazard. This study has two main aims: 1) to determine the spatial distribution of multi-hazard levels in Gunungkidul Regency; and 2) to discover the interactions, interdependencies, and cascading effects among hazards. It is therefore hoped that this research will expand the knowledge available on the risk of disaster hazards in Gunungkidul Regency.

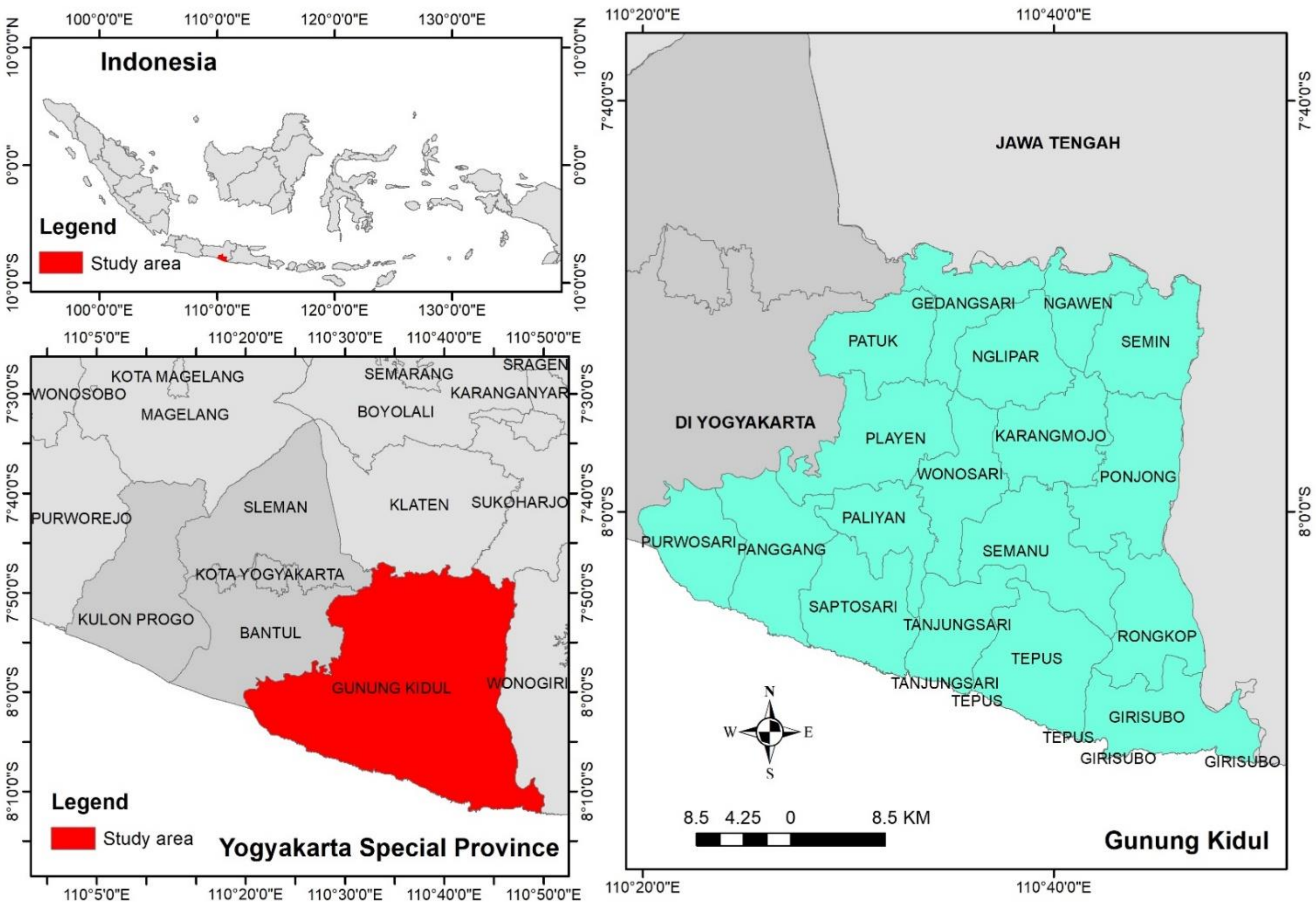

Figure 1. Research Location Map.

2. Research Methods

The study area was located in Gunungkidul Regency, Special Region of Yogyakarta (Figure 1). Gunungkidul Regency has three dominant landscapes due to structural and solutional processes

(Baturagung Fault Hills, the Wonosari Basin, and the Gunungsewu Hills). Karst landscape dominates the study area. A karst landscape is defined as an area that is unique because it is composed of limestone ($CaCO_3$) which easily undergoes a solutional process or chemical dissolution due to acid rainwater (Zhao *et al.*, 2022). Tropical climate conditions with high annual rainfall levels support the process of the formation of the karst landscape in Gunungkidul. The diversity of geomorphological aspects in one district administration area both presentspotential and poses problems. Various geomorphological conditions will cause various hazards. This multi-hazard study can be used to plan an integrated disaster mitigation policy. Overall framework of this study is presented in Figure 2.

2.1. Hazard assessment

The study aims to establish a technique for quantitative and descriptive analysis of the multiple hazards that occur in the Gunungkidul Regency using Spatial Multi-Criteria Evaluation (SMCE). ITC originally developed this method for ILWIS software. It is used in decision-making processes whose analysis processes consider and evaluate criteria spatially (Rohaendi, 2017). The SMCE method has been widely used for various purposes such as land use evaluation (Rohaendi, 2017), development planning (Marsh *et al.*, 2021), land suitability evaluation (Wahyu *et al.*, 2023).

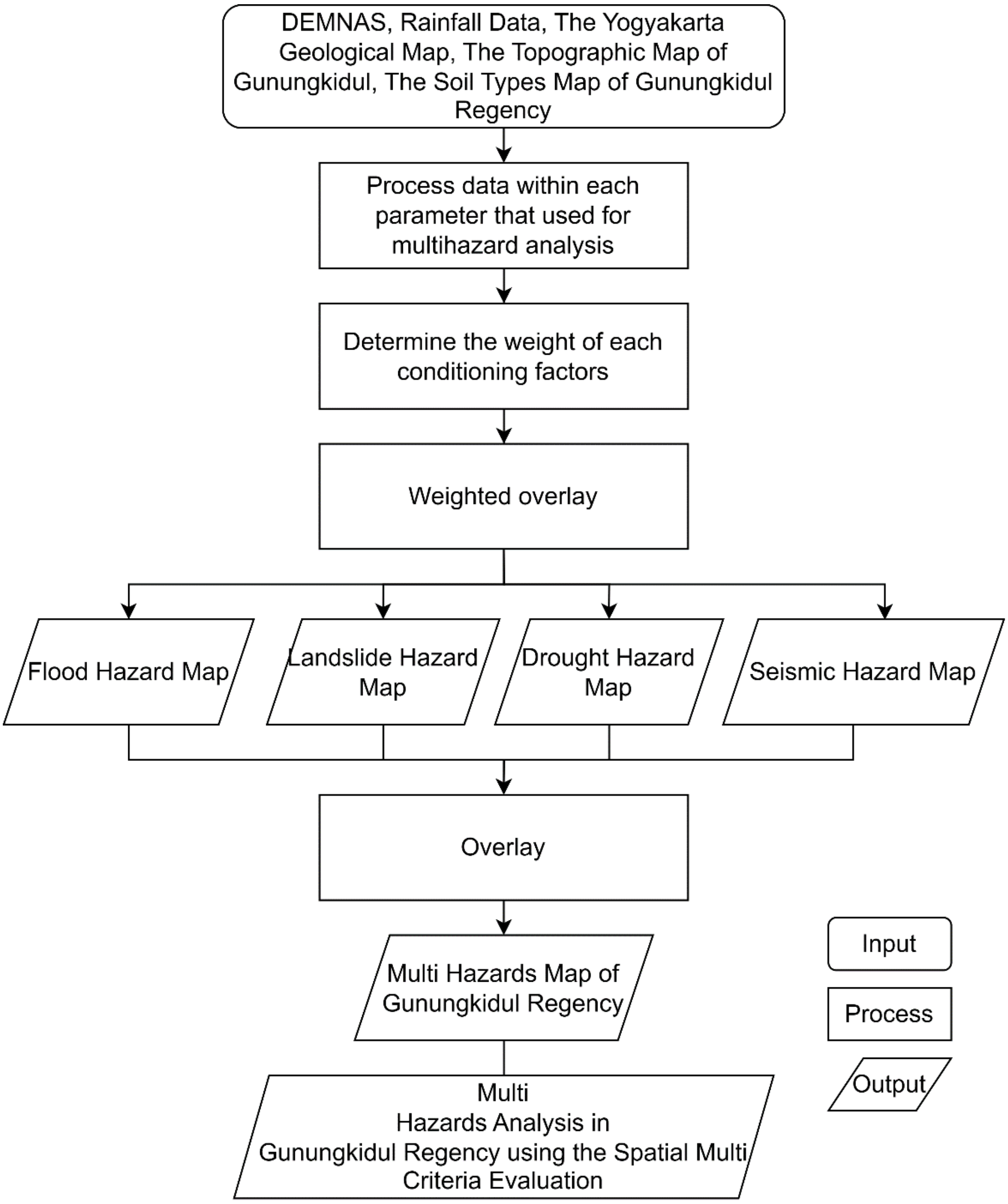

Figure 2. The framework of research.

This study examines four types of hazards, floods, landslides, earthquakes, and droughts. These hazards have occurred in Gunungkidul Regency, according to the Indonesian Disasters Information Database (DIBI). In addition, the four hazards have the potential to interact and form cascading hazards. When the data is available, other types of hazards can be added.

Each hazard has a unique parameter derived from primary and secondary data (see Table 1 and Table 2). The SMCE method using ArcGIS software can be performed using Weighted Overlay Analysis. Each conditioning factor for weighted overlays is adjusted based on its interaction with the causes and the frequencies of specific disasters (Arumugam *et al.*, 2023). The SMCE formula is expressed as Equation 1.

$$S = \sum_{i=0}^{n} WiXi \quad (1)$$

S is the suitability of the Spatial Multi-criteria Evaluation; Wi is the weight factor; and Xi is the factor score.

Table 1. The conditioning factors for multi-hazard mapping.

Conditioning Factor	Source	Classification Method
Slope	DEMNAS	SK Mentan No. 837/Kpts/Um/11/80
Rainfall	BBWS	Ministry of Forestry
Historical Data	Indonesian Disaster Information Database (DIBI), Local News	Administration units
River Distance	DEMNAS	Natural breaks
Geomorphology	DEMNAS	Geomorphological units
Land Cover	Indonesian Ministry of Environment and Forestry (KLHK)	Land cover units
Lithology	Geological Map	Lithological units
Fault Distance	Geological Map	Natural breaks

Table 2. Hazard assessment.

Hazard	Conditioning Factor	Weight
Flood	Slope	28
	Rainfall	24
	Historical data	19
	River distance	14
	Geomorphology	10
	Land Use	5
Landslide	Slope	28
	Rainfall	24
	Lithology	19
	Historical data	14
	Geomorphology	10
	Land use	5
Seismic	Fault distance	33
	Geomorphology	27
	Slope	20
	Historical data	13
	Lithology	7
Drought	Rainfall	28
	River distance	24
	Geomorphology	19
	Lithology	14
	Historical data	10
	Land use	5

The conditioning factors were selected based on data availability and adjusted to the characteristics of the study area. The conditioning factors for multi-hazard mapping consist of the parameter used to determine the weight for each hazard that yields the scoring and is given the total weight values shown in Table 2. The weights are obtained from the results of a series of experiments carried out using the SMCE method and are adjusted based on the magnitude of the effect on certain types of hazards. Each hazard is then overlayed and classified.

2.2. Multi-hazards risk mapping

Flood, landslide, seismic, and drought hazard maps were created from the conditioning factors using the Spatial Multi-Criteria Evaluation approach. The maps of the four natural hazards (flood, landslide, earthquake, and drought) were combined using ArcGIS to create an integrated multi-hazard map. The multi-hazard map was then analysed to see possible interactions between hazards.

3. Results and Discussion

3.1. Hazard assessment

Assessment of each hazard using a weighted overlay shows a varying spatial distribution (see Figure 3). This variation in spatial distribution is caused by differences in conditioning factors and by the weights used for each hazard. Around 56.72% of the Gunungkidul area has a high flood hazard classification (see Table 3). This high flood-class area has a flat to sloping topography (Figure 3). In addition, according to historical data, flood events in Gunungkidul are strongly influenced by extreme rainfall. Tropical Cyclone Cempaka that occurred in 2017 resulted in groundwater flooding in the Ngreneng Karst Window, Gunungsewu Karst Area (Cahyadi *et al.*, 2019). Tropical Cyclone Savannah passed through the Special Region of Yogyakarta on 17th March 2019 and also caused groundwater flooding in the Kalinongko Karst Window (Riyanto *et al.*, 2020). Based on past events, the hydrology of the karst area is known greatly to contribute to the flood hazard even though the area looks arid.

In terms of the landslide hazard, 65.96% of the Gunungkidul area is in the low hazard class. Most areas are classified as low landslide hazards because the Gunungsewu karst has a thin soil layer with an average soil thickness of <50cm (Cahyadi *et al.*, 2017). The characteristics of soil and rock materials in Gunungsewu tend to allow for subsurface landslides to occur and for collapses/sinkholes to form. This process is supported by the factor of the average annual rainfall in this area which is classified as moderate (2,000 m. a year). This rainfall feeds into a solutional process (Wijayanti & Noviani, 2020). The topography of Gunungkidul is undulating, with half of the area sloping >15%, namely the northern zone (Baturagung Hills), and the western, southern, and eastern zones sloping (Gunungsewu Karst Hills) (Bappeda Gunungkidul, 2019). Faults and fractures strongly influence the northern zone and is the location of the Nglanggeran Ancient Volcano. Most of the population in this area work as farmers (BPS-Statistics of Gunungkidul Regency, 2022b). Nglanggeran Agricultural Technology Park farmers develop agroforestry plants (Saputro *et al.,* 2021). These agricultural activities trigger intensive erosion and increase the potential for landslides in the Baturagung Zone.

The results of the drought hazard assessment show that Gunungkidul is dominated by moderate (30.92%) and high (48.86%) hazard classes. Spatially, the distribution of high drought hazards dominates the karst landscape—the southern part of the Wonosari Basin and the Gunungsewu hills. Even though this area has high rainfall (about 1,875 – 2,125 mm/year), Panggang District which is part of the Gunungsewu Karst Hills often experiences drought because rainwater cannot be stored as groundwater (Nugroho *et al.*, 2020). The dry characteristics of the karst area, with the characteristics of subsurface flow make this area prone to drought in the dry season.

The Baturagung Hills area is influenced by fault activity from the Opak and Dengkeng Faults (Mulyasari *et al.*, 2020). This condition is described bythe results of the seismic hazard assessment which shows that the northern part has a moderate (28.86%) and high (20.83%) hazard level. In addition to the influence of faults, this area's geomorphology is a significant contributor to hazard levels. This area is at risk of landslides because the northern part of Gunungkidul Regency is composed of loose material such as the Gunung Merapi Muda Formation in which it is easier for seismic waves to be propagated, so the impact of landslides is more severe (Husein *et al.*, 2007).

The seismic hazard profile of Gunungkidul Regency is generally dominated by a low level of hazard (40.87%) which spreads from the centre to the southern part of the district (Figure 3). This is because the central and southern parts of this regency are relatively far from faults. On the other hand, the northern part has a high to very high level of seismic hazards due to the presence of faults and fractures. The effect of distance from the fault is evidenced by the distribution of damage to buildings by the earthquake measured at a magnitude of 6.3 by the US Geological Survey that occurred on May 27, 2006 in the Special Region of Yogyakarta. The earthquake had a pattern following the direction of the fault (Marsell, 2013). Earthquakes occurring in Gunungkidul generally originate from Opak fault activity or from fault activity around the Indian Ocean. Therefore, historical data on earthquake events originating in the northern area of Gunungkidul is hard to find. Another cause of the high level of seismic hazard in the northern part of Gunungkidul is that it has unconsolidated sediment rocks which are included in the earthquake-prone category (Gunawan & Khadiyanto, 2012). This contrasts with the karst hill zone (consolidated sediments).

Table 3. Areas of different classes of hazards.

Hazard	Classification									
	Very Low		Low		Moderate		High		Very High	
	Area (km^2)	Per cent (%)	Area (km^2)	Per cent (%)	Area (km^2)	Per cent (%)	Area (km^2)	Per cent (%)	Area (km^2)	Per cent (%)
Flood	0	0	6.04	0.42	490.50	33.92	820.27	56.72	129.26	8.94
Landslide	42.36	2.93	954.48	65.96	317.10	21.91	132.21	9.14	0.97	0.07
Drought	0	0	182.12	12.58	447.48	30.92	707.22	48.86	110.63	7.64
Seismic	12.16	0.84	591.62	40.87	417.74	28.86	301.51	20.83	124.56	8.60

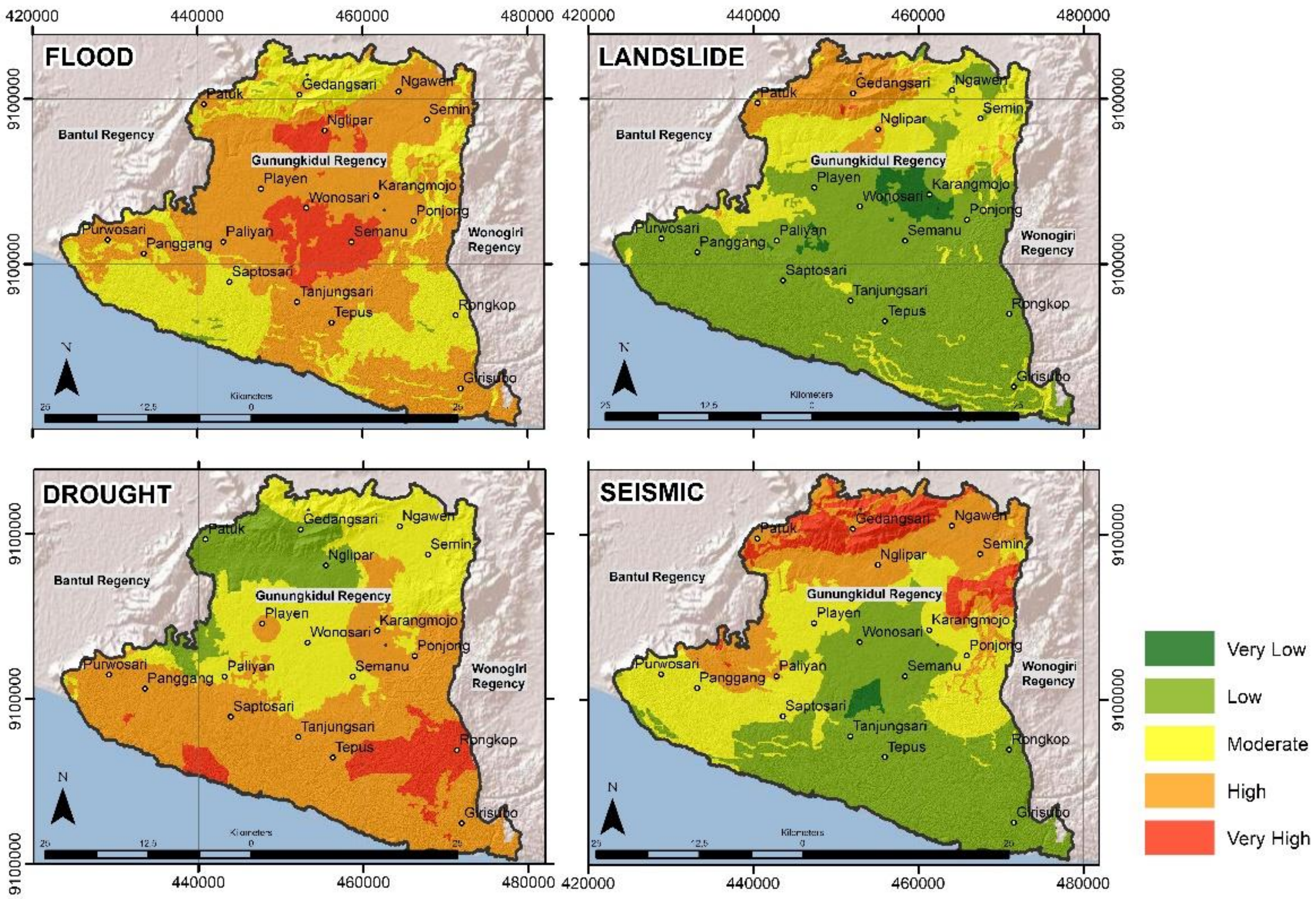

Figure 3. Hazard maps of Gunungkidul Regency.

3.2. Integrated multi-hazard map

Figure 3 shows that all areas in Gunungkidul have more than one type of hazard. The distribution of the multi-hazard classes follows a pattern. The high to very high multi-hazard areas are mostly in the north, moderate multi-hazard areas are spread out in the north, west, and east, and very low to low multi-hazard areas are in the south and centre of the Gunungkidul Regency. The number of hazard types in an area and the class of each hazard affect the area's multi-hazard class.

Most areas of Gunungkidul have low multi-hazard levels. The area around Playen is a low multi-hazard area because it consists of a combination of high flood hazards and high drought hazards. However, the area south of Saptosari, which also consists of high flood and drought hazards, has a very low multi-hazard classification. This is because, in addition to the composition of the high and very high hazard classes, the multi-hazard assessment also considers each hazard's very low, low, and medium hazard classes. Thus, even though two areas are both at risk of two high-level hazards, it could be that the areas have different multi-hazard classifications. The composition of the weights of each hazard is very influential because it affects the results of the multi-hazard assessment. The results of the multi-hazard assessment in Gunungkidul Regency are very low 12.32% (177.98 km^2), low 39.35% (568.51 km^2), moderate 28.47% (411.38 km^2), high 16, 44% (237.57 km^2), and very high 3.42% (49.36 km^2) (Table 4).

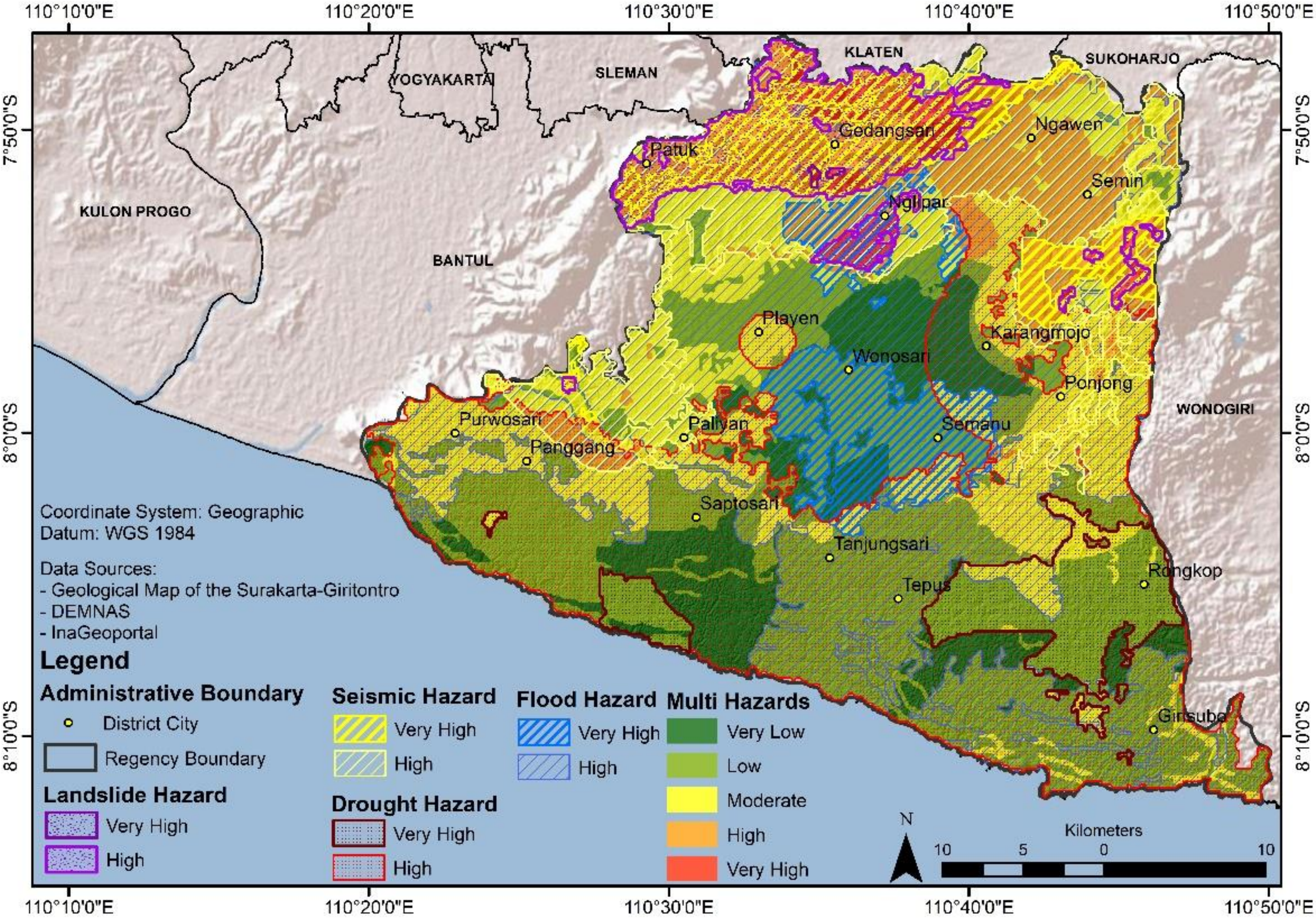

Figure 4. Multi-hazard map of Gunungkidul Regency.

The results of this multi-hazard mapping in Gunungkidul Regency also show the uniqueness of this area. The area around Wonosari and Semanu districts is a low-level multi-hazard area. What is highlighted is that this area has a very high level of flood hazards (see Figure 3). This very high flood hazard is due to the area's sloping topography and proximity to the river. However, the vicinity of Semanu District also has a high level of drought hazard due to the factors of the average annual rainfall of 1500-2000 mm and soil composed of limestone material. Limestone is a good aquifer after volcanic rocks and alluvial deposits, nevertheless, the potential for groundwater in limestone areas is not evenly distributed and its potential is highly dependent on the dissolution holes (Kementrian PUPR, 2017). There is an intersection area with a very high level of flood hazard and a high level of drought hazard. This area has serious water problems because in the rainy season it experiences flooding and in the dry season it experiences drought.

Table 4. Areas of different classes of multi-hazard in Gunungkidul Regency.

Hazard	**Classification**									
	Very Low		Low		Moderate		High		Very High	
	Area (km^2)	Per cent (%)	Area (km^2)	Per cent (%)	Area (km^2)	Per cent (%)	Area (km^2)	Per cent (%)	Area (km^2)	Per cent (%)
Multi-hazard	177.98	12.32	568.51	39.35	411.38	28.47	237.57	16.44	49.36	3.42

3.3. Multi-hazard effects

Gunungkidul Regency has a multi-hazard potential consisting of landslides, earthquakes, droughts, and floods. Diverse potential disasters require good mitigation and adaptation planning. Multi-hazard mapping is one of the efforts required to reduce the potential for damage and losses when a disaster occurs, such as loss of life and damage to infrastructure, utilities, and public facilities (Khan *et al*., 2020 ; Wang *et al.*, 2020). Multi-hazard mapping can show the spatial distribution of several hazards that can have regional interactions. These hazards are also related to the geomorphological conditions and characteristics of the landscape in Gunungkidul Regency.

One of the objectives of multi-hazard analysis is to determine the interactions, interdependencies, and cascading effects between hazards. Gill & Malamud (2016) describe five hazard relationships or interactions, including: Natural disasters triggering other natural disasters, human activities triggering natural disasters, human activities exacerbating natural hazards triggers, cascading effects, and the encounter of two or more hazards. The approach that can be used to analyze the relationship between disasters is to identify the triggering factors for each disaster, especially in the study area. According to Van Westen & Greiving (2017), several factors, such as topography, geomorphology, geology, soil, and human activities, contribute to creating hazards.

Multi-hazards can have effects related to other disaster risks. The relationship can be triggering, amplifying, compounding, or consecutive. However, the general effect of interaction between hazards is triggering and amplifying. It can result in an increase in the probability of occurrence (Gill & Malamud, 2017 ; He & Weng, 2020), . Furthermore, several examples of interactions between hazards are explained, such as earthquakes as primary disasters that can trigger secondary disasters in the form of erosion or erosion and flooding which have a tendency to trigger and strengthen each other. Based on Table 5, we can see that there are several hazard factors including local landscape conditions in Gunungkidul Regency.

Table 5. The Interrelation of Multi-hazard Factors in Gunungkidul Regency.

Hazard	**Driven Factor**
Seismic	1.Areas of meeting plates or faults (Structural geomorphology of the Baturagung Fault) 2.Plate movement
Landslide	1.Mountain or hilly areas (Structural geomorphology of the Baturagung fault) 2.High rainfall 3.Earthquake 4.Flood 5.Development and human activities in hilly areas
Flood	1.High rainfall 2.Soil with low infiltration 3.Infrastructure development and human activities around the river
Drought	1.Low average annual precipitation 2.High average temperature 3.Numerous underground rivers (Geomorphology of Gunung Sewu Karst)

Source: Liu *et al.*, (2016)

Another type of interaction between hazards is the domino effect, also known as the cascading effect. This interaction explains how a disaster can trigger further disasters or other disasters. Based on the results of the multi-hazard mapping, we can say that several areas have either very high levels or high levels of hazard, especially in the northern region of Gunungkidul Regency. Referring to the northern region, especially in the geomorphological area of the Nglanggeran fault hills, we can see how seismic and landslide hazards are found with very high and high classifications. In line with Table 5, we can conclude that seismic waves can trigger landslides. This makes the area potentially prone to a hazard domino effect, that is the relationship between earthquakes and landslides is one of triggering. Good disaster mitigation, specifically measures controlling human activities in some hilly areas which tend to exacerbate hazard-triggering factors, is needed to minimize losses from hazards.

One of the recent huge disaster events in Indonesia that caused cascading effects was the earthquake that occurred on September 28, 2018, with a magnitude of Mw 7.4, in Palu, Central Sulawesi (Mason *et al.*, 2021; Triyanti *et al.*, 2022). The earthquake has triggered cascading secondary hazards (tsunami, liquefaction, and landslides) and tertiary hazards (flash floods in several areas in the Sigi Regency). Gunungkidul Regency has also experienced cascading hazards. An example of such cascading effects in this area is the 2017 Cempaka hurricane. According to Gunungkidul Bappeda (2020), the Cempaka storm was one of the triggers for the worst flooding in Gunungkidul, which also damaged several forms of infrastructure due to its triggering of landslides. The Cempaka storm acted as a primary hazard that increased the probability of secondary hazard events as a form of cascading.

Referring to the multi-hazard map (Figure 4), we can see how some areas, especially Nglipar and Semin districts, have a high risk of flooding and landslides. The results of the analysis explain that the area has the potential for cascading effects in particular due to meteorological tiggering factors for floods – landslides. However, the cascading effect analysis is quite difficult to analyze, considering that there are differences in the pattern and magnitude of disasters and vulnerabilities in any given area (Van Westen & Greiving, 2017 ; Qie & Rong, 2022). This also explains why some areas which are classified as low multi-hazard can experience disasters because they have vulnerabilities and are hit by disasters on a large scale. Furthermore, Van Westen & Greiving's explanation can also mean that a disaster in an area that has several types of hazards does not always cause a cascading effect.

4. Conclusion

Gunungkidul has a variety of landscapes, including the Baturagung Fault Hills in the north, the Wonosari Karst Basin in the middle, and the Gunungsewu Karst Hills in the south. This variation raises the threat of several hazards such as floods, landslides, earthquakes, and droughts that may interact with each other and have the potential to cause extreme events called disasters. All areas in Gunungkidul Regency have the potential to be exposed to multi-hazards. The distribution of multi-hazard levels varies depending on the characteristics of the conditioning factors for each disaster. Although most areas of Gunungkidul Regency have low multi-hazard levels (568.51 km^2 or 39.35% of the total area), the interactions between hazards cannot be ignored. The interaction between hazards can trigger other disasters called cascading effects. The cascading effects in the study area have the most potential to occur in the north of Gunungkidul Regency with a very high seismic and landslide hazard due to the geological and geomorphological conditions of the Baturagung Structural Hills. It is important to study the interactions between these hazards because the interaction of more than one hazard can result in extreme events called disasters. Further research in Gunungkidul Regency is needed to plan disaster mitigation methods based on existing multi-hazard analysis and further multi-hazard analysis has the potential to increase capacity and create resilience to disasters.

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