GEOMATICS AND ENVIRONMENTAL ENGINEERING • Volume 20 • Number 1 • 2026

https://doi.org/10.7494/geom.2026.20.1.23

Assessing Urban Growth Toward Earthquake-Hazard Zone in Yogyakarta and Bantul, Indonesia

Nur Miladan[1]*, Tendra Istanabi[2], Lintang Suminar[1], Muhammad Rizal Fernandita Pamungkas[3], Vicky Dwi Settyawan[2], Arifian Dwi Wijayanto[2]

[1] Universitas Sebelas Maret, Faculty of Engineering, Urban and Regional Planning Program, Center for Regional Information and Development, Surakarta, Indonesia

[2] Universitas Sebelas Maret, Faculty of Engineering, Urban and Regional Planning Program, Surakarta, Indonesia

[3] Universitas Tunas Pembangunan, Smart City Information System Program, Surakarta, Indonesia

* Corresponding author

Abstract: Bantul and Yogyakarta are regions with earthquake-hazard risks in Indonesia. The earthquake that occurred in 2006 produced deaths, high economic losses, and significant damages to the housing and infrastructure. This research aimed to assess the urban growth in the earthquake-hazard zone in Bantul and Yogyakarta. The study used the remote sensing method of nighttime light (NTL), zonal statistics, and ClockBoard zone analysis. The combination of these analysis techniques for linking urban growth and earthquake hazards has not been widely discussed by previous studies. The earthquake-hazard data was retrieved from the United States Geological Survey website; meanwhile, the NTL data was based on the Visible Infrared Imaging Radiometer Suite (VIIRS) satellite. The results indicated that those zone segments at very high earthquake-hazard levels were also areas with night-light intensities of more than ten units (meaning increasing urban growth). Based on these facts, local governments should evaluate spatial planning to limit the density of built-up areas in earthquake-hazard areas and ensure the effective implementation of urban sustainability and resilience.

Keywords: earthquake hazard, urban growth, nighttime light, zonal statistics, ClockBoard analysis, Bantul, Yogyakarta

Received: November 1, 2024; accepted: October 1, 2025

E-mails & ORCID iDs: nurmiladan@ft.uns.ac.id, https://orcid.org/0000-0002-8372-7162 (N.M.); istanabi@staff.uns.ac.id, https://orcid.org/0000-0002-0089-9146 (T.I.); lintangsuminar@staff.uns.ac.id, https://orcid.org/0000-0002-1587-7417 (L.S.); m.rizal@lecture.utp.ac.id, https://orcid.org/0009-0002-7051-3701 (M.R.F.P); vickydwisettyawan@gmail.com, https://orcid.org/0009-0004-5404-8365 (V.D.S.); rifiandwiwijaya@gmail.com, https://orcid.org/0009-0009-6813-018X (A.D.W.).

1. Introduction

An earthquake is one of the most significant urban disasters; it can produce many impacts in a city or region, including physical, social and economic aspects [1–3]. The occurrences of earthquakes are often not predicted; however, mitigation efforts for earthquake risk should remain implemented. One of the mitigation efforts that should be implemented is to assess the existence of earthquake-hazard risk toward the spatial and land-use patterns that are related to urban (built-up area) growth and expansion. Settlements and built-up regions that develop without reference to earthquake risks can increase the risks of material damages and casualties when earthquakes occur [4–6]. Identifying the high risk of being affected by earthquakes can be used as a reference in spatial planning. A comprehensive understanding of earthquake risk in urban and regional planning is fundamental for ensuring urban and regional sustainability [7–12]. An understanding of earthquake risk in spatial planning could be done through analyses to assess the relationship between the earthquake-hazard levels and urban growth/expansion. Spatial planning that considers earthquake risks becomes essential for disaster-risk reduction. The negative impacts of deaths and material and immaterial losses can be minimized in an earthquake because of proper land-use planning and management.

Generally, the evaluations of the impact of earthquakes in a city or region have been predominantly based on comparisons between earthquake hazards and urban growth and existing land uses; these have been analyzed by satellite imagery [13–16]. Nowadays, urban development can be identified by the technology of nighttime light data [17–20]. Nighttime light data can produce an understanding of human well-being and urban activities and monitor disasters in more detail than other satellite imagery can [21, 22]. Understanding nighttime light data can identify the direction and the centers of urban growth in a city or region.

In the context of earthquake-disaster risk, the utilization of nighttime light data can be compared to the existence of an earthquake hazard to support the proper spatial planning. Recent studies have demonstrated the relationship between earthquake hazards and the utilization of nighttime light data [23–28]. Our research seeks to support the comprehension of nighttime light data for directing spatial planning, thus accommodating the mitigation efforts for earthquake-risk impacts in Indonesia. Furthermore, our research developed a particular analysis method that combined the utilization of the remote-sensing method of nighttime light and the zonal statistics method (which was ClockBoard zone analysis). In general, zonal statistics were used to analyze the zoning and landscape system in a city or region [29, 30]. In our research, the zonal statistics were focused on the earthquake-hazard-impacted areas.

Indonesia is an archipelagic country that is situated at the meeting place of active tectonic plates (including the Eurasian Plate, the Indo-Australian Plate, and the Pacific Plate) as well as being in the Ring of Fire in the volcano line; this results in a high risk of earthquake disasters [31–35]. The natural movements of the tectonic plates cause sudden shifts in the rock layers in the Earth's crust, which cause earthquakes in the region of Indonesia. Based on Indonesian Disaster Information Data (DIBI), earthquakes occurred at 18 location points in 2023; of these, 8 locations were located on the Island of Java. One of the largest earthquakes ever in Indonesia was the earthquake in 2006 on Java Island; this had a significant impact on Daerah Istimewa Yogyakarta (DIY)/Special Region of Yogyakarta Province. After this occurrence, the municipalities and the national government (including the central and provincial governments) carried out various disaster-recovery efforts through the reconstructions of settlements and regional infrastructures. Furthermore, a resettlement process occurred [36, 37], and urban growth and expansion also occurred until recently.

By synthesizing the challenges that were discussed above, our research examined the urban growth in DIY Province toward earthquake-hazard risks. This research was conducted to ensure that the development paid attention to disaster-risk-mitigation measures.

2. Study Area

DIY Province is one of the provinces of Java; it is located in the southern part of the island. It includes one city (namely, Yogyakarta) and four regencies (Sleman, Gunung Kidul, Bantul, and Kulon Progo). Chosen as case studies, Yogyakarta and Bantul have rapidly grown the built-up areas; on the other hand, these regions are at high risk of earthquake-hazard areas. Bantul Regency and Yogyakarta City were the most-impacted areas by the earthquake in 2006.

Yogyakarta City is the capital of DIY Province; it had 375,699 inhabitants in 2023, and its total area was about 3,282 hectares [38]. The average density of the population was about 11,447 people per hectare. Nevertheless, the average population growth rate of Yogyakarta City was 0.38 per cent each year from 2010 through 2020 [39]. While Bantul is a regency in DIY Province (with 1,013,170 inhabitants in 2022), its total area was about 50,685 ha [40]. The average density of the population was about 1998 people per hectare. In comparison, the average population growth rate of Bantul Regency was 0.76 per cent each year from 2010 through 2020. Based on a 2022 report of disaster-risk assessment in Yogyakarta, it is known that 57.5% of the Yogyakarta area is an impacted area of earthquake-hazard risk [41].

The earthquake occurred on May 27, 2006, with a magnitude of 6.3–6.4 on the Richter scale (Mw); it caused death and damage to various infrastructures and settlements. According to the Bantul Disaster Management Agency, this earthquake lasted 57 seconds and had aftershocks that were 750-fold, resulting in 6,234 fatalities and 36,299 severe and minor injuries; housing damages reached more than 616,458 units, and 1.5 million people lost their residences [42, 43]. The earthquake risk was caused by the movement of the Opak Fault [44]. The earthquake's epicenter in 2006 was located about 5–10 km from the Opak Fault [45] (see Fig. 1).

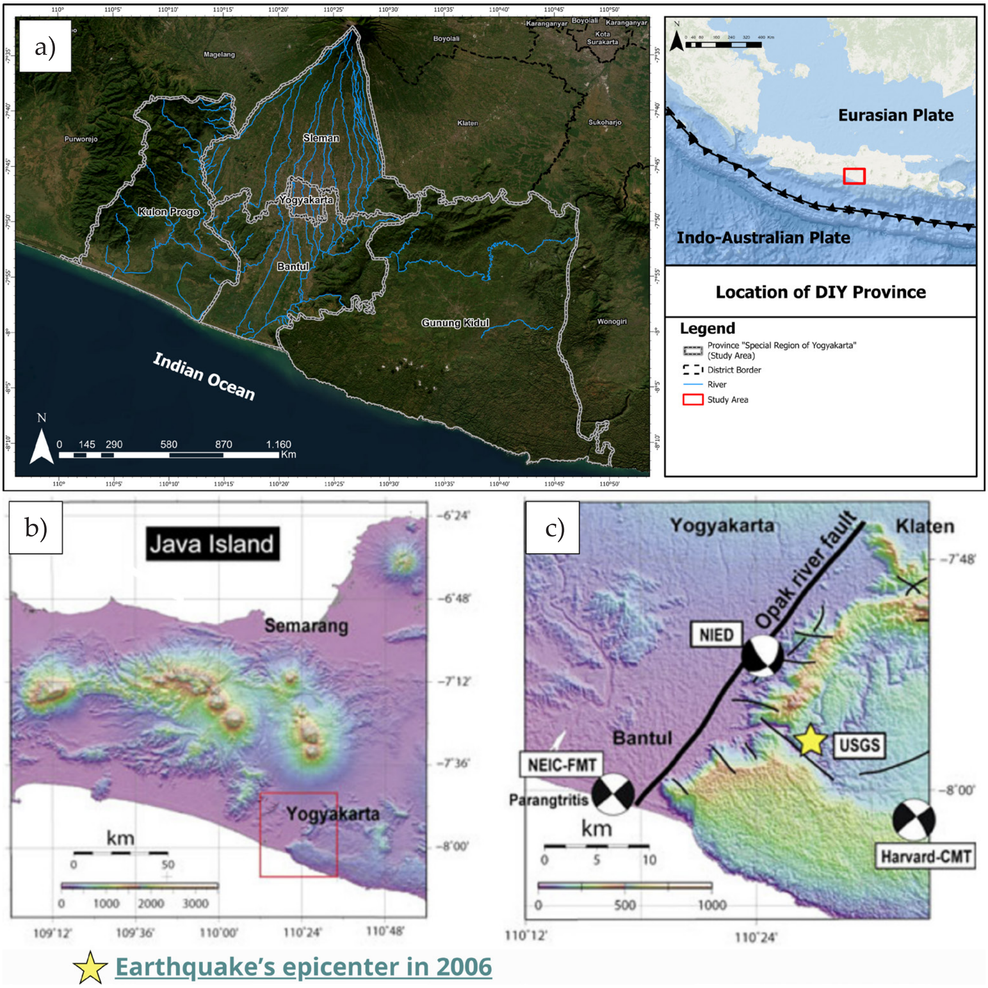

Fig. 1. Location of DIY Province, Opak Fault, and earthquake's epicenter in 2006: a) position of the study area in a regional and tectonic context; b) map of Java Island with the study area indicated (red rectangle); c) enlargement of the area marked in panel b

Source: modification from [46] and [47]

3. Materials and Methods

The data and information of this research was mainly secondary data from eligible institutions. The earthquake-hazard data was obtained from the United States Geological Survey (USGS) (https://www.usgs.gov/). This data covered the Yogyakarta and Bantul areas that were impacted by the earthquake in 2006. Meanwhile, spatial urban growth was identified by the remote-sensing method using nighttime light (NTL) data. Residential and built-up activities can be identified by looking at lighting at night [48]. This method uses a satellite's artificial lighting data at night to measure the intensity of human activity and urbanization. The use of nighttime lights has a higher level of accuracy than other traditional remote-sensing methods regarding urbanization dynamics [49].

To analyze the city's growth, the nighttime light data can be analyzed using map-overlay techniques with other data that was related to the research (in this case, earthquake-hazard risk). The nighttime light data that was used in this research was from the Visible Infrared Imaging Radiometer Suite (VIIRS). This is a remote-sensing instrument on the Suomi National Polar-orbiting Partnership (S-NPP) satellite that was launched by Vandenberg Air Force Base, California, in 2011; its data produces high-quality images and is collected by the National Aeronautics and Space Administration/ National Oceanic and Atmospheric Administration NASA/NOAA [50–53]. VIIRS data is divided into sensor data records (SDRs), which includes temperature data and nocturnal visible and near-infrared light data, and environmental data records (EDRs), such as land and ocean surface properties to cloud and aerosol properties [54–58]. The VIIRS data that was used in this research was retrieved from light pollution map (https://www.lightpollutionmap.info/); nighttime images were captured from the Visible Infrared Imaging Radiometer Suite (VIIRS) satellite. Artificial lights raise night sky luminance, creating the most visible effect of light pollution; they also provide data on climate change, environmental monitoring, and energy on a global scale [59–61]. This research used VIIRS data from 2013 through 2023. The initial year of the data was based on the first data that was provided by NOAA. During the last decade, the research has analyzed and compared the land-use changed in earthquake-hazard-risk areas.

The research used the quantitative method. The spatial analysis of the geographic information system (GIS) was used to analyze the information concerning the nighttime light data and the urban growth in the impacted earthquake risk areas. Quantum GIS (QGIS) was used to support the spatial analysis; this is a simple GIS process that can be used to visualize spatial patterns of importance to a variety of fields (including natural resources, agriculture, and urban planning) as well as information and communication technologies (ICTs) [62, 63]. One of the main features of QGIS is zonal statistics, which played an essential role in evaluating the light-pollution data in the research area [64, 65]. This feature helps to calculate specific statistics for a defined zone based on raster data, which is the light-pollution data. The nighttime light data was analyzed using the ClockBoard analysis technique and overlaid into the urban growth to determine the evaluation of nighttime light describing the urban development toward the impacted area of earthquake risk identified by the occurrence of an earthquake with a high impact level in 2006. ClockBoard analysis is a tool for zoning systems to assess a city or a region based on the building blocks for mono-centric and clockwise patterns [66, 67]. This research was supported by the website of ClockBoard Zone Generator (https://zonebuilders.github.io/zonebuilder-rust/) to determine the form of concentric zones used for zonal statistics in QGIS as well as the area typologies of earthquake-hazard risk and nighttime light.

4. Results

4.1. Earthquake Hazard in Yogyakarta and Bantul

The earthquake in Yogyakarta and Bantul in 2006 was caused by the movement of the Opak Fault (located in the eastern part of Bantul Regency). This situation makes the eastern part of Bantul more hazardous than the western part of Bantul. In the area of the Opak Fault, a severe level of hazard occurs. Most of the eastern region has an extreme earthquake-hazard level. In comparison, most of the western areas have strong earthquake-hazard levels (the further away from the Opak Fault, the safer). Some western Bantul regions have a moderate earthquake-hazard levels.

Yogyakarta, which borders the northern part of Bantul, has an extreme earthquake-hazard level in its southeastern part. Meanwhile, most of the western and northern parts of Yogyakarta have substantial earthquake-hazard levels. The levels of the earthquake hazards in Yogyakarta and Bantul are shown in Figure 2.

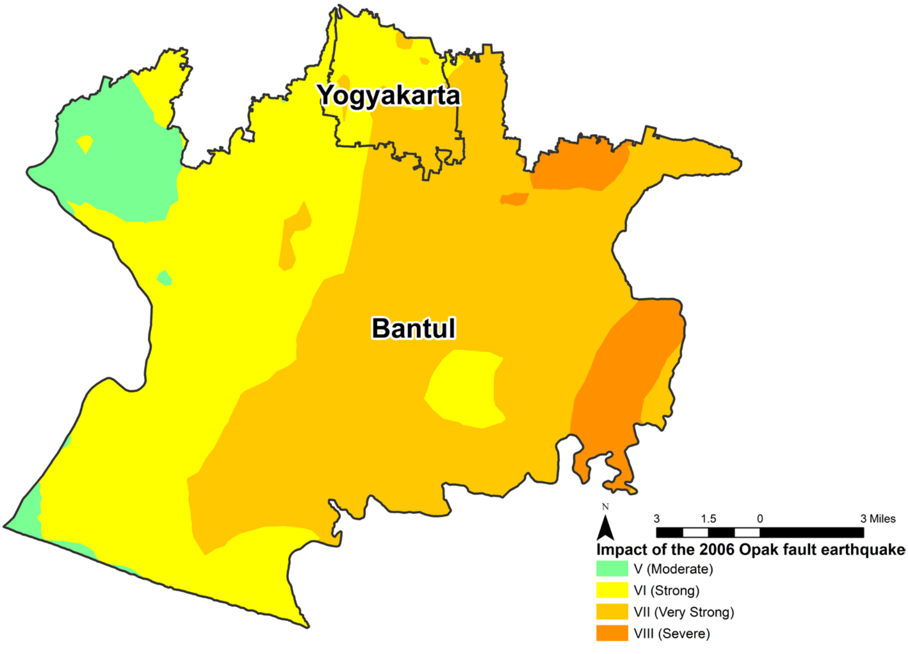

Fig. 2. Map of impacts of 2006 Opak Fault earthquake in Yogyakarta and Bantul Regency
Source: Data from USGS elaborated by authors, 2024

Based on the earthquake-impact map that is shown in Figure 2, the eastern part of Bantul was the most-impacted area compared to the surrounding areas. More than half of the Bantul area is included in those areas with high to very high hazards – especially in the eastern part that is situated on the Opak Fault. A more detailed picture can be seen in the overlay of the ClockBoard map and its hazards (as follows).

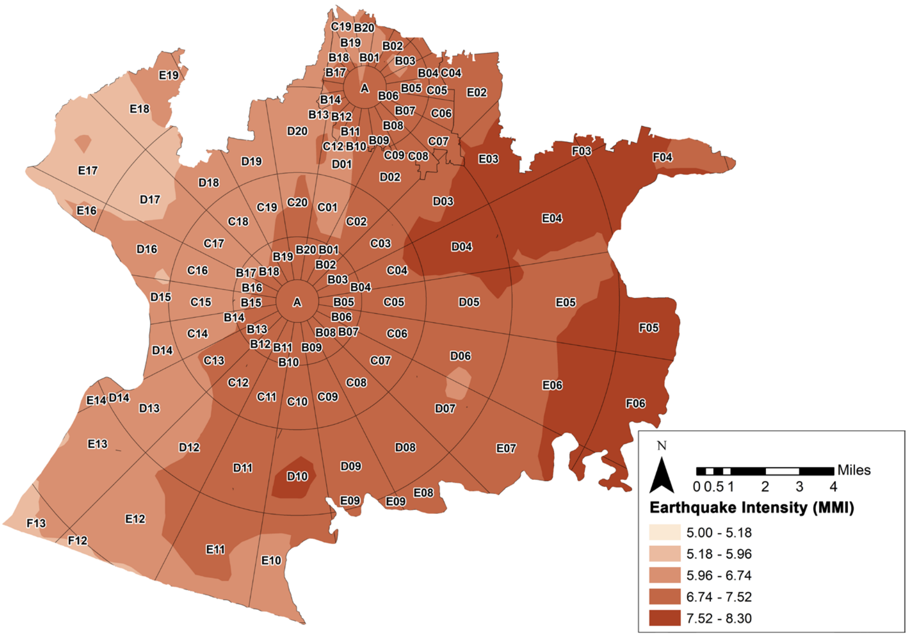

Fig. 3. Earthquake-hazard overlay map and ClockBoard zone in Yogyakarta and Bantul

With the overlay of the earthquake-hazard and ClockBoard zones shown above (Fig. 3), Table 1 can be prepared to indicate which areas or segments have specific earthquake-hazard levels. This analysis was implemented in the Bantul and Yogyakarta cases.

Table 1. Distribution of earthquake-prone areas in each zone segment in Yogyakarta City and Bantul Regency

Municipality	Hazard Level		
	Medium	High	Very High
Yogyakarta	B01, B18, B19, B20	A, B02–B17, C1–C9, C20	–
Bantul	C01, C14, C15, C16, C17, C18, C19, D01, D13, D14, D15, D16, D18, D19, D20, E12, E13	A, B01-B20, C02–C13, D02, D03, D05-D11, E02, E05, E07, E08, E09, E11	D04, E03, E04, E06, F04, F05, F06

4.2. Nighttime Light in Yogyakarta and Bantul

Nighttime light data were used in the advanced stage of the distribution of earthquake-prone areas in Yogyakarta and Bantul. This was carried out to analyze the development trend or growth of the built-up areas using nighttime light (NTL) data.

Based on Figure 4, Yogyakarta had the highest light intensities from 2013 to 2023; this was because it is the provincial capital and the center of regional activities. The surrounding areas tended to develop following the main roads connecting the municipalities. This data was then further processed using a Zonal Statistics analysis to find the average value of each ClockBoard zone segment through the QGIS application for each area to describe the growth of the built-up land per segment.

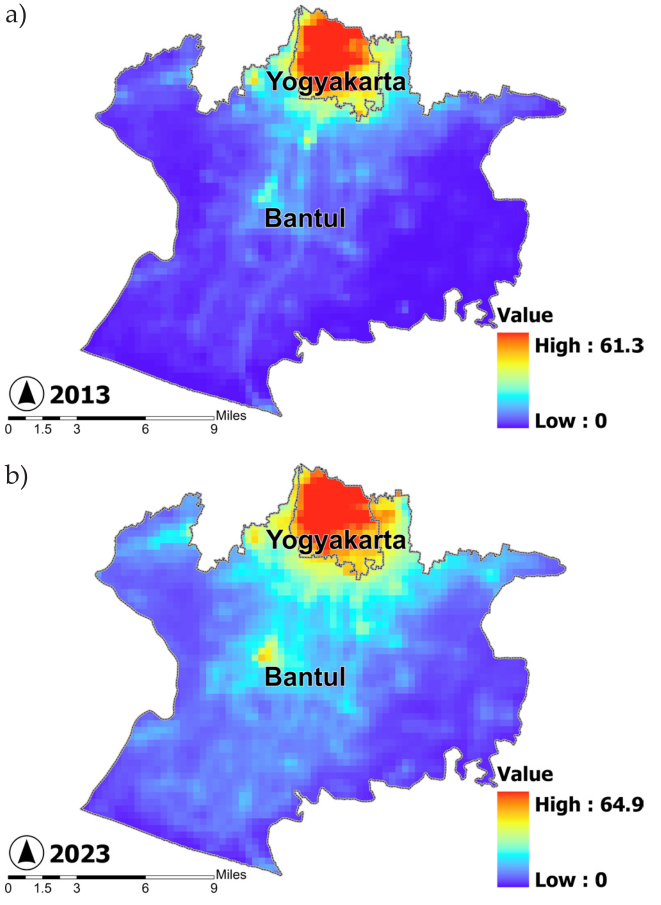

Fig. 4. Maps of nighttime light levels of Yogyakarta and Bantul in 2013 (a) and 2023 (b)

Based on Figure 5, which described the zonal statistics for nighttime light in Yogyakarta and Bantul, it is known that Yogyakarta tended to have a high night light intensity of more than 15 in 2013. For ten years, most of the zones that experienced an increase were Zone B (around the city center) and a small part of the suburbs. Only 6 out of the 20 zone segments in Zone B still have light intensities at 15–23 levels. Meanwhile, Bantul's nighttime light data indicated the average light intensity values in each ClockBoard zone segment.

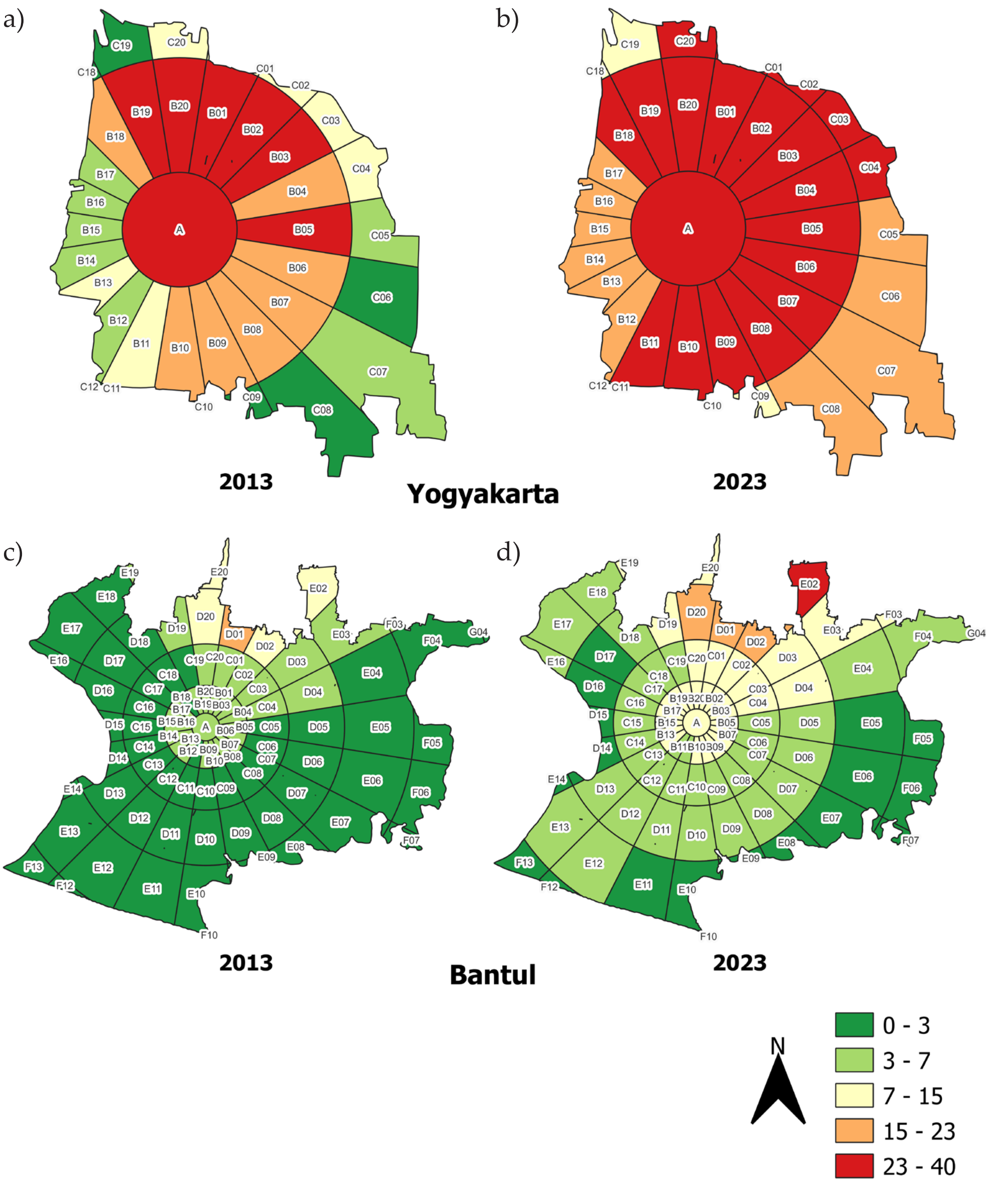

Fig. 5. Zonal statistics nighttime light levels in Yogyakarta and Bantul in 2013 (a, c) and 2023 (b, d)

4.3. Urban Growth Toward Earthquake-Prone Zones

By overlaying earthquake hazards and nighttime light intensity, the growth of Yogyakarta can be detailed in each zone segment through Table 2.

Table 2. Average night light intensity of each zone segment of Yogyakarta City

Segment	2013	2023	Segment	2013	2023
A	35.04	44.89	B18	19.38	27.60
B01	33.45	45.30	B19	24.35	32.88
B02	31.68	45.50	B20	33.63	43.60
B03	24.57	34.69	C01	17.87	30.27
B04	21.83	30.42	C02	18.02	28.87
B05	24.26	33.64	C03	18.54	28.67
B06	18.83	27.22	C04	16.30	25.94
B07	21.28	27.76	C05	11.74	21.61
B08	19.92	25.92	C06	11.33	20.41
B09	21.43	28.70	C07	13.09	20.40
B10	20.17	26.65	C08	10.62	18.32
B11	17.83	23.80	C09	7.12	14.52
B12	14.53	21.25	C10	8.38	13.99
B13	15.40	21.96	C11	7.97	12.89
B14	13.55	20.85	C12	6.07	11.19
B15	14.37	21.35	C18	8.78	14.70
B16	12.38	19.52	C19	7.71	13.57
B17	14.40	22.14	C20	15.13	24.13

Based on the Table 2, the following findings regarding the relationship to the earthquake-hazard level in Yogyakarta City were obtained:

– In those areas with moderate earthquake vulnerabilities (B1, B18, B19, and B20), all of the zone segments experienced high increases in night light intensity (greater than 5 units); even in the B1 segment, the increase reached 11.85. This segment is located in the northern part of the city center (Zone A).
– All of the segments in areas with high earthquake vulnerabilities experienced high increases (greater than 5 units); there were even five zone segments with more than ten (namely, Segments B2, B3, C1, C2, and C3). Due to the increasing trends in several of the zone segments, policies should be prioritized to prevent and overcome earthquake disasters (such as establishing policies regarding the density and limits on the number of building floors).

From 2013 to 2023, most of the areas of Bantul experienced increases in their intensities of night light. The northern part bordering Yogyakarta experienced the highest intensity increase, as it is a buffer area with the dominant use of residential land and service trade following Bantul's spatial planning. The western and south-eastern parts also experienced increases in night light intensity (although not as high as in the north); this was due to their designation as agricultural lands and plantations. Meanwhile, the eastern part did not observe an increase in light intensity, as it is the location of the Opak Fault and is designated as a cultural heritage and tourism area; so, land use transfer activities have been limited. Table 3 presents a detailed comparison of the average intensity of each segment in 2013 and 2023.

Table 3. Average night light intensity of each zone segment of Bantul Regency

Segment	2013	2023	Segment	2013	2023
A	5.91	14.26	B18	2.98	8.08
B01	3.84	9.19	B19	4.40	10.12
B02	3.98	8.72	B20	3.96	10.97
B03	4.82	9.53	C01	6.07	10.27
B04	3.52	8.15	C02	4.91	9.25
B05	3.40	8.43	C03	3.34	8.69
B06	3.46	8.58	C04	3.26	7.27
B07	4.37	8.96	C05	2.50	6.62
B08	4.64	8.54	C06	2.35	6.68
B09	3.23	7.03	C07	2.73	6.54
B10	3.10	7.06	C08	1.93	5.25
B11	2.65	6.27	C09	2.18	5.17
B12	3.13	6.53	C10	2.02	4.78
B13	4.22	8.76	C11	1.92	4.61
B14	4.07	8.94	C12	2.16	4.73
B15	3.50	8.39	C13	1.95	5.07
B16	4.40	10.48	C14	1.81	5.79
B17	3.96	10.46	C15	1.44	4.48

Table 3 cont.

Segment	2013	2023	Segment	2013	2023
C16	1.61	4.09	E03	5.00	10.87
C17	1.59	4.26	E04	1.57	4.48
C18	1.73	4.88	E05	0.79	2.52
C19	2.76	6.25	E06	0.55	1.84
C20	4.68	8.98	E07	0.46	1.51
D01	16.10	22.36	E08	0.11	1.17
D02	11.97	19.29	E09	0.29	1.18
D03	5.27	12.04	E10	0.92	2.22
D04	3.00	8.01	E11	0.95	2.80
D05	1.58	4.77	E12	1.03	3.07
D06	1.02	3.46	E13	1.25	3.04
D07	1.23	3.64	E14	1.12	2.51
D08	1.20	3.86	E16	1.38	3.54
D09	1.07	3.54	E17	1.90	4.08
D10	1.51	4.43	E18	2.34	5.44
D11	1.91	4.56	E19	3.74	7.59
D12	1.57	3.74	E20	8.47	14.54
D13	1.65	4.02	F03	3.30	7.24
D14	1.09	2.56	F04	1.56	3.92
D15	0.94	2.42	F05	0.54	1.46
D16	0.97	2.48	F06	0.44	1.51
D17	1.13	2.59	F07	0.11	0.75
D18	2.00	4.99	F10	0.08	0.41
D19	4.53	9.18	F12	0.01	0.12
D20	8.37	15.00	F13	0.24	0.66
E02	14.28	23.07	G04	0.95	2.08

Table 3 was made in such a way that it could be used to compare the average growth of night light intensity against the level of hazard in each segment. Based on the above table, the following observation results were obtained:

– In those areas with moderate earthquake hazard levels in Bantul, several segments experienced an increase in high night light intensity (greater than 5 units) compared to those segments with the same hazard level (namely, the D1 and D20 segments, which increased by 6.26 and 6.63, respectively). These locations were in the northern part of a dense urban residential area.
– In those areas with high hazard levels, the segments with increased intensity of high night light (greater than 5 units) were more numerous than in those regions with medium vulnerabilities (namely, as many as 12 segments with details of segments A, B1, B5, B6, B16, B17, B18, B19, B20, C3, D3, and E2). Most of the segments that experienced this increase were in the center of Bantul and its surroundings. This needs to be considered and acted upon further, such as providing regulations regarding building densities and the numbers of building floors in order to minimize the losses that will be incurred in the event of an earthquake disaster in the future.
– In those areas with very high earthquake hazard levels, two segments experienced increases in high night light intensity (greater than 5 units); namely, Segments D4 and E3. Responding to this, the local government must take firm action to divert the existing built-up land in the area. These two segments are in the northern part of Bantul Regency (bordering Yogyakarta and Sleman).

5. Discussion

5.1. Role of Zonal Statistics in Earthquake-Hazard-Level Identification

The zonal statistics with the ClockBoard system can play a role in describing the structural characteristics of earthquake-hazard zonation; it can explain the earthquake-hazard levels in impacted areas in detail. In the cases of Yogyakarta and Bantul, it can identify those areas with medium, high, and very high levels of earthquake hazard. Furthermore, it can help describe the spatial configurations of earthquake-hazard levels (which is essential for assessing mitigation efforts) – particularly through spatial planning. From this case, it is known that the urban centers of Yogyakarta and Bantul are situated in high earthquake-hazard levels. Meanwhile, a very high earthquake-hazard level occurs around the Opak Fault, which is located in the hinterland area. This situation indicates that the spatial planning in both municipalities needs to pay attention to earthquake hazards. The urban development and extension are expected to avoid those areas with a high levels of earthquake hazard [68–70].

The spatial analysis that was supported by the zonal statistics in this research demonstrated that structural and non-structural mitigation efforts could be done based on the zonation of earthquake-hazard levels. However, the assessment of earthquake hazards based on zonal statistics has a limitation: it is based on only one center point (urban center) of the zonal statistics analysis. It is probable that in a city has several center points. Based on this constraint, the results of zonal statistics for earthquake-hazard levels should be combined with another spatial analysis such as kernel-density estimation [71, 72].

5.2. Utilization of Nighttime Light Data in Urban Growth Analysis

Nighttime light data is a valuable tool for analyzing urban growth. Our research revealed that utilizing nighttime light data could describe the changes in the urban development in the case study areas. The intensity of the light could clarify the urban centers in the research area. In addition, it could show the changes in the degrees of urbanization. So far, this advantage has not been utilized by any other satellite imagery. By tracking changes in nighttime lighting over one decade in our research, it was known that the increase in urbanization degree generally occurred in our study area. The nighttime light data also showed that the extension of the urban regions tended to take place in the surrounding areas of the urban centers. The surrounding area of the fault, which was the source of the earthquake occurrence, tended to grow slowly. Our research also demonstrated that bright light in the nighttime light data was correlated with the existence of urban centers (such as commercial zones). The case study showed that Yogyakarta (as the capital of DIY Province) experienced an increase in its degree of urbanization. Our research also indicated that nighttime light data was a valuable tool for predicting urban growth and could be used for spatial planning. Nevertheless, our research proved that the existing nighttime light data could only be used for large-scale applications (such as regions) [73, 74]. This constraint was due to the resolution of nighttime light data not being used for small scales of space (such as a city or town). The utilization of nighttime light data should be combined with other satellite data imagery to produce more-detailed results of spatial analysis.

5.3. Linking Urban Growth, Earthquake-Hazard Level, and Spatial Planning

The comparison between the earthquake-hazard level and the urban growth through the zoning system showed that the urban development in Yogyakarta and Bantul occurred in high earthquake-hazard areas during the last decade. The urban growth occurred the most in the severe earthquake-hazard areas, thus increasing the earthquake risks. Indeed, urban development was linked to the increased densities in built-up regions [75–79]. This situation indicated that the spatial planning and management did not align with earthquake-risk reductions. Recently, efforts in earthquake-risk management have been approached by emergency response preparedness and the development of resistant buildings in several settlement locations as well as urban and public facilities (such as hospitals and universities) with high earthquake-hazard levels [80–82]. Therefore, spatial planning and management is essential considering the earthquake-hazard levels in the reviews of Bantul's and Yogyakarta's spatial planning. As the high and significant subduction process of the earthquake in the western and southern parts of Indonesia [83–87], the issue of megathrust should be considered in spatial planning and management.

Spatial-planning strategies for earthquake-risk reduction are to minimize the high density of built-up areas in the high regions that are impacted by earthquake-hazard risks. These areas should be planned as conservation spaces, such as green areas, parks, and forests. Furthermore, the development of built-up areas such as residential areas, commercial areas, and public spaces should be supported by buildings that are resistant from earthquakes and the implementations of building codes that accommodate the earthquake risks in the moderate regions that are impacted by earthquake-hazard risks. However, the existing buildings in the settlements and public spaces should be led to develop resistant buildings when renovating buildings. Highly built-up areas should be created in the low-impacted regions of earthquake-hazard risk. Urban expansion led to these regions.

An earthquake-hazard-risk map should be well-informed in Bantul and Yogyakarta. The communities should know the existence of earthquake hazards – particularly the people who live around the high-impact regions of earthquake hazards. The community awareness of earthquake risk should be increased through the collaboration of urban stakeholders in Bantul and Yogyakarta. Furthermore, assessing early warning systems, routes, and evacuation facilities is essential for reducing the impacts of earthquake occurrences (which are sometimes unpredictable). These mitigation strategies should be integrated into the spatial planning of Yogyakarta and Bantul.

6. Conclusions

Mapping earthquake-risk areas and controlling the growth of built-up land are steps to mitigate the risks of earthquake disasters. The identification of earthquake-hazard levels that is supported by zonal statistics and ClockBoard analysis could make a zonation of earthquake-hazard level in detail. The growth trend of the built-up area can be determined using the nighttime light (NTL) remote-sensing method, zonal statistics, and ClockBoard zone analysis. Nevertheless, limitations of the analysis occurred due to the zonal statistics that only used one center point (urban center area); in reality, it is possible that there are several urban center areas to consider. Furthermore, nighttime light data only covers a large scale of space (such as a region), so there is a limitation of the analysis in the small scales of space (such as a city or town).

However, our research revealed that Yogyakarta and Bantul (zone segments at very high levels of disaster hazard) experienced increases in night light intensity of more than ten units. The local government needs to develop a policy regarding limiting the density and growth of the built-up areas in the impacted area of each earthquake hazard (particularly the high and very high levels) as well as to provide the assessment and implementation of an early warning system, evacuation routes, and facilities for anticipating earthquake occurrences. Spatial planning that accommodates the earthquake-hazard level is needed to ensure sustainable and resilient urban growth and expansion. Spatial planning should be included in the policy-formulation process to prevent the development of land being built in inappropriate locations and minimize losses caused by earthquake disasters in the future. Community awareness concerning earthquake-hazard areas in Bantul and Yogyakarta must also improve to create comprehensive mitigation efforts for earthquake and megathrust risks.

Funding

This research was funded through the Non-State Budget of Universitas Sebelas Maret No. 194.2/UN27.22/PT.01.03/2024.

CRediT Author Contribution

N. M.: conceptualization, funding acquisition, methodology, project administration, supervision, validation, writing – original draft, writing – review & editing.
T. I.: data curation, investigation.
L. S.: formal analysis, project administration.
M. R. F. P.: software, visualization.
V. D. S.: formal analysis, resources, visualization.
A. D. W.: software, visualization.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

This research uses the public data include:
- Earthquake-hazard data available at https://www.usgs.gov/.
- VIIRS data available at https://www.lightpollutionmap.info/; https://viirsland.gsfc.nasa.gov/Products/NASA/BlackMarble.html.
- Yogyakarta Municipality in Figures 2024 available at https://jogjakota.bps.go.id/en/publication/2024/02/28/6a6d984e3d10d2113c9d3f3b/yogyakarta-municipality-in-figures-2024.html.

- Population growth rate based on regency/city in 1971–2020 available at https://yogyakarta.bps.go.id/en/statistics-table/1/MTY4IzE=/growth-rate-of-population-by-regency-municipality--1971-2020--persen-year-.html.
- Bantul Regency in Figures 2023 available at https://bantulkab.bps.go.id/en/publication/2023/02/28/e90ab2b5613a5bd94f524fcb/kabupaten-bantul-dalam-angka-2023.html.
- Disaster risk assessment of Yogyakarta city for 2022–2026 available at https://bpbd.jogjakota.go.id/assets/instansi/bpbd/files/dokmen-kajian-risiko-bencana-kota-yogyakarta-2022-2026-13325.pdf.
- Grief from the land of Projotamansari: Archive of the victims of the 2006 earthquake in Bantul available at https://perpusda.bantulkab.go.id/pc/59323#pablo.
- Map of Indonesian earthquake hazard and source in 2017 available at https://luk.staff.ugm.ac.id/gempa/pdf/Pusgen2017PetaGempaIndonesia.pdf.

Use of Generative AI and AI-Assisted Technologies

No generative AI or AI-assisted technologies were employed in the preparation of this manuscript.

Acknowledgements

This work was supported by the Institute of Research and Community Service, Universitas Sebelas Maret.

References

[1] Erdik M.: *Urban earthquake risk*, [in:] *Geohazards*, ECI Symposium Series, 2006, ECI Digital Archives. https://dc.engconfintl.org/geohazards/17 [access: October 26, 2024].

[2] Giovinazzi S., Marchili C., Pietro A.D., Giordano L., Costanzo A., Porta L.L., Pollino M., Rosato V., Lückerath D., Milde K., Ullrich O.: *Assessing earthquake impacts and monitoring resilience of historic areas: Methods for GIS tools*. ISPRS International Journal of Geo-Information, vol. 10(7), 461. https://doi.org/10.3390/ijgi10070461 2021.

[3] Ao Y., Zhang H., Yang L., Wang Y., Martek I., Wang G.: *Impacts of earthquake knowledge and risk perception on earthquake preparedness of rural residents*. Natural Hazards, vol. 107, 2021, pp. 1287–1310. https://doi.org/10.1007/s11069-021-04632-w.

[4] Ehrlich D., Melchiorri M., Florczyk A.J., Pesaresi M., Kemper T., Corbane C., Freire S., Schiavina M., Siragusa A.: *Remote sensing derived built-up area and population density to quantify global exposure to five natural hazards over time*. Remote Sensing, vol. 10(9), 2018, 1378. https://doi.org/10.3390/rs10091378.

[5] Ehrlich D., Kemper T., Pesaresi M., Corbane C.: *Built-up area and population density: Two essential societal variables to address climate hazard impact*. Environmental Science & Policy, vol. 90, 2018, pp. 73–82. https://doi.org/10.1016/j.envsci.2018.10.001.

[6] Chen Y., Xie W., Xu X.: *Changes of population, built-up land, and cropland exposure to natural hazards in China from 1995 to 2015*. International Journal of Disaster Risk Science, vol. 10(4), 2019, pp. 557–572. https://doi.org/10.1007/s13753-019-00242-0.

[7] Bostenaru Dan M., Armaş I., Goretti A.: *Earthquake hazard impact and urban planning – an introduction*, [in:] Bostenaru Dan M., Armaş I., Goretti A. (eds.), *Earthquake Hazard Impact and Urban Planning*, Environmental Hazards, Springer, Dordrecht 2014, pp. 1–12. https://doi.org/10.1007/978-94-007-7981-5_1.

[8] Motamed H., Ghafory-Ashtiany M., Amini-Hosseini K., Mansouri B., Khazai B.: *Earthquake risk-sensitive model for urban land use planning*. Natural Hazards, vol. 103(1), 2020, pp. 87–102. https://doi.org/10.1007/s11069-020-03960-7.

[9] Kodag S., Mani S.K., Balamurugan G., Bera S.: *Earthquake and flood resilience through spatial planning in the complex urban system*. Progress in Disaster Science, vol. 14, 2022, pp. 100219. https://doi.org/10.1016/j.pdisas.2022.100219.

[10] Tudes S.: *Correlation between geology, earthquake and urban planning*, [in:] D'Amico S. (ed.), *Earthquake Research and Analysis: Statistical Studies, Observations and Planning*, InTech, Rijeka 2012, pp. 417–434.

[11] Mileu N., Queirós M.: *Integrating risk assessment into spatial planning: RiskOTe decision support system*. ISPRS International Journal of Geo-Information, vol. 7(5), 2018, 184. https://doi.org/10.3390/ijgi7050184.

[12] Barua U., Islam I., Ansary M.A.: *Integration of earthquake risk-sensitivity into landuse planning: An approach for a local level area at development phase*. International Journal of Disaster Risk Reduction, vol. 50, 2020, 101836. https://doi.org/10.1016/j.ijdrr.2020.101836.

[13] Xu S., Dimasaka J., Wald D.J., Noh H.Y.: *Seismic multi-hazard and impact estimation via causal inference from satellite imagery*. Nature Communications, vol. 13(1), 2022, 7793. https://doi.org/10.1038/s41467-022-35418-8.

[14] Li X., Bürgi P.M., Ma W., Noh H.Y., Wald D.J., Xu S.: *Disasternet: Causal Bayesian networks with normalizing flows for cascading hazards estimation from satellite imagery*, [in:] *KDD 23: Proceedings of the 29th ACM SIGKDD Conference on Knowledge Discovery and Data Mining*, Association for Computing Machinery, New York 2023, pp. 4391–4403. https://doi.org/10.1145/3580305.3599807.

[15] Xu S., Dimasaka J., Wald D.J., Noh H.Y.: *Bayesian updating of seismic ground failure estimates via causal graphical models and satellite imagery*. arXiv, 2022. https://doi.org/10.48550/arXiv.2204.07653.

[16] Williams J.G., Rosser N.J., Kincey M.E., Benjamin J., Oven K.J., Densmore A.L., Milledge D.G., Robinson T.R., Jordan C.A., Dijkstra T.A.:

Satellite-based emergency mapping using optical imagery: Experience and reflections from the 2015 Nepal earthquakes. Natural Hazards and Earth System Sciences, vol. 18(1), 2018, pp. 185–205. https://doi.org/10.5194/nhess-18-185-2018.

[17] Habibie M.I., Purwono N.: *Identification of socio-economic activities as urban growth based on nighttime light data (study on kendal district-indonesia)*, [in:] *2022 IEEE Asia-Pacific Conference on Geoscience, Electronics and Remote Sensing Technology (AGERS)*, IEEE, 2022, pp. 169–173. https://doi.org/10.1109/AGERS56232.2022.10093456.

[18] Jiang S., Wei G., Zhang Z., Wang Y., Xu M., Wang Q., Das P., Liu B.: *Detecting the dynamics of urban growth in Africa using DMSP/OLS nighttime light data*. Land, vol. 10(1), 2020, 13. https://doi.org/10.3390/land10010013.

[19] Yu T., Liu C., Li W., Huang W., Wu H., Fan Z.: *Characterizing urban actively populated area growth in the Yangtze River Delta using nighttime light data*. International Journal of Applied Earth Observation and Geoinformation, vol. 129, 2024, 103857. https://doi.org/10.1016/j.jag.2024.103857.

[20] Liu L., Wu W., Bai X., Shang W.: *Spatio-temporal evolution, internal diversity, and driving factors of economy of Guanzhong Plain urban agglomeration in Northwestern China based on nighttime light data*. Land, vol. 13(12), 2024, 2093. https://doi.org/10.3390/land13122093.

[21] Tian H., Liu Y., Tian Y., Jing Y., Liu S., Liu X., Zhang Y.: *Advances in the use of nighttime light data to monitor and assess coastal fisheries under the impacts of human activities and climate and environmental changes: A case study in the Beibu Gulf*. Marine Policy, vol. 144, 2022, 105227. https://doi.org/10.1016/j.marpol.2022.105227.

[22] Määttä I., Ferreira T., Leßmann C.: *Nighttime lights and wealth in very small areas*. Review of Regional Research, vol. 42(2), 2022, pp. 161–190. https://doi.org/10.1007/s10037-021-00159-6.

[23] Wang L., Li Z., Han J., Fan K., Chen Y., Wang J., Fu J.: *A cost-effective earthquake disaster assessment model for power systems based on nighttime light information*. Applied Sciences, vol. 14(6), 2024, 2325. https://doi.org/10.3390/app14062325.

[24] Pan Y., Jiang L., Wang J., Ma J., Bao S., Lin Y., Shi K.: *Mapping and evaluating spatiotemporal patterns of urban expansion in global earthquake-affected areas: A nighttime light remote sensing perspective*. International Journal of Digital Earth, vol. 17(1), 2024, 2419938. https://doi.org/10.1080/17538947.2024.2419938.

[25] Liu Z., Zhang J., Li X., Chen X.: *Long-term resilience curve analysis of Wenchuan earthquake-affected counties using DMSP-OLS nighttime light images*. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 14, 2021, pp. 10854–10874. https://doi.org/10.1109/JSTARS.2021.3121789.

[26] Li X., Liu Z., Chen X., Meng Q.: *Assessment of the impact of the 2010 Haiti earthquake on human activity based on DMSP/OLS time series nighttime light data*. Journal of Applied Remote Sensing, vol. 13(4), 2019, 044515. https://doi.org/10.1117/1.JRS.13.044515.

[27] Xiao Z., Pan Y., Jiang L., Wang Z., Shi K.: *Remote sensing nighttime lights reveal the post-earthquake losses and reconstruction situations in Turkey–Syria earthquake areas*. IEEE Geoscience and Remote Sensing Letters, vol. 21, 2024, 3002405. https://doi.org/10.1109/LGRS.2024.3397864.

[28] Zhang D., Huang H., Roy N., Roozbahani M.M., Frost J.D.: *Black marble nighttime light data for disaster damage assessment*. Remote Sensing, vol. 15(17), 2023, 4257. https://doi.org/10.3390/rs15174257.

[29] Chanief A.Z., Yola L.: *Analysis of urban mobility patterns in Jakarta city during pandemic Covid-19*, [in:] Nia E.M., Awang M., Aulady M.F.N., Traykova M., Yola L. (eds.), *Selected Articles from the 8th International Conference on Architecture and Civil Engineering: ICACE 2024, 12–13 December, Penang, Malaysia*, Lecture Notes in Civil Engineering, vol. 635, Springer, Singapore 2025, pp. 304–310. https://doi.org/10.1007/978-981-96-5654-7_30.

[30] Alders W.: *Open-access archaeological predictive modeling using zonal statistics: A case study from Zanzibar, Tanzania*. Journal of Computer Applications in Archaeology, vol. 6(1), 2023, pp. 117–142. https://doi.org/10.5334/jcaa.107.

[31] Pambudi N.A.: *Geothermal power generation in Indonesia, a country within the ring of fire: Current status, future development and policy*. Renewable and Sustainable Energy Reviews, vol. 81(2), 2018, pp. 2893–2901. https://doi.org/10.1016/j.rser.2017.06.096.

[32] Cummins P.R., Pranantyo I.R., Pownall J.M., Griffin J.D., Meilano I., Zhao S.: *Earthquakes and tsunamis caused by low-angle normal faulting in the Banda Sea, Indonesia*. Nature Geoscience, vol. 13, 2020, pp. 312–318. https://doi.org/10.1038/s41561-020-0545-x.

[33] Masum M., Akbar M.A.: *The Pacific Ring of Fire is working as a home country of geothermal resources in the world*. IOP Conference Series: Earth and Environmental Science, vol. 249, 2019, 012020. https://doi.org/10.1088/1755-1315/249/1/012020.

[34] Chelminski K.: *Harnessing the Ring of Fire: Political Economy of Clean Energy Development Finance on Geothermal Development in Indonesia and the Philippines*. Energy Policy Research Group, University of Cambridge, 2018. http://www.jstor.org/stable/resrep30435 [access: October 26, 2024].

[35] Fuady M., Munadi R., Fuady M.A.K.: *Disaster mitigation in Indonesia: Between plans and reality*. IOP Conference Series: Materials Science and Engineering, vol. 1087, 2021, 012011. https://doi.org/10.1088/1757-899X/1087/1/012011.

[36] Pribadi K.S., Kusumastuti D., Sagala S.A.H., Wimbardana R.: *Post-disaster housing reconstruction in Indonesia: Review and lessons from Aceh, Yogyakarta, West Java and West Sumatera earthquakes*, [in:] Shaw R. (ed.), *Disaster Recovery: Disaster Risk Reduction*, Springer, Tokyo 2014, pp. 197–223. https://doi.org/10.1007/978-4-431-54255-1.

[37] Kusumasari B., Alam Q.: *Local wisdom-based disaster recovery model in Indonesia*. Disaster Prevention and Management, vol. 21(3), 2012, pp. 351–369. https://doi.org/10.1108/09653561211234525.

[38] BPS-Statistics of Yogyakarta Municipality: *Yogyakarta Municipality in Figures 2024*. 2024. https://jogjakota.bps.go.id/en/publication/2024/02/28/6a6d984e3d10d2113c9d3f3b/yogyakarta-municipality-in-figures-2024.html [access: October 26, 2024].

[39] BPS-Statistics of DI Yogyakarta Province: *Growth Rate of Population by Regency/Municipality, 1971–2020 (persen/year)*. 2024. https://yogyakarta.bps.go.id/en/statistics-table/1/MTY4IzE=/growth-rate-of-population-by-regency-municipality--1971-2020--persen-year-.html [access: October 26, 2024].

[40] BPS-Statistics of Bantul Regency: *Bantul Regency in Figures 2023*. 2023. https://bantulkab.bps.go.id/en/publication/2023/02/28/e90ab2b5613a5bd94f524fcb/kabupaten-bantul-dalam-angka-2023.html [access: October 26, 2024].

[41] Disaster Management Agency of Yogyakarta Municipality: *Kajian risiko bencana kota Yogyakarta 2022–2026* [Disaster risk assessment of Yogyakarta city for 2022–2026]. Yogyakarta, 2022. https://bpbd.jogjakota.go.id/assets/instansi/bpbd/files/dokmen-kajian-risiko-bencana-kota-yogyakarta-2022-2026-13325.pdf [access: October 26, 2024].

[42] Sulistiyana A.: *Duka dari bumi Projotamansari: Arsip korban gempa bumi 2006 di Bantul* [Grief from the land of Projotamansari: Archive of the victims of the 2006 earthquake in Bantul]. Bantul Library and Archive Agency, Bantul 2018. https://perpusda.bantulkab.go.id/pc/59323#pablo [access: October 26, 2024].

[43] National Center for Earthquake Studies: *Peta Sumber Dan Bahaya Gempa Indonesia Tahun 2017* [Map of Indonesian earthquake hazard and source in 2017]. https://luk.staff.ugm.ac.id/gempa/pdf/Pusgen2017PetaGempaIndonesia.pdf [access: October 26, 2024].

[44] Widjajanti N., Nata B., Parseno P.: *Displacement velocity and strain analysis of Opak Fault monitoring stations*. IOP Conference Series: Earth and Environmental Science, vol. 936, 2021, 012042. https://doi.org/10.1088/1755-1315/936/1/012042.

[45] Abidin H.Z., Andreas H., Meilano I., Gamal M., Gumilar I., Abdullah C.I.: *Deformasi koseismik dan pascaseismik gempa Yogyakarta 2006 dari hasil survei GPS*. Indonesian Journal on Geoscience, vol. 4(4), 2009, pp. 275–284. https://doi.org/10.17014/ijog.4.4.275-284.

[46] Steinritz V., Pena-Castellnou S., Marliyani G.I., Reicherter K.: *GIS-based study of tsunami risk in the Special Region of Yogyakarta (Central Java, Indonesia)*. IOP Conference Series: Earth and Environmental Science, vol. 851, 2021, 012007. https://doi.org/10.1088/1755-1315/851/1/012007.

[47] Tsuji T., Yamamoto K., Matsuoka T., Yamada Y., Onishi K., Bahar A., Meilano I., Abidin H.Z.: *Earthquake fault of the 26 May 2006 Yogyakarta earthquake observed by SAR interferometry*. Earth, Planet and Space, vol. 61(7), 2009, pp. e29–e32. https://doi.org/10.1186/BF03353189.

[48] Yuan Y., Chen Z.: *The impacts of land cover spatial combination on nighttime light intensity in 2010 and 2020: A case study of Fuzhou, China*. Computer Urban Science, vol. 3(1), 2023. https://doi.org/10.1007/s43762-023-00077-y.

[49] Ma T., Zhou Y., Zhou C., Haynie S., Pei T., Xu T.: *Night-time light derived estimation of spatio-temporal characteristics of urbanisation dynamics using DMSP/OLS satellite data*. Remote Sensing of Environment, vol. 158, 2015, pp. 453–464. https://doi.org/10.1016/j.rse.2014.11.022.

[50] Cao C., De Luccia F.J., Xiong X., Wolfe R., Weng F.: *Early on-orbit performance of the Visible Infrared Imaging Radiometer Suite onboard the Suomi National Polar-Orbiting Partnership (S-NPP) satellite*. IEEE Transactions on Geoscience and Remote Sensing, vol. 52(2), 2014, pp. 1142–1156. https://doi.org/10.1109/TGRS.2013.2247768.

[51] Csiszar I., Schroeder W., Giglio L., Ellicott E., Vadrevu K.P., Justice C.O., Wind B.: *Active fires from the Suomi NPP Visible Infrared Imaging Radiometer Suite: Product status and first evaluation results*. Journal of Geophysical Research: Atmospheres, vol. 119(2), 2014, pp. 803–816. https://doi.org/10.1002/2013jd020453.

[52] Elvidge C.D., Zhizhin M., Baugh K., Hsu F.C., Ghosh T.: *Methods for global survey of natural gas flaring from Visible Infrared Imaging Radiometer Suite data*. Energies, vol. 9(1), 2016. https://doi.org/10.3390/en9010014.

[53] Trishchenko A.P.: *Clear-sky composites over Canada from Visible Infrared Imaging Radiometer Suite: Continuing MODIS time series into the future*. Canadian Journal of Remote Sensing, vol. 45(3–4), 2019, pp. 276–289. https://doi.org/10.1080/07038992.2019.1601006.

[54] Miller S.D., Straka W. III., Mills S.P., Elvidge C.D., Lee T.F., Solbrig J., Walther A., Heidinger A.K., Weiss S.C.: *Illuminating the capabilities of the Suomi National Polar-Orbiting Partnership (NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band*. Remote Sensing, vol. 5(12), 2013, pp. 6717–6766. https://doi.org/10.3390/rs5126717.

[55] Seaman C., Hillger D.W., Kopp T.J., Williams R., Miller S., Lindsey D.: *Visible Infrared Imaging Radiometer Suite (VIIRS) Imagery Environmental Data Record (EDR) user's guide*. U.S. Department of Commerce National Oceanic and Atmospheric Administration, Washington 2015. http://doi.org/10.7289/V5/TR-NESDIS-150.

[56] Eplee R.E., Turpie K.R., Meister G., Patt F.S., Franz B.A., Bailey S.W.: *On-orbit calibration of the Suomi National Polar-Orbiting Partnership Visible Infrared Imaging Radiometer Suite for ocean colour applications*. Applied Optics, vol. 54(8), 2015, pp. 1984–2006. https://doi.org/10.1364/ao.54.001984.

[57] Guillevic P.C., Biard J.C., Hulley G.C., Privette J.L., Hook S.J., Olioso A., Göttsche F.M., Radocinski R., Román M.O., Yu Y., Csiszar I.: *Validation of Land Surface Temperature products derived from the Visible Infrared Imaging Radiometer Suite (VIIRS) using ground-based and heritage satellite measurements*. Remote Sensing of Environment, vol. 154, 2014, pp. 19–37. https://doi.org/10.1016/j.rse.2014.08.013.

[58] Setiawan Y., Kustiyo K., Hudjimartsu S.A., Purwanto J., Rovani R., Tosiani A., Usman A.B., Kartika T., Indriasari N., Prasetyo L.B., Margono B.A.: *Evaluating Visible-Infrared Imaging Radiometer Suite imagery for developing near-real-time nationwide vegetation cover monitoring in Indonesia*. Remote Sensing, vol. 16(11), 2024, 1958. https://doi.org/10.3390/rs16111958.

[59] Falchi F., Cinzano P., Duriscoe D., Kyba C.C., Elvidge C.D., Baugh K., Portnov B.A., Rybnikova N.A., Furgoni R.: *The new world atlas of artificial night sky brightness*. Science Advances, vol. 2(6), 2016, e1600377. http://doi.org/10.1126/sciadv.1600377.

[60] Yang Y., Zhao C., Sun L., Wei J.: *Improved aerosol retrievals over complex regions using NPP Visible Infrared Imaging Radiometer Suite observations*. Earth and Space Science, vol. 6(4), 2019, pp. 629–645. https://doi.org/10.1029/2019EA000574.

[61] Li P., Xiao C., Feng Z., Li W., Zhang X.: *Occurrence frequencies and regional variations in Visible Infrared Imaging Radiometer Suite (VIIRS) global active fires*. Global Change Biology, vol. 26(5), 2020, pp. 2970–2987. https://doi.org/10.1111/gcb.15034.

[62] Flenniken J.M., Stuglik S., Iannone B.V.: *Quantum GIS (QGIS): An introduction to a free alternative to more costly GIS platforms: FOR359/FR428, 2/2020*. EDIS, vol. 2020(2), 2020. https://doi.org/10.32473/edis-fr428-2020.

[63] Novo A., Garrido I., Lorenzo H., Arias P.: *Use of geographic information systems (GIS) in higher education: Practical geomatics applications with Quantum GIS software*, [in:] *2022 International Symposium on Computers in Education (SIIE)*, IEEE, 2022, pp. 1–6. https://doi.org/10.1109/SIIE56031.2022.9982364.

[64] Alders W.: *Open-access archaeological predictive modelling using zonal statistics: A case study from Zanzibar, Tanzania*. Journal of Computer Applications in Archaeology, vol. 6(1), 2023, pp. 117–142. https://doi.org/10.5334/jcaa.107.

[65] Singla S., Eldawy A.: *Raptor Zonal Statistics: Fully distributed zonal statistics of big raster + vector data*, [in:] *2020 IEEE International Conference on Big Data (Big Data)*, IEEE, 2020, pp. 571–580. https://doi.org/10.1109/BigData50022.2020.9377907.

[66] Lovelace R., Tennekes M., Carlino D.: *ClockBoard: A zoning system for urban analysis*. Journal of Spatial Information Science, no. 24, 2022, pp. 63–85. https://doi.org/10.5311/JOSIS.2022.24.172.

[67] Koktavá N., Horák J.: *Options for micro-mobility data visualization*. European Journal of Geography, vol. 14(4), 2023, pp. 46–52. https://doi.org/10.48088/ejg.n.kok.14.4.046.052.

[68] Nurhaci D.S., Setianto A., Wilopo W.: *Analysis and evaluation of earthquake hazard zones based on spatial models for regency regional development Bantul*. IOP Conference Series: Earth and Environmental Science, vol. 1373(1), 2024, 012014. https://doi.org/10.1088/1755-1315/1373/1/012014.

[69] Ambarwulan W., Nahib I., Widiatmaka W., Dewi R.S., Munajati S.L., Suwarno Y., Sutrisno D., Suprajaka S.: *Delineating suitable site for settlement in potential earthquake vulnerable areas using spatial multi-criteria decision analysis in the Sukabumi regency, Indonesia*. Journal of Water and Land Development, no. 53, 2022, pp. 10–21. https://doi.org/10.24425/jwld.2022.140775.

[70] Ningrum R.W., Fauzi H., Aswan M., Suryanto W., Mei E.T.W.: *Analysis of physical vulnerability assessment due to 2015 swarm earthquake based on amplification zone in Jailolo District*, [in:] *5th International Conference on Food, Agriculture and Natural Resources (FANRes 2019)*, Atlantis Press, 2020, pp. 306–310. https://doi.org/10.2991/aer.k.200325.060.

[71] Fadli A., Priyambodo T.K., Putra A.E., Suryanto W.: *Kernel density estimation for seismic hazard mapping in Indonesia: Influence of kernel function, bandwidth size, and grid resolution*. Trends in Sciences, vol. 22(8), 2025, 10064. https://doi.org/10.48048/tis.2025.10064.

[72] Han S., Liu B., Yang J., Feng T., Luo J., Zhou Z., Gong H.: *Impact assessment of the effects of strong earthquake-induced hazards on the socioeconomic development level of earthquake-stricken areas after the 2008 Wenchuan earthquake*. Mobile Information Systems, vol. 2022(1), 2022, 1695637. https://doi.org/10.1155/2022/1695637.

[73] Xu C., Du X., Yan L., Fan X.: *LION: Spatiotemporal data fusion model for nighttime light*, [in:] *IGARSS 2024 – 2024 IEEE International Geoscience and Remote Sensing Symposium*, IEEE, 2024, pp. 7907–7910. https://doi.org/10.1109/IGARSS53475.2024.10641673.

[74] Guo W., Zhang J., Zhao X., Li Y., Liu J., Sun W., Fan D.: *Combining Luojia1-01 nighttime light and points-of-interest data for fine mapping of population spatialization based on the zonal classification method*. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 16, 2023, pp. 1589–1600. https://doi.org/10.1109/JSTARS.2023.3238188.

[75] Dutta D., Rahman A., Paul S.K., Kundu A.: *Estimating urban growth in peri-urban areas and its interrelationships with built-up density using earth observation datasets*. The Annals of Regional Science, vol. 65(1), 2020, pp. 67–82. https://doi.org/10.1007/s00168-020-00974-8.

[76] Aburas M.M., Ho Y.M., Ramli M.F., Ash'aari Z.H.: *Monitoring and assessment of urban growth patterns using spatio-temporal built-up area analysis*. Environmental Monitoring and Assessment, vol. 190(3), 2018, 156. https://doi.org/10.1007/s10661-018-6522-9.

[77] Zhou D., Li Z., Wang S., Tian Y., Zhang Y., Jiang G.: *How does the newly urban residential built-up density differ across Chinese cities under rapid urban expansion? Evidence from residential FAR and statistical data from 2007 to 2016*. Land Use Policy, vol. 104, 2021, 105365. https://doi.org/10.1016/j.landusepol.2021.105365.

[78] Shahfahad S., Mourya M., Kumari B., Tayyab M., Paarcha A., Asif A., Rahman A.: *Indices based assessment of built-up density and urban expansion of fast*

growing Surat city using multi-temporal Landsat data sets. GeoJournal, vol. 86(4), 2021, pp. 1607–1623. https://doi.org/10.1007/s10708-020-10148-w.

[79] Mustafa A., Van Rompaey A., Cools M., Saadi I., Teller J.: *Addressing the determinants of built-up expansion and densification processes at the regional scale*. Urban Studies, vol. 55(15), 2018, pp. 3279–3298. https://doi.org/10.1177/0042098017749176.

[80] Muntafi Y., Nojima N., Jamal A.U.: *Damage probability assessment of hospital buildings in Yogyakarta, Indonesia as an essential facility due to an earthquake scenario*. Journal of the Civil Engineering Forum, vol. 6(3), 2020, pp. 225–236. https://doi.org/10.22146/jcef.53387.

[81] Kurniati D., Nurhidayatullah E.F., Hasibuan S.A.R.S.: *Rapid assessment of earthquake threat vulnerability in Campus 3 of the University of Technology Yogyakarta based on an Android application*. International Journal of Engineering Technology and Natural Sciences, vol. 4(2), 2022, pp. 119–127. https://doi.org/10.46923/ijets.v4i2.178.

[82] Yunizar D.K., Ricardo D.: *Post earthquake house reconstruction management based on community participation of Monggang Srihardono Pundong village of Bantul city, Yogyakarta*. IOP Conference Series: Earth and Environmental Science, vol. 1404, 2024, 012048. https://doi.org/10.1088/1755-1315/1404/1/012048.

[83] Widiyantoro S., Gunawan E., Muhari A., Rawlinson N., Mori J., Hanifa N.R., Susilo S., Supendi P., Shiddiqi H.A., Nugraha A.D., Putra H.E.: *Implications for megathrust earthquakes and tsunamis from seismic gaps south of Java, Indonesia*. Scientific Reports, vol. 10, 2020, 15274. https://doi.org/10.1038/s41598-020-72142-z.

[84] Supendi P., Widiyantoro S., Rawlinson N., Yatimantoro T., Muhari A., Hanifa N.R., Gunawan E., Shiddiqi H.A., Imran I., Anugrah S.D., Daryono D., Prayitno B.S., Adi S.P., Karnawati D., Faizal L., Damanik R.: *On the potential for megathrust earthquakes and tsunamis off the southern coast of West Java and southeast Sumatra, Indonesia*. Natural Hazards, vol. 116(1), 2023, pp. 1315–1328. https://doi.org/10.1007/s11069-022-05696-y.

[85] Megawati M., Ma K., Chen P., Sianipar D., Hsieh M.: *Source characterisation of intermediate-depth earthquakes in southern Java, Indonesia*. Journal of Asian Earth Sciences, vol. 264, 2024, 106040. https://doi.org/10.1016/j.jseaes.2024.106040.

[86] Grevemeyer I., Tiwari V.M.: *Overriding plate controls spatial distribution of megathrust earthquakes in the Sunda–Andaman subduction zone*. Earth and Planetary Science Letters, vol. 251(3–4), 2006, pp. 199–208. https://doi.org/10.1016/j.epsl.2006.08.021.

[87] Koulali A., McClusky S., Cummins P., Tregoning P.: *Wedge geometry, frictional properties and interseismic coupling of the Java megathrust*. Tectonophysics, vol. 734–735, 2018, pp. 89–95. https://doi.org/10.1016/j.tecto.2018.03.012.