Remote sensing spatial analysis of waterlogging due to cyclones and storms in Bangladesh

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Ⅰ. Abstract

Ground impacts of seasonal natural hazards, such as cyclones and storms, are enormous in the Bengal delta. This remote sensing study aims to estimate the intensity of inundation on physical settlement generated from two cyclones and one storm between 2007 and 2019 based on 2,282 mauzas or villages between inland and coastal districts in the southwest of Bangladesh (SWB). Based on reliable secondary data such as Landsat observations, elevations, physical settlement, and mauzas, it appeared 348.8 km^2 of the coastal and 26 km^2 of the inland district was either high-risk or risk zone of waterlogging due to the cyclone in 2007. Similar waterlogging risks were observed around 399.6 and seven km^2 in the respective districts from the convective storm in 2012. The cyclone in 2019 generated the lowest risk compared to the others in both districts. For the cyclone, 891 and 395 mauzas in inland and coastal districts, respectively, were appeared without any surface water. The inundated area in the mauzas>50% water pixel was enlarged in the inland but reduced in the coastal by the cyclone in 2019 compared to storm in 2012. The study provided the credibility to investigate village-level waterlogging risks generated from cyclones and storms in the coastal area of Bangladesh.

Ⅱ. Introduction

The hydro-meteorological disasters generated over the Bay of Bengal during the post-monsoon (October-November, sometimes in May), defined as a cyclone, is considered one of the most destructive natural hazards in the Ganges-Brahmaputra delta that covers India, Bangladesh, and part of Myanmar. Among them, Bangladesh experienced the most severe ground impacts of the cyclone due to its geographical position. The country has a long history of such storms earliest recorded in 1584 according to Banglapedia (https://en.banglapedia.org). Moreover, future climate change such as global warming, sea-level rise (1) will accelerate the ground impact of cyclones and storms in Bangladesh because of the existing vulnerable socio-economic condition, high density of population, low elevated land, and lack of preparation and prevention mechanism. After investigating existing elevation, population change, and climate conditions, a study found that an estimated 0.9 million people may displace by direct flooding in 2050 from the coastal area of Bangladesh (2). The most recent fatal cyclones of the country were in 1970 and 1991.

The death toll increased by around 500,000 in the first and 138,958 in the latter. Though the number of fatalities decreased after 1991, damage to physical infrastructure and property is still in concern due to the frequency of the storms in Bangladesh (3). After the 1991 cyclone, a shift from response or recovery to preparedness has been observed in the disaster management cycle in the country that focused on empowering the community to be resilient against natural hazards (4). However, the preparedness phase of the cyclone demands accurate estimation and design for possible ground impacts even for a small area of interest where population density is high such as southwest of Bangladesh (SWB).

Although remote sensing data such as optical, thermal, and Synthetic Aperture Radar (SAR) can produce such risk assessment tasks in every phase of the disaster management cycle (5), an enormous interest observed in the prevention phase since 2005. These remote sensing studies often use before and after optical imagery of the most recent cyclone event to detect the changes in land use land classes (LULCs) where the dominant land class is vegetation (6). Such multi-class classification of land use through remote sensing method in the Bengal delta lacks the proper definition and estimation of the land cover area from a reliability and validity point of view. The Bengal delta, covering 60% of Bangladesh, is a highly populated wetland. The coastal area of the country is likely to be affected by cyclones where people experience the immense seasonality of waterbodies around their locality (7). The major livelihood option is Aquaculture (8). Thus, we selected our study area in the coastal area of the Bay of Bengal located in the SWB.

Previous remote sensing studies focusing on ground impacts of cyclones did not provide a clear definition of settlement (9) or built-up (10). Multi-classes land covers damage estimation, from heterogeneous land classes, based on satellite imagery remains a challenge (11). The 'physical settlement' denotes any built-up such as rural and urban housing, institutions, industries, parks, roads, etc. defined by the source. And the area of physical settlement was collected and processed from a reliable source. The present study will primarily estimate the expansion of surface water on the physical settlement area after cyclones and stormthat refers to as waterlogging in the study area. We assume physical settlement as the most crucial land cover in Bangladesh. Because recent modernization and urbanization may accelerate people to rely on physical settlements more especially where physical settlement land is scarce such as SWB. The study, hence, aims to estimate the waterlogging risk developed from two cyclones and one severe storm on the physical settlement area based on zonal statistical analysis. Although we assume that the elevation does not fluctuate much in the Bengal delta, the study will further report the causal association of elevation and its waterlogging spatial distribution on physical settlement.

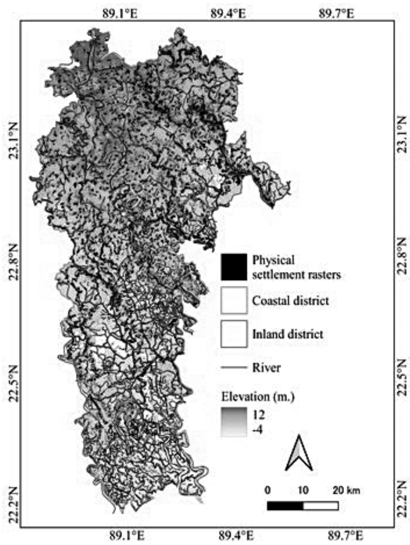

Figure 1. Location of the study

Ⅲ. Methodology

Study area: The study area has been selected purposively at SWB, the downstream coastal area of the Bengal delta, where seasonal cyclones and storms create huge ground impacts. Figure-1 shows that the study further selected two adjacent administrative boundaries of Bangladesh, intending to compare cyclone ground impact between inland and coastal land. The inland and coastal districts' names are Jessore and Satkhira. The geographical extent of the area is 88.84E–88.56E and 21.65N–23.37N, where the inland area is 2,578.4 km^2 includes 1,315 mauzas, and the coastal area is 2,306.5 km^2 with a total of 967 mauzas. The total population of the inland and coastal area is 1.8M and 1.3M, based on population census-2011, Bangladesh Bureau of Statistics (BBS) (http://www.bbs.gov.bd/). The highest elevation of the study area is 14.2m., whereas the lowest is -01.3m. The mean elevation is higher in the inland area than that of the coastal. Mangrove forest which occupies the southern portion of the coastal district was excluded from the present study due to the absence of physical settlement. The area is under a sub-tropical climate, and usually, cyclones develop during post and pre-monsoon. As a delta region, the area is open to numerous rivers, channels, and canals. The rivers and their distributaries have either direct or indirect connections with the Bay of Bengal. The coastal district of the study site is widely known for its aquaculture. And physical settlement is denser in the inland district than that in the coastal (Figure-1).

Case selection: According to historical natural disasters data emergency events (EM-DAT) – (1) a category-5 cyclone named 'Sidr' with a maximum wind speed of 260km/h and lowest pressure of 944hPa., landfall on 15 November 2007 in the SWB generated a 3m. surge around the coastal area. At least 4,234 people have confirmed the death, with 8.9M affected. Estimated damage from the Sidr is around $2.31B. (2) A convective storm transited through SWB on 6 April 2012 with a maximum wind speed of 56km/h. The total number of fatalities reported was 25, and around 55,121 people had been affected. (3) A category-1 cyclone named 'Bulbul' with a maximum wind speed of 195km/h landed on the Indian coast on 9 November 2019 affected SWB as well. The Bulbul caused 40 deaths. The total number of people affected by Bulbul was 251k. The estimated damage was $31.6M. The Bulbul also generated storm surges and flash floods (https://www.emdat.be/). The crucial reasons for selecting these natural disaster cases are (a) the availability of the LS data immediately after the disasters, and (b) EM-DAT data shows the disasters had significant ground impacts.

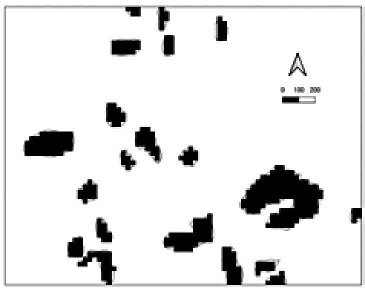

Figure 2. Conversion of vector data to (30 × 30) m raster

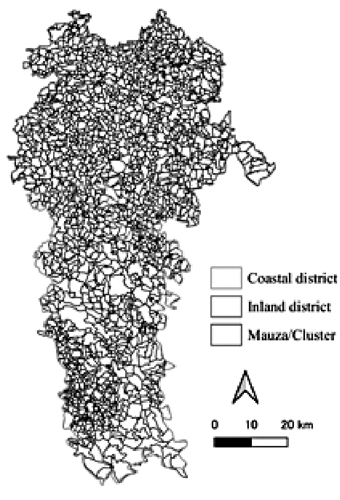

Figure 3. Mauza or village map

Data, and techniques of analyses: For estimating the surface water area, the study used three United States Geological Survey (USGS) archival level-1 collection-1 Landsat (LS) missions' satellite reflectance observations which have 30m. ground resolution. The Satellite observations from LS-07 of 21 November 2007, 24 April 2012, and 22 November 2019, have been used to estimate surface water originated from 15 November 2007, 6 April 2012, and 9 November 2019 cyclones and convective storm respectively. The existing gap mask and radiometric rescaling were fixed to complete the full-scale images and for atmospheric correction of the LS file. Wavelength ranging from (0.52–0.60) μm and (0.77–0.90) μm for Green and Near Infrared (NIR) bands of LS-07 observations utilized to produce Normalized Difference Water Index (NDWI) image introduced by McFeeters (12). The NDWI>0.0 is considered as water pixels. Thus, binary layer legends, water, and no-value were finalized for all the images. The NDWI>0.0 equals water has already been proven a reliable threshold value between water and non-water pixels of LS image in SWB by our previous research method (7). The 30m. ground resolution elevation data of 2002 had been collected from the Shuttle Radar Topography Mission (SRTM), USGS. However, we used the high-resolution spatial map of physical settlement of the study area provided as GIS shapefiles compiled by the Local Government of Engineering Department (LGED), ministry of Local Government, Rural Development and Co-operative, Bangladesh in 2015 (https://www.lged.gov.bd/). The QGIS tool allows converting the vector shapefile into 30m. raster image data. Figure-2 shows the conversion of the vector data layer into a raster layer. The raster layer of physical settlement has been used as a reference layer.

Table 1: Inundation after the disasters

		Surface water (SW)								
		SW >50%			SW > (10-50%)			No SW		
Natural Hazard	District	No. of Vil.	Area in sq. km.	Pct. of land	No. of Vil.	Area in sq. km.	Pct. of land	No.of Vil.	Area in sq. km.	Pct. of land
Sidr	Inland	138	247.2	9.6	232	537.2	20.8	271	361.1	14.0
	Coastal	232	722.4	31.3	252	647.7	28.1	158	209.5	9.1
Storm	Inland	14	28.1	1.1	107	197.7	7.7	852	1479.0	57.4
	Coastal	205	642.4	27.8	222	543.2	23.5	334	643.5	27.9
Bulbul	Inland	93	178.2	6.9	79	156.1	6.1	891	1596.3	61.9
	Coastal	135	477.8	20.7	202	574.3	24.9	395	715.3	31.0

The physical settlement raster layer legends have been arranged in a binary manner like the water pixel layer of the LS. Change matrix tool used to overlap the water raster layer on the physical settlement raster. Finally, the water pixels that overlapped on physical settlement pixels were separated and considered as the waterlogging pixels. For zonal analysis, we used the small area atlas of mauza or village level shapefile of the study area developed by the statistics and informatics division of Bangladesh Bureau of Statistics (BBS) in 2012 published in 2016, which presented in Figure-3 (http://www.bbs.gov.bd/). The mauza or mahalla name and area are often alternatively used as a village name and boundary respectively in Bangladesh, which is considered as spatial zone. A total of 2,282 such villages was identified in the study area presented in Figure-3. We calculated the mean elevation, percent of physical settlement, percent of water pixels, and percent of waterlogging pixels from each village. The mauza containing >75% waterlogging

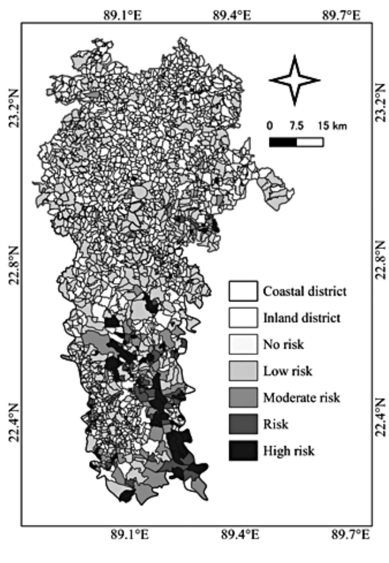

Figure-4. Waterlogging risk due to the cyclone Sidr in 2007 pixels, considered to very high-risk zone derived by cyclone or storm. Similarly, (>50–75)% as risk zone, (>25–50)% as moderate-risk zone, (>0–25)% as the low-risk zone, and the area without any waterlogging pixel as a no-risk zone were defined as waterlogging risks.

Ⅳ. Results

Physical settlement and elevation: We have already mentioned that the study area was divided into 2,282 mauzas or villages. A total of 1,315 villages covers the inland district, and the rest of them, 967, covers the coastal one. Around 198 villages covering 295.6 km^2 in the inland district and another 126 villages covering 178.7 km^2 in the coastal have no physical settlement raster. Hence, physical settlement exists in 1,958 villages of the entire study area. Furthermore, the mean elevation of each mauza was calculated that indicated the average value for the inland district is 7.7m. compared to 4.7m. in the coastal one. The maximum and minimum mean elevation of the villages in the inland district is 14.2m. and 1.0m., respectively. Similarly, the values are 12.7m. and -1.3m. for the coastal (Figure-1). Almost all the villages containing no physical settlement have relatively low mean elevation observed high intensity of water pixels in both districts in 2007, 2012, and 2019 NDVI images.

Surface water: Table-1 shows the nature of inundation after cyclones and storm. Three types of villages were observed and presented – 1. mauza containing >50% water pixels, 2. (10–50)% of water pixels, and 3. without any water pixel. It appears that cyclone Sidr generated the highest number of villages that contain over 50% of water pixels compared to the storm and the Bulbul both in inland and coastal districts. The Bulbul seemed a higher impact compared to the storm in the inland district. Because, after the Bulbul, similar villages increased in the inland district and decreased in the coastal. However, the Sidr produced the highest and the Bulbul produced the lowest number of villages that hold water pixels between 10 and 50 percent in both the districts. Although a lower number of similar villages was observed after the Bulbul compared to the storm, the percent of the area inundated appeared higher in the coastal district. Even so, the Bulbul developed the highest and the Sidr left the lowest number of villages without any water pixels in both districts. The area and percent of land follow the same.

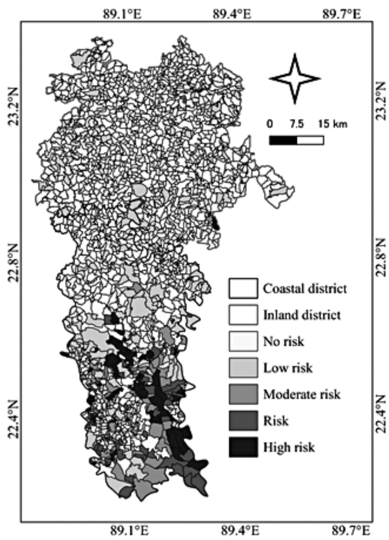

Figure-5. Waterlogging risks due to convective storm in 2012

Waterlogging risk: Th study found eight villages covering 12.7 km^2 and nine villages covering 13.9 km^2 in the inland district appeared as high-risk and risk-waterlogging villages, respectively, due to the Sidr presented in Figure-4. Around 54 km^2 containing 34 villages were identified as moderately-risk waterlogging. Again, around one-third of the land, which has 323 villages in total covering 862.3 km^2 in the inland district, has been observed as a low-risk zone. The waterlogging risk was not identified around 63.4% of the land covering 941 villages in the inland area after the Sidr. Figure-4 also shows that waterlogging risk is much more severe in the coastal district due to the Sidr. A total of 70 villages covering 220.9 km^2, or 9.6% of the coastal district land appeared as high-risk villages, but only 5.5% of the area containing 45 villages categorized as risk villages. A total of 70 villages covering 321.9 km^2 appeared as moderately-risk villages. One-third of the coastal district land remained without any waterlogging risk after the Sidr. Figure-5 shows the waterlogging risk generated from the convective storm in 2012. It appears that only two villages in the inland district are categorized in both high-risk and risk zones accommodating, 4.6 and 2.9 km^2, respectively, due to the storm. However, only one mauza covering only around three km^2 is identified as a moderate-risk area, while 61 villages covering 179.7 km^2 as low-risk zones. A significant portion of the inland area containing 1,249 villages covering 92.6% of the district land remains without waterlogging risk after the convective storm in 2012. But the waterlogging risk is noticeably high in the coastal district. Figure-5 also shows that around 209.8 km^2, containing 79 villages, were identified as high-risk waterlogging zones in the coastal district. Again 62 villages cover 189.5 km^2 and 61 villages covering around 241 km^2 are distinguished as risk, and moderate-risk zones, respectively. However, nearly half of the coastal district land remained somewhat waterlogging risk in 2012. Lastly, Figure-6 shows that waterlogging did not widen in the inland district due to the category-1 cyclone in 2019. Only one and three villages in the inland district, both covering around two km^2 have been observed as highrisk and risk zone of waterlogging, respectively, due to the cyclone Bulbul. A total of nine villages covering 166.1 km^2 has been distinguished as a moderate-risk zone, while 58 covers 166.1 km^2 which is around six percent of the inland district observed as the low-risk zone. But over 90% of the inland district land remains without waterlogging risk after the Bulbul. But Figure-6 shows a significant waterlogging risk in the coastal district. Because 34 villages cover 169.6 km^2, and 14 villages covering 28.9 km^2 have been categorized as high-risk and risk zones, respectively, in the coastal district due to the Bulbul. Again, a total of 32 villages covering 120.1 km^2 has been observed in the moderate-risk zone. And one-third of the coastal district land cover 192 villages separated as a low-risk zone. However, more than half of the land in the coastal district covers 1265.6 km^2 remained without waterlogging risk after the Bulbul.

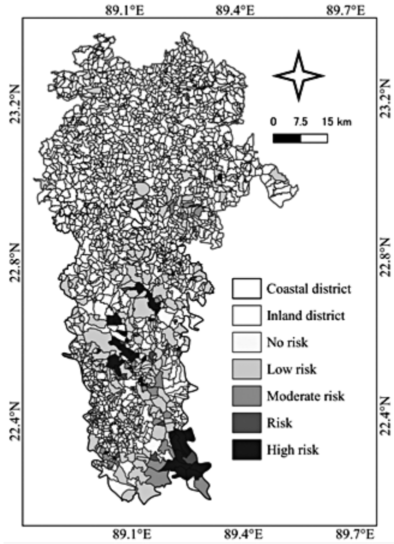

Figure-6. Waterlogging risks due to the cyclone Bulbul in 2019

V. Discussion

Zonal analysis: The study analyzed physical settlement that was compiled from a reliable source and considered mauza or village-level zones as a unit of spatial analysis. It defined the settlement pixel overlapped by water pixel from two cyclones and one severe storm between 2007 and 2019 as waterlogging. The data and result may not deliver for the whole scenario of waterlogging, but the investigation does not limit initiating an experimental method for future investigation considering more cases of natural hazards and other possible elements of waterlogging. The area of different types of waterlogging risks in inland and coastal districts was compiled in Table-2. Different types of waterlogging risks were impacted differently depending on the districts. Sidr created the highest highrisk and moderated-risk zones in both districts. But the storm in 2012, created the highest risk zones in the coastal district and the lowest moderate-risk zones in the inland district. Area of low-risk zones for both the districts suggested that the waterlogging is widening for recent natural hazards compared to the previous. However, the spatial distribution of the study area analysis shows that cyclone Sidr of 2007 created the most severe waterlogging in both districts. And, both cyclones and convective storm generated significant waterlogging risks in the coastal area. However high-risk and risk villages of waterlogging appeared in the southeast region of both districts (Figure-4, 5 & 6). The physical settlement near the rivers appears the riskiest for waterlogging from cyclones and storm (Figure-3 vs. 4 & 5). Convective storm and the Bulbul created the least and almost similar waterlogging in the inland district (Figure 4 & 5). And cyclone Sidr and convective storm generated the most similar severe waterlogging risks in the coastal area (Figure 5 & 6). However, the villages without any physical settlement either have water pixels or no water pixels located mostly in the north and northwest part of the inland district. Similar villages are observed in the northwest part of the coastal district (Figure-4, 5 & 6).

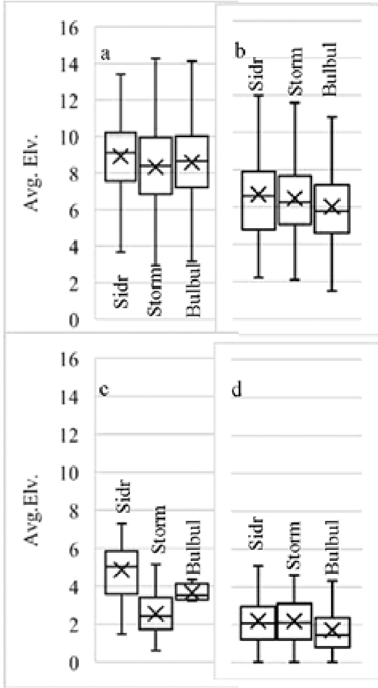

Figure-7. Average elevation distribution of each village; a. without water pixel in inland, b. without water pixel in coastal, c. with waterlogging percent ≥ 50% in inland, d. with waterlogging percent ≥ 50% in the coastal district.

Table 2: Waterlogging risks area

Natural Disaster	District	Waterlogging risks area (sq. km.) High	Risk	Moderate	Low	None
Sidr	Inland	12.7	13.9	54.0	862.3	1635.6
	Coastal	220.9	127.9	321.9	890.0	746.3
Storm	Inland	4.7	2.9	3.0	179.7	2388.0
	Coastal	209.8	189.6	241.0	529.0	1137.5
Bulbul	Inland	1.9	2.3	22.0	166.1	2385.9
	Coastal	169.6	28.9	120.1	722.7	1265.6

Elevation and waterlogging: We assume that elevation may influence both the existence of surface water and waterlogging risks generated from natural hazards. Thus, the mean elevation from extreme villages was calculated separately. The villages have been selected based on two criteria 1. the mauza having no surface water after the hazards (Figure 7.a & b), 2. the mauza has ≥50% of waterlogging pixels (Figure 7.c & d). Figure 7 shows the comparison of the mean elevation for both districts in all three events. Data arranged in boxplot where marker and line-mark are for the average and median value, respectively. The upper limit of the box is for the 75th percentile, the lower limit shows the 25th percentile, upper whisker for maximum, and lower whisker for minimum value. It is perceivable that the higher elevation precludes surface water in both coastal and inland districts (Figure 7. a & b). The physical settlement in the lower elevation area has a much higher chance of waterlogging risk generated from cyclones and storm (Figure 7. b & c). However, cyclone Sidr accelerated more waterlogging villages in high-elevated areas in the inland district compared to the storm in 2012 and the Bulbul (Figure 7.c).

Ⅳ. Conclusion

The study described the waterlogging risks on physical settlement developed from two cyclones in 2007 and 2019, and a convective storm in 2012 based on 2,282 mauzas or villages analysis. The observed mauza analysis showed a higher chance of inundation where physical settlement is low in percentage and vis versa. Around 7% of the villages without settlement were found no inundation pixel in 2007, while 50% of the similar zones experienced at least 80% of inundation pixels. The chance of waterlogging risks is very high in the mauza when the percent of inundation is high, and the percent of settlement is low. The spatial distribution of the villages appeared that cyclones and storm generated significant waterlogging risks in the coastal district. High-risk and risk zones of waterlogging remained in the southeast region of the study area. The physical settlement near the rivers seemed riskier than the others located in the north and northwest part of the inland and the northwest of the coastal districts. The investigation provides credence that remote sensing research is workable even for the village-level ground impacts such as inundation and waterlogging caused by hydrometeorological hazards.

Nevertheless, the risk of inundation on physical settlement from cyclones and storms depends on other factors. Cyclone tracks, storm surges, precipitation, ground elevation are crucial indicators. This research rigorously considered inland and coastal administrative boundaries to compare the waterlogging risks. Future development for spatial analysis requires considering the cyclone and storm land tracks for presenting a holistic waterlogging risk. Existing SAR imagery penetrating the cloud might produce a better ground scenario than LS observation. The LS observation also limits timely and useable data to analyze the ground impacts of hazards due to the cloud. Present research only considered waterlogging risks in the aftermath of the events. Thus, the SAR imagery might be more suitable to check the existing waterlogging scenario before the natural hazards as well. Field surveys regarding existing socio-economic conditions of each region, and distance from river and emergency facilities may help develop other risks developed from natural hazards.

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