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The cost of rapid and haphazard urbanization: lessons learned from the Freetown landslide disaster

Abstract Urbanization has been linked to destructive geo-hazards that can cause loss of life, destruction of property, and environmental damage. On August 14, 2017, a devastating geo-hazard chain—a debris slide, debris flow, and sediment-laden flood—in Freetown, Sierra Leone resulted in at least 500 deaths and over 600 missing persons and the destruction of hundreds of houses. This study uses 10 years of high-resolution satellite images to conduct a remote sensing analysis of the disaster. Although rainfall was the trigger, rapid and haphazard urbanization acted to increase both hazard and vulnerability. Specifically, poor urban planning with inadequate consideration of risk led to housing construction in dangerous areas; clearance of hillside vegetation increased erosion potential; very low cost buildings using frail construction material and methods lacked resilience; and insufficient risk management led to weak emergency response.

Keywords Rapid urbanization · Haphazard urban planning · Geo-hazards · Disaster · Land-use change

Introduction

Urbanization is the process of human migration from rural to urban areas (Goryakin et al. 2017) and involves change of land use from agricultural to non-agricultural (Li et al. 2017). Generally, urbanization is considered as the foundation for advancing human civilization (Christensen and McCord 2016) and has had a significant impact on society. However, urbanization has also been linked to destructive geo-hazards around the world, where implemented in an uncontrolled way. Ng et al. (2016a), who was the first one to investigate both the mechanical and hydrological effects on slope stability in centrifuge systematically, investigated innovatively the influence of planting density on tree growth and induced soil suction, which showed the role of vegetation in soil and water conservation from a more subtle point of view. Mass-wasting hazards such as landslides (Douglass et al. 2005; Li et al. 2017), floods (Fedeski and Gwilliam 2007), and debris flows (Cannon and DeGraff 2009) can be initiated when large areas of vegetation are destroyed or removed (Ng et al. 2016b; Cui et al. 2019). In Sierra Leone, deforestation is a major issue, and in the case of the study event, it may have been the crucial problem. Land use change, including both urbanization and deforestation, have been mapped using remote sensing over the peninsula area of Western Sierra Leone (Gbanie et al. 2018), showing an expansion of Freetown into what was forest, though in some areas of the peninsula the forest expanded from 1976 to 2011. In our work, we zoom into the northern peninsula area near Freetown and address specifically the 2017 Freetown landslide disaster site. Deforestation damages the natural ecosystem, adversely affecting rainfall infiltration and enhancing runoff, which promotes initiation of landslides and debris flows (Yin et al. 2016; Rahman et al. 2017). Enhanced runoff causes erosion and transport of sediment, and at high rates it also contributes to higher river discharge and flooding (Huang et al. 2008; Prosdocimi et al. 2015; Pumo et al. 2017).

Freetown, the capital and largest city of Sierra Leone (Fig. 1a), is a major Atlantic port and has a population of just over a million (Statistics Sierra Leone 2017). Mountains constrain urban expansion in the southern part of the city, and limited space for urban development has resulted in the progressive encroachment of infrastructure on hillsides. In the early morning of August 14, 2017, a devastating chain of geo-hazards occurred in the Lumley Creek watershed after several days of rainfall during a particularly rainy season (Fig. 1b). More than 1102 people were confirmed dead or missing and > 300 houses were destroyed, with > 3000 residents left homeless. The area worst affected by the disaster was located on a hillside (Fig. 2), where many houses were swept away along with their occupants. The source zone of the debris slide was identified based on image interpretation of pictures in Fig. 2 and high-resolution remote sensing images in Fig. 4.The steep terrain is regarded as the source area of landslide and the gentle terrain with massive accumulation is regarded as the accumulation area (Mantovani et al. 2010; Cui et al. 2014). Although the disaster is commonly attributed to have been caused by heavy rainfall, this study reveals that human activities were definitive conditioning factors—by placing thousands of people in an obvious hazardous situation, and by disturbing the natural ecology and hydrology of the mountain slope. The link between mountain hazard disasters and expansion of mountain cities is gaining more scientific and management attention due to the potential of significant harm to poorly situated villages and densely populated urban areas, for example, the 2017 Mocoa landslide, Colombia (Cheng et al. 2018), the 2014 Malin landslide, India (Singh et al. 2016), the 2010 Gansu mudslide, China (Tang et al. 2011), and the 2010 Atabad landslide and dammed river (Kargel et al. 2010). This study examines how rapid land use change and haphazard urbanization acted as a catalyst for the Freetown disaster. This case might be considered an archetype example and a warning regarding a problem that is widespread in developing mountainous regions around the world.

Natural causal factors and damage assessment

The Freetown event occurred in the Lumley Creek watershed which has a topographic relief of 746 m and an average slope of 35° (Fig. 1c). In the Köppen climate classification (Peel et al. 2007), the region is characterized as a tropical monsoon climate and has a rainy season from May to October and a dry season in the rest of the year. The average annual temperature of Freetown is around 27 °C (81 °F) and annual rainfall averages at 3657 mm (Climate-data.org 2018). The combination of steep slopes and high rainfall makes the area prone to landslides. Sierra Leone was amid a particularly rainy season when the Lumley Creek disaster occurred, with a total rainfall of 1014 mm since July 1, 2017, compared with only 840 and 906 mm in the corresponding periods of 2015 and 2016. This amount of precipitation is nearly triple the seasonal average for Freetown (Clarke 2017) and provides sufficient water to saturate soil. From August 10–14, Freetown experienced three consecutive days with 126 mm rainfall (Fig. 3), which led to severe

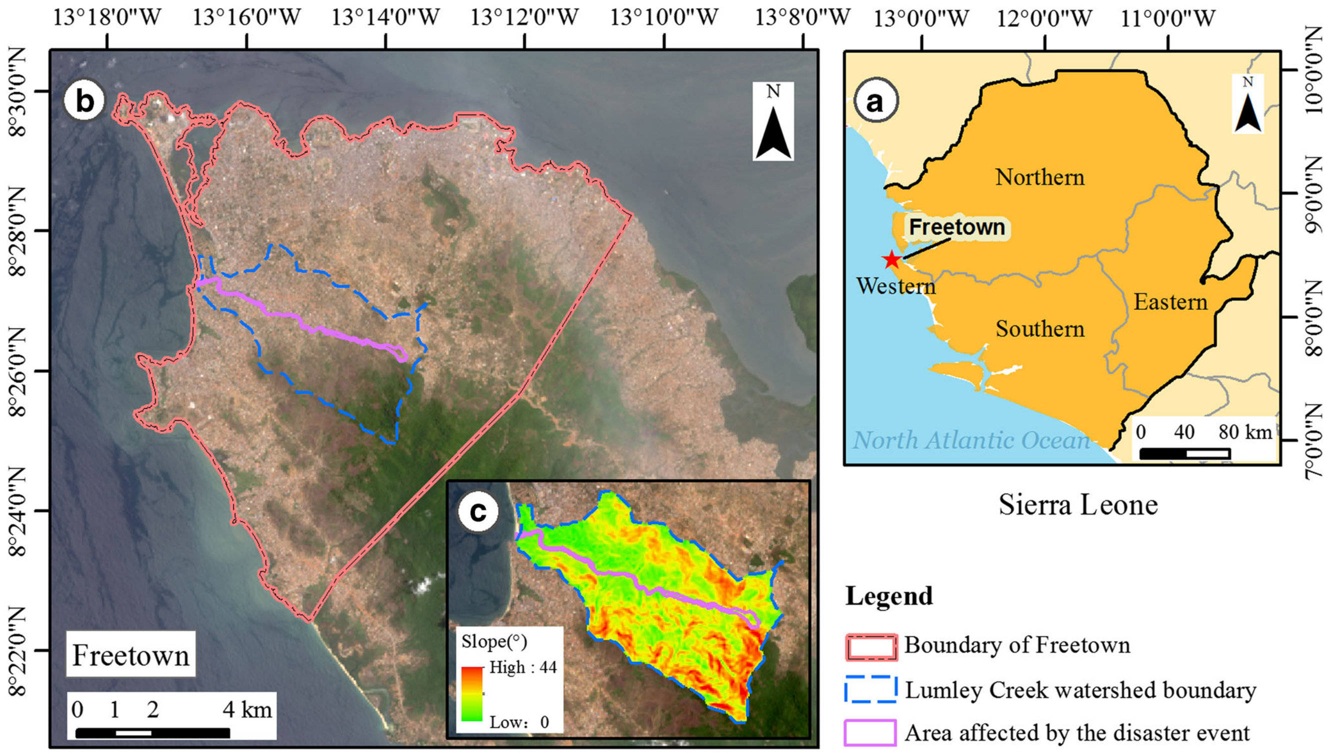

Fig. 1 Location of the Lumley Creek watershed (outlined in blue) (University of Texas Libraries 2005), Freetown, Sierra Leone. (a) Location of Freetown; (b) Lumley Creek watershed and area affected by the disaster event; (c) Slope characteristic of Lumley Creek watershed, the area affected by the event is shown in purple

flooding in the city and surrounding suburbs (Hindustan Times 2017). Heavy rainfall during the morning of August 14, 2017, provided the trigger for the geo-hazard chain.

Cui et al. (2007) established precipitation indices for forecasting geophysical flows based on separating antecedent precipitation (AP) into three categories: (i) triggering precipitation (TP), defined as the short-duration precipitation that stimulates hazard occurrence; (ii) direct antecedent precipitation (DAP), defined as rainfall immediately before the TP in the same rainfall event; and (iii) indirect antecedent precipitation (IAP), the weighted sum of precipitation before the hazard event. Using Cui's relationships and method, with an attenuation coefficient of 0.9 and an AP period of 27 days (July 19 to August 14), IAP, DAP, and TP were calculated for the Freetown event. The results indicate total rainfall contributing to hazard occurrence was 494.6 mm, of which TP contributed 84.8 mm, DAP contributed 44.1 mm and IAP contributed 365.7 mm.

High-resolution (0.5 m) pre- and post-disaster images of Freetown were acquired to enable an enhanced interpretation of the disaster. The pre-disaster image (March 3, 2017) was obtained from Google Earth, and the post-disaster image (August 15, 2017) was obtained from GeoEye Satellite Imaging Company. Based on image

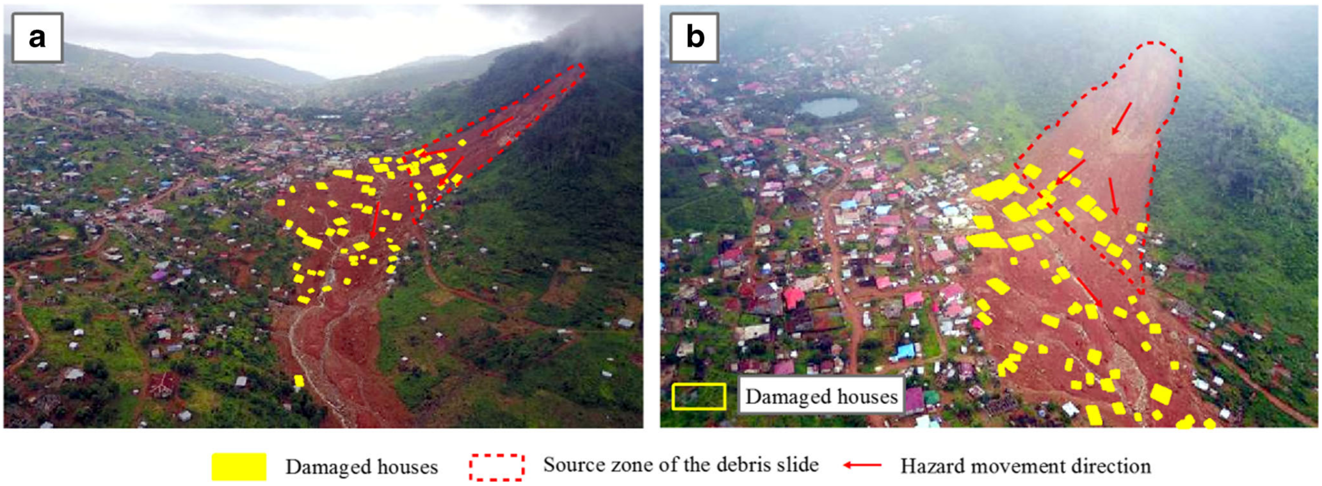

Fig. 2 Photographs of the debris slide and aftermath (Xinhua News 2017). (A) View from the west of the debris slide; (B) View from the northwest of the debris slide

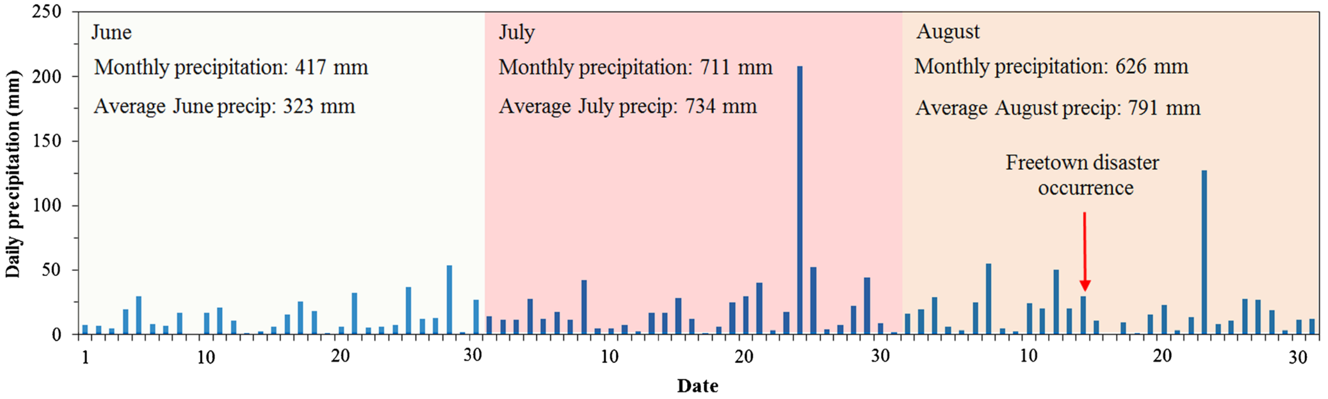

Fig. 3 Daily precipitation in Freetown, June to August 2017 (World Weather Online 2017). Rainfall peak on August 14, 2017, followed weeks of heavy rainfall. Antecedent precipitation for the rainfall peak on July 24, 2017, did not reach the geo-hazard induction threshold

interpretation, the affected area was delineated (red line in Fig. 4) and the hazard development process recorded. This showed the Freetown event comprised a geo-hazard chain of about 6.5 km length from source to terminal deposit. Using the key features of different geo-hazards outlined in Table 1, such as color, texture, and shape (Fig. 4a–c), the geo-hazard cascade was identified comprising a debris slide in the upper reaches of the catchment, followed downslope by a debris flow, which later developed into a highly-concentrated sediment-laden flood in the lower reaches (Unitar 2017). Furthermore, the cascading nature of the geo-hazard processes enhanced the scale of the disaster in terms of duration and spatial influence (Huang and Fan 2013) and, undoubtedly, enlarged the disaster losses.

Comparison of the pre- and post-disaster images enabled a detailed assessment of damage to buildings. The affected zones were divided into two categories: destroyed, where buildings were completely obliterated, and threatened, where buildings were less damaged but were susceptible to secondary hazards, for instance, buildings situated on the edge of the debris slide scar (Fig. 4II). About 234 buildings were destroyed and 109 threatened as a result of the disaster (Table 2). The debris slide area was worst affected as many buildings had been constructed on the hillside during urban expansion (Fig. 4A), with 141 buildings destroyed. Buildings located at, and adjacent to, the edge of the debris slide (Fig. 4a) are at continued risk due to the unstable eroded, vegetation-free slopes that have potential to collapse or slide as a result of future stress accumulation and/or rainfall stimulation (Ng et al. 2016c). The debris flow–affected area is smaller than that of the debris slide as it is confined to the original river course (Fig. 4b). In this area, the major causes of building destruction were the driving force of the debris flow, silt burial, and gully bank collapse. The destructive capacity of the debris flow diminished downstream. The area affected by the sediment-laden flood has fewer destroyed and more threatened buildings (Fig. 4c). The destroyed buildings were mainly washed away by flood waters, especially those on the lowermost flood plain. Threatened buildings include those which were flooded but the structure remains intact, requiring post-event assessment of their security.

Conditioning factors for devastating losses

The variable thickness loamy to clay soils (Usamah 2017) and poorly consolidated, weathered rock of the mountainside is a result of the humid tropical weathering of olivine and plagioclase-rich rocks (anorthosite, troctolite, olivine gabbro, and related mafic rock types; Chalokwu et al. 1995) of the Freetown Igneous Complex of layered igneous intrusives (Goodenough et al. 2018). These rock and mineral types are prone to rapid and deep chemical weathering by hydrolysis, producing weakened clay-rich rocks and soils. The geologic structure of the Freetown complex includes rhythmic layering and juxtaposition of lithologically distinct rock types, which weather differentially and produce failure-prone weak horizons. Froude and Petley (2018) have constructed a global dataset of fatal non-seismic landslides, covering the period from January 2004 to December 2016. According to this dataset, Freetown is a mountainous, hazard-prone area where at least six landslides have occurred between 2014 and 2016 (ESRI ArcGIS online 2018). For this disaster of 2017, natural factors such as heavy rainfall, steep slopes, intensely-weathered plutonic rocks, and abundant unconsolidated soil are major causal contributors of the Freetown cascading geo-hazard undoubtedly. Nevertheless, human activity is the critical factor for rapid, unconstrained development of exposure and vulnerability, and the principal causes of the heavy loss of life and building damage are land use change and haphazard urban expansion within an area that was already hazard prone.

Land use change intensely affects the surficial processes of mass movement and leads to the occurrence of geo-hazards. The abrupt change in land use in Freetown—especially the rapid reduction in vegetation—is likely to have been an important formative factor in hazard generation. The head scarp of the landslide and a large sector of development is located within an area formally designated as the Western Area Peninsula Forest (Sesay 2005), a reserve status that if heeded would have prevented this disaster or at least limited its scope (Munro 2009). The landslide is immediately adjacent to the new preserve boundaries of the proposed Western Area Peninsula National Park, still also referred to as a non-hunting forest reserve, and which also was submitted as a candidate for a UNESCO World Heritage Site (UNESCO 2012; Jackson 2018). If finally enforced, the elevated conservation status of the forest's remnants would be a landmark of conservation for Sierra Leone and the world, but it also would prevent further encroachment and disasters in additional geologically unstable areas.

Landsat remote sensing images of Freetown in the dry season, obtained from the United States Geological Survey (USGS 2017), were used to identify land use changes between 2007 and 2017 at

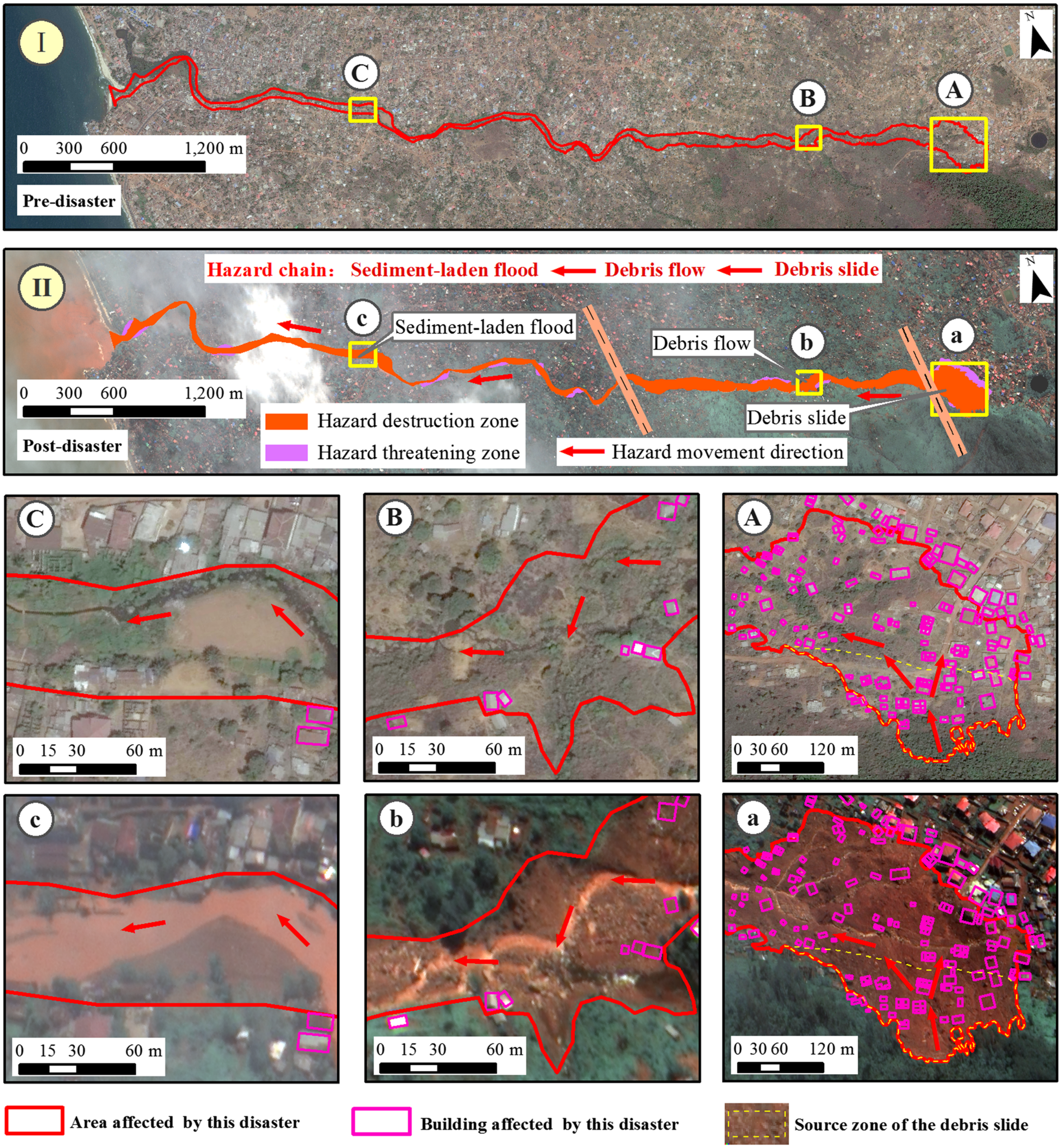

Fig. 4 Comparison of pre-disaster (I) and post-disaster (II) images with enlarged details. A–C denotes pre-disaster; a–c denotes post-disaster. Location A represents debris slide area; location B represents debris flow area; location C represents sediment-laden flood area

two-year intervals. Analysis was carried out using the Supervised Classification Method (Erbek et al. 2004) embedded in Environment for Visualizing Images software. Six types of land use categories were identified (Hu et al. 2015): "bare," "urban," "cropland," "forest," "grassland," and "water" (definitions in Table 3). Results for the spatial distribution of land use in Freetown show a substantial decrease in grassland and forest between 2007 and 2017 (Fig. 5), with a switch in the most extensive coverage from grassland to urban in 2013. The area of urban land increased progressively. For the whole of Freetown, over the 10-year period, grasslands decreased by 25% and urban areas increased by 34%. The increase in urban area is relatively large for a small city (pop. 1 million), given an increase of only 10% over the same period for an average developing city in a mountainous region such as Chongqing, China, with a population of 20 million (Nation Bureau of Statistics 2018). For the Lumley Creek watershed (Fig. 5),

Table 1 Image features of different geo-hazards

Geo-hazard	Image features
Debris slide (Fig. 4a)	Debris slides are characterized by the chaotic movement of rocks, soil, and debris mixed with water. This hazard results in an incoherent mixture of broken timber, smaller vegetation, and other debris (Easterbrook 1999). As the debris moves down the slope, it generally follows stream channels leaving a V-shaped scar (Schuster and Krizek 1978). This kind of hazard can remove, destroy, and bury buildings.
Debris flow (Fig. 4b)	Slope material that becomes saturated with water may develop into a debris flow. The resulting slurry of rock and mud may pick up trees, houses, and cars and some houses could be enveloped and buried by debris (Takahashi 1981) or collapsed and transported in the debris flow. There are mud marks on both sides of streamways.
Sediment-laden flood (Fig. 4c)	A flood is an overflow of water that submerges land which is usually dry (Kuenzer et al. 2013). When this hazard occurs, water escapes its usual boundaries and appears brownish yellow due to sediment. Buildings are submerged (Schumann et al. 2009), residents and animals are drowned or washed away, and weak constructions can collapse.

degradation of forests and grassland served as the main source of the increase in urban land. Grassland decreased by 29% and forest by 24%, while urban land increased by 34% and bare ground by 5% (especially in the last 4 years up to the disaster).

Ecosystem regulation of rainfall is reduced by forest and grassland degradation, causing soils and weathered rocks to be prone to rainfall infiltration, saturation, runoff, and erosion (Yin et al. 2016; Rahman et al. 2017; Defries et al. 2010). Therefore, rapid vegetation clearance on steep hillsides for construction in the Lumley Creek watershed further enhanced the effects of rainfall runoff and led to soil erosion and reduction in soil strength (Roy-Macaulay 2017). Antecedent rainfall plays an important role for saturating soil on hillslopes (Zhao et al. 2013) and further degrading its shear resistance (Schulz et al. 2009). In this disaster event, the induced effect of an antecedent rainfall of 547.7 mm cannot be ignored. Jiang et al. (2009) indicated that a 1% increase in soil water content results in a decrease in shear resistance of about 2.5 kPa. Hence, wet summer and the heavy rainfall on August 13 and pre-dawn on August 14 triggered slope failure.

Aside from rapid land use change, the haphazard expansion of human settlement is another critical factor in the disaster. Changes in the number of buildings on hillsides over the last 10 years were analyzed using high-resolution satellite images acquired from Google Earth. The results show an increase from 3 buildings in 2006 to 413 in 2017 over the whole area (Fig. 6), with a particularly rapid increase from 1 building in 2009 to 141 in 2017 in the debris flow area (Fig. 6).

The distribution and quality of buildings can be used as indicators of resilience for disaster risk in urban areas. Our study examines mainly the macroscale layout of the Freetown neighborhoods affected by the disaster. We only surmise some possible details about the individual structures. Detailed interpretation reveals that most new buildings in Freetown were timber-stone structures; the rapid development and haphazard layout suggests the possibility that many houses did not adhere to design codes and had weak resistance to the debris slide impacts (Fig. 2). Most victims lived in small dwellings in informal settlements at the bottom of the mountain; in other affected areas, the victims were slum-dwellers living near sea-level or close to rivers and streams, with very poor or no drainage or irrigation systems (Cole 2017). The high losses of human life and infrastructure were aggravated by poorly planned urban development (Burby et al. 2000; MLCPE and FCC 2014), with increased exposure of population and property on formerly sparsely populated, heavily vegetated hillsides; vegetation removal and increased impervious surface area lacking adequate compensating constructed drainage; and the possible lower quality of many of the houses.

Discussion

Urbanization is an indicator of economic growth and social development. However, the Freetown disaster reveals that there is a steep price to pay if growth is carried out rapidly and haphazardly. In the Freetown disaster, abnormal rainfall was the trigger for the cascading geo-hazards, while rapid and haphazard urban expansion was the catalyst. Rapid, uncontrolled, and poorly planned urban expansion occurred in an area that was already hazard-prone due to its mountainous situation, and included ecological damage due to deforestation and slope denudation, thus suggesting insufficient risk management by the government and insufficient risk awareness by individuals. Such factors reduce the resilience of local communities. As an example, Hong Kong, another mountainous city, suffered many fatalities and extensive infrastructure damage due to natural hazards such as landslides and debris flows in the 1970s, due to its growing population and urbanization. In the last decade, there have been zero casualties due to safe and sustainable development planning.

Table 2 Building damage statistics. The number of buildings is counted from the comparison between Fig. 4 A–C and a–c

Geo-hazard type	Hazard length (km)	Damage condition	Area (km^2)	Number of buildings
Debris slide	0.35	Destroyed	0.155	141
		Threatened	0.019	48
Debris flow	2.10	Destroyed	0.077	69
		Threatened	0.007	16
Sediment-laden flood	4.00	Destroyed	0.145	24
		Threatened	0.020	45

Table 3 Land used definitions used in this study

Land use type	Description
Bare	Area with exposed bare soil, rock or gravel, and little vegetation cover.
Urban	Area occupied by urban construction, residential communities, and industry, including mining, transportation, and other structures.
Cropland	Area of cultivated land including cereal crops and vegetables.
Forest	Area with trees, bamboo, and shrubs.
Grassland	Area dominated by grasses and herbaceous plants.
Water	Surface water bodies, such as reservoirs and river channels.

Mountain cities should pay more attention to issues such as urban planning, infrastructure and building quality, and education on the mountain hazard (Geotechnical Control Office 1984; Morgenstern 1997; Wong and Ko 2006; Cui et al. 2013). Cities in the mountainous region undergoes rapid development could benefit from the experiences of Hong Kong when dealing with mountain hazards during its urbanization. Mountain cities should make use of enforced conservation planning to achieve dual use both for conservation and hazard mitigation. We again note that the 2017 Freetown landslide occurred within the Western Area Peninsula Forest reserve (Munro 2009), whose sanctity was violated by uncontrolled urban growth, and the predictable (and preventable) landslide disaster consequences resulted. The same conditioning factors—climatic, geological, and land use change—uncontrolled growth within the forest reserve and other hazard prone areas near Freetown—still persist, so unfortunately this will not be the last big disaster of this type in this area.

Importance of urban planning

The explosive development of somewhat randomly scattered buildings in Fig. 6, particularly in a hazardous environment, suggests that there may be either insufficient urban planning or poor execution of a well-designed urban plan. In the case of Freetown, the latter is most likely as the "Freetown Structure Plan 2013–2028" (MLCPE and FCC 2014)—prepared by the Ministry of Land, Country Planning, and the Environment and Freetown City Council—provided institutional support to the urban planning authorities, but this plan came after considerable hasty unplanned growth had already occurred. The plan identified the need for housing development to provide for a growing population and relocation of those in disaster prone areas. However, the topographic restrictions on urban development space in such a mountainous region complicate the issue: many buildings have to be constructed on hillsides without proper slope stability protective measures, although this is contrary to the plan's sustainable development aims (MLCPE and FCC 2014; Kechebour 2015). Also, the construction of houses on the landslide site could have further caused disturbance to the slope which may reduce the slope stability (Zhu et al. 2005). These factors reduce resilience (i.e., increase vulnerability) and capacity to resist risks. In Hong Kong when any structures near a slope are to be constructed, the Civil Engineering and Development Department of Hong Kong must be notified and assessment must be conducted to ensure the safety of the proposed project and the slope prior to any work being carried out (Wong and Ko 2006).

Capacity of houses for disaster resistance

The quality and design standards of a building determine its vulnerability to geo-hazards such as floods and landslides. Construction costs could reflect the quality of houses to some extent, incorporating factors such as building materials, codes of practice, quality control, and building design-life. The 2016 UNDP Human Development Index report pointed out that the income of 52.3% of the population of Sierra Leone is below 2 USD/day. Such low-income levels prevent people from making a significant investment in housing. Indeed, records show construction costs in Freetown of only 72 USD/m^2 in 2017 (CAHF 2017), compared with 3140 USD/m^2 in Hong Kong (Langdonseah 2017). The quality and disaster resistance capacity of the buildings in these two cities plays an important role in the effect of natural hazards and contributed to the disastrous situation in Freetown. The 2004 census indicates that most Freetown households live in poor-quality housing, with ca. 25% of dwelling units having walls and roofs of zinc (MLCPE and FCC 2014; SSL 2017). A national survey of Sierra Leone in 2015 found 7.2% of the population lived in houses constructed with clay bricks, 14.9% in houses with mud walls, and 24.8% in cement constructed houses. The lack of money available for house construction in Freetown not only affects the quality of the materials used for building but also results in the lack of good foundations for the houses. Additionally, most housing and other buildings in Freetown are built by workers from the informal sector, with no proper training or supervision of construction quality (MLCPE and FCC 2014). Furthermore, the rapidity of urbanization in Freetown has led to the development of many informal settlements and slums that have no design resistance to natural hazards, with 28 informal settlements in 2015 and 30 in 2017 (CAHF 2017).

Implementation of risk management

Early warning systems and disaster emergency plans can save lives when a hazard occurs. The large death toll in Freetown may indicate the lack of an effective early warning system and disaster emergency plan prior to the August 14, 2017, event, as we have not located any such information. An early warning system could include, for instance, slope movement sensors coupled with analysis of sustained meteorological conditioning and weather predictions of extreme conditions, and monitoring of runoff and suspended sediment in streams.

Several studies (Su et al. 2008; Butz et al. 2014) have found that there is a positive correlation between education and cognition of disaster risk. Education can directly influence risk perception, skills, and risk reaction, which helps people to be more empowered and adaptive to hazards, to make decisions on where to build, and to recover from disasters. Without such education, the Sierra Leone government's efforts to evacuate and relocate communities in disaster prone areas have proved unsuccessful. For instance, after landslide and flooding incidents on September 16, 2015, affected communities were relocated to "Mile 6" on the outskirts of Freetown, but by November 2015, people had returned and were beginning to construct new settlements (Reliefweb 2018). Government expenditure on education is indicative of a population's education level. An education program related to natural hazards might be included in formal education, as has been done

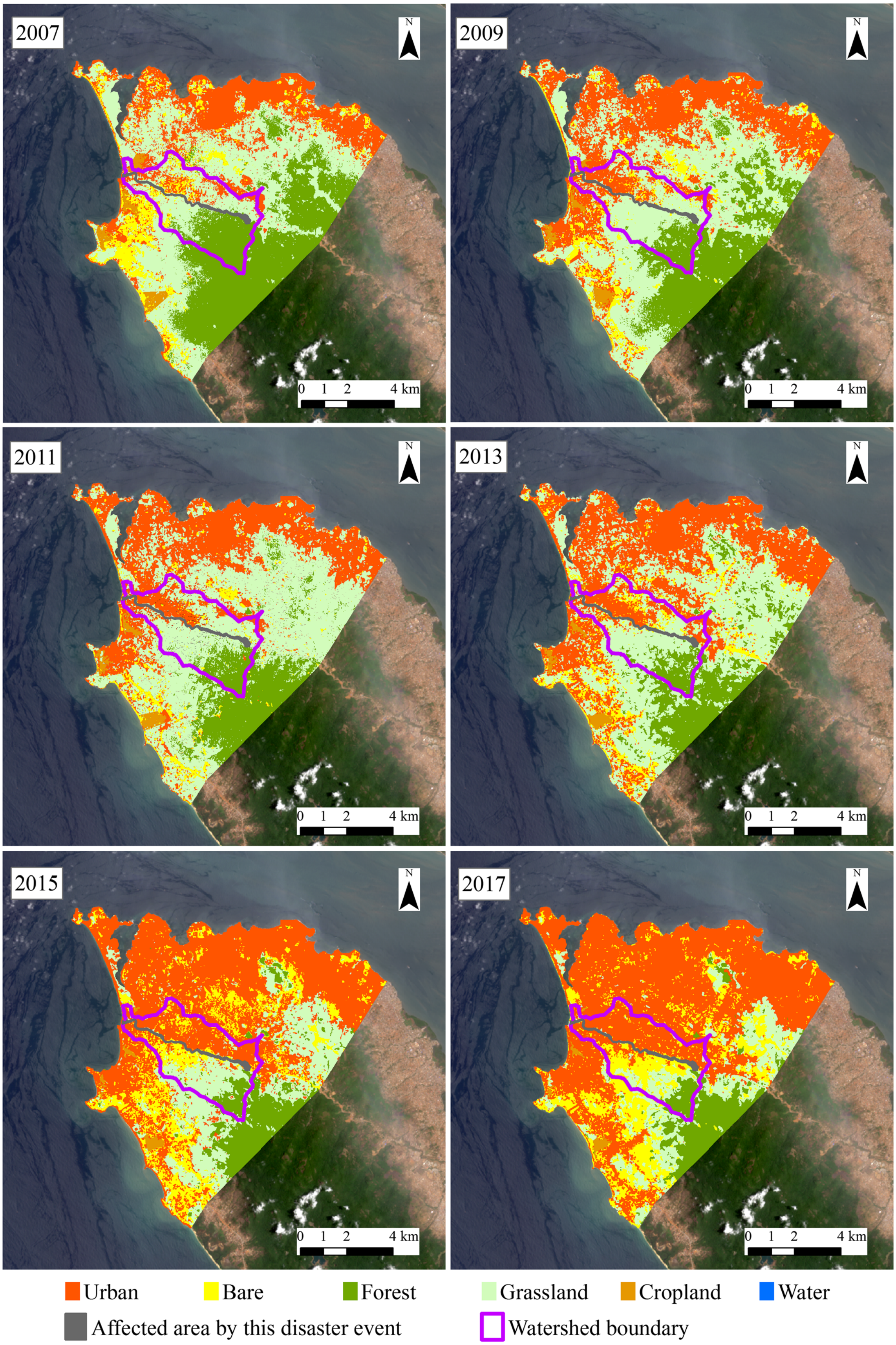

Fig. 5 Changes in land use in Freetown, Sierra Leone, 2007–2017. The maps show progressive expansion of the urban area into the mountains

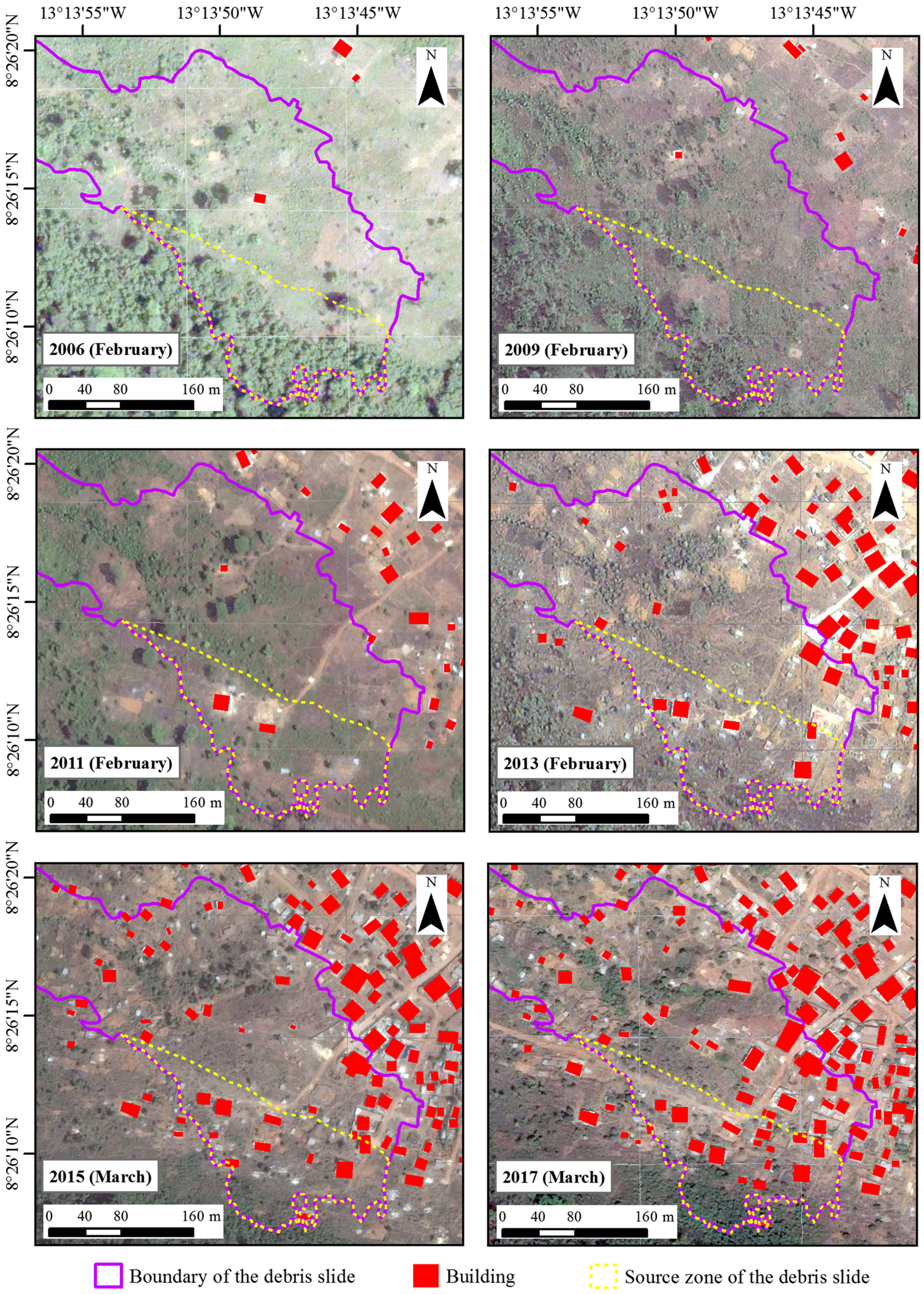

Fig. 6 Change in number of buildings around the debris slide area, 2006–2017. Progressive, but disordered, construction of buildings took place on the hillside over the period

in Hong Kong. There, lessons related to identifying and responding to natural hazards have been developed and are taught at a variety of levels of education. Based on the difference in expenditure, and access to formal education, the format and mode of delivery of education and training would likely be quite different in different countries. Records showed government expenditure on education in Sierra Leone in 2014 was only 2.66% of GDP (UNESCO 2017), lower than 3.57% in Hong Kong (UNESCO 2017). Hence, it is probable that the large disaster impact in Sierra Leone was, in part, due to its lower level of education and lower investment in improving community knowledge of risk reduction.

In summary, the Freetown disaster was due to human encroachment into an area of high intrinsic hazard. The combination of steep slopes and high rainfall made the area prone to landslides even before human intervention. The probability of hazard occurrence was greatly increased as a result of vegetation removal—in violation of a forest reserve status—and increased runoff from impervious urban surfaces. All elements of the Risk Equation (Risk = Hazard × Exposure × Vulnerability) (Lummen and Yamada 2014) increased, leading to the disaster. Had these aggravating factors not been operative, the Freetown event might have been inconsequential or not have occurred at all. The high-risk situation persists.

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