Disparities in exposure to geomorphic hazards in Bangladesh

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Abstract

Natural hazards can impair socio-economic development and disproportionately affect the poorest and most vulnerable. While global and regional studies have quantified population exposure to various natural hazards, they have so far ignored exposure to geomorphic hazards, such as coastal and riverine erosion, land subsidence and siltation of waterbodies. Using high-resolution geomorphic hazard modelling, population and poverty data, this study provides the first-ever spatial assessment of exposure to geomorphic hazards across population and poverty groups, taking Bangladesh as a case study. Bangladesh is an exceptionally geo-dynamic country, where multiple geomorphic hazards coincide with a high population density and poverty rate. We calculate that over 22 million people live within geomorphically hazardous regions, a figure that has increased by 5 million in the last 20 years. Of this exposed population, 86% live in poverty. Given such high levels of exposure disparities, geomorphic hazards need to be incorporated into disaster risk management and poverty alleviation responses in Bangladesh and beyond.

1. Introduction

Natural hazards and poverty dynamics are interconnected in complex and reinforcing ways. It is widely acknowledged that people living in poverty are particularly vulnerable to external shocks, such as natural hazards [1–4], but also that poverty can be a key driver in increasing the vulnerability of households to be harmed by these external shocks [4–6]. These mutually reinforcing factors can result in poverty traps, where the continuous setbacks can prevent individuals or whole populations from achieving their development potential, or result in households fluctuating across the poverty line over the course of their lifetimes[3,4,7–12]. These poverty traps are exacerbated when individuals have climate-sensitive, resource-dependent livelihoods and limited access to knowledge and information about adaptation [1,6,12]. The impacts of extreme weather events on poverty could be responsible for up to US$520 billion of annual well-being losses, and could push 26 million people into poverty every year [13]. Moreover, climate change could drive a further 32 to 132 million people into poverty, depending on the scenario considered [14].

The interactions between different natural hazards and poverty have been widely assessed, linking poverty with flooding[1,2,4], droughts[3,4,8,10], cyclones[15], extreme heat[3,16], saline intrusion[17] and sea level rise[18]. However, there is a gap in understanding the impacts of geomorphic hazards. Geomorphic hazards may take several forms, including coastal erosion, subsidence, siltation, landslides, river avulsions, and river erosion and deposition[19]. In this paper, our focus is upon fluvially-induced landscape changes that affect human and environmental systems[5,20], including deltaic and riverine erosion, land subsidence and siltation of waterbodies. Geomorphic hazards are not inherently bad; these are natural processes and attempts to interrupt them usually have consequences elsewhere, but they can generate risks where they intersect with dense human population with very limited capacity to adapt. In such circumstances, these processes have been acknowledged to be key drivers of socio-economic deprivation[19], particularly in highly populated and geomorphically complex landscapes that are continuously changing.

A prime example of this type of environment is Bangladesh, a country that is situated in a global hotspot for natural hazards and is also home to one of the most geomorphically complex and dynamic landscapes of the world: the Ganges-Brahmaputra-Meghna (GBM) delta. More than 80% of Bangladesh consists of floodplain land[2] exposed to frequent and severe fluvial, pluvial and tidal inundation, cyclonic storm surges, and widespread erosion. It is one of the world's most densely populated countries, with 165 million people living on just under 150,000km^2 of land. Of the 165 million people, approximately 20.5% live below the national poverty line (as of 2019)[21]. Given that fertile floodplain lands are densely settled, the migration of river channels due to sudden as well as gradual channel shifting means that valuable cultivable land is lost, settlements are destroyed and hundreds of thousands of people are displaced annually[22]. In those circumstances, geomorphic hazards may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, ecosystems and environmental resources[19,23].

As a result, key policy documents for the GBM delta, such as the Bangladesh Delta Plan 2100, have acknowledged that widespread geomorphic hazards, particularly river and coastal erosion, can act as key drivers in furthering poverty[24]. However, at present, there is no spatial understanding of population exposed to these hazards, and how this exposure is linked with poverty dynamics. This study addresses this gap, and quantifies the population exposed to geomorphic hazards in Bangladesh and assesses the variation in exposure across different poverty groups. This is achieved through the (i) identification of hotspots of geomorphic change, (ii) assessment of the key processes responsible for impacts felt by exposed populations, and (iii) assessment of the spatial dynamics of poverty within the geomorphic hotspots. This is the first-ever spatially explicitly assessment linking high-resolution geomorphic hazard maps with population and poverty data. The approach taken in this Bangladesh case study is applicable and relevant to other geomorphically dynamic river deltas in the world, where more than 500 million people live and where these interactions have similarly never been assessed[25,26].

2. Methods

The concept of exposure refers to the presence of people, livelihoods, species or ecosystems, environmental functions, infrastructure, or assets in places and settings that could be adversely affected by geomorphic hazards[23,27–29]. Exposure has been reported to be the most significant determinant of disaster risk[30,31]. This study examines whether there is an exposure bias for poorer populations to geomorphic hazards in Bangladesh by intersecting high-resolution geomorphic modelling with population and poverty data. A poverty exposure bias is defined as a measure of the number of people living in poverty exposed to hazards compared to all people exposed across the country[4,32].

The methodology is broken down into the following four main steps, as outlined in the flowchart below (Fig. 1), with quantitative statistical analyses undertaken in each step: (i) generating a national geomorphic hotspot map for Bangladesh; (ii) assessing population exposed to geomorphic hazards nationally and regionally; (iii) assessing how geomorphic hazards impact different poverty groups; and (iv) exploring how population exposure to geomorphic hazards may change in the future. Each of these steps is discussed in more detail in the following sections.

2.1. Geomorphic hotspot analysis

Until recently, there has not been detailed mapping of geomorphic change in Bangladesh. However, Jarriel et al.[33] developed the DeepWaterMap model, which is entirely based on remotely sensed imagery and automatically distinguishes water from land, clouds, and shadows within each satellite image, producing an almost binary representation of channel presence[33]. Their analysis was applied to the coastal area of the GBM delta, and builds on previous work by Isikdogan et al.[34,35] and Passalacqua[36], who developed the first automatic extraction of channel networks from satellite imagery. This approach eliminates the laborious process of manual inspections and delineation, and enables monitoring of near-live changes in complex channel networks[34,35].

Here we apply the DeepWaterMap model to all of Bangladesh from 1987 to 2022. Nation-wide satellite imagery is obtained from Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI, at a resolution of 1 arc second (approximately 30m x 30m). Images from the dry season (October until March) are chosen, as there is less cloud cover and channels are at their lowest stage[33]. For each of the 35 years assessed, one composite image is created by taking the median value of all cloud-free pixels[33,34]. This approach constrains the effects of changes in channel levels and dampens the unavoidable fluctuations in tidal levels[33].

The composite images are subsequently incorporated into the DeepWaterMap model. The model uses a convolutional neural network approach to produce maps of water presence, where, after normalisation, land surface pixels are given a value of zero, channels are given a value of 255, and non-channelised features (flooded polders or shrimp ponds) are given values in between[33]. The resulting DeepWaterMap channel system is then used to map the Channelised Response Variance (CRV), a metric developed to track changes in channel morphodynamics over space and time[33]. High positive CRV values illustrate hotspots of increasing channel presence (erosion) or wetting (waterlogging) over time, whilst high negative CRV values represent key areas that are decreasing in channel presence (accreting land). The two extremes on the CRV spectrum therefore provide an indication of where the most frequent and significant fluvial geomorphic hazards are located across Bangladesh. Using Geographic Information Systems (GIS) to analyse the outputs of the CRV model, the overall geomorphically unstable land area can be calculated, as well as for the erosion and deposition extremes.

2.2. Population exposure to geomorphic hazards

WorldPop[37] data for Bangladesh is used to map the population exposed to geomorphic hazards. This population data is simulated using a semi-automated dasymetric modelling approach that combines census data with remotely-sensed and secondary data within a “Random forest” estimation technique[38]. This open-access dataset provides spatial annual population data from 2000 until 2020, at a resolution of 3 arc seconds (approximately 100m x 100m) available at the country level. This spatial population layer for each year is intersected with the geomorphic hotspot map from the above CRV model to assess the proportion of the Bangladeshi population living within these geomorphically unstable areas. Where erosion or accretion cuts partially across a population grid (due to differences in resolution), the proportion of the population grid impacted is calculated, assuming uniform population density across the population grid cell. The analyses are then repeated for each of the eight administrative divisions (Rangpur, Rajshahi, Mymensingh, Sylhet, Dhaka, Khulna, Barisal, and Chittagong) to understand the spatial trends in changing population exposure from 2000 until 2020. These spatio-temporal trends within hotspots for both Bangladesh and the eight administrative divisions are then compared to background population growth over the same 20-year time period across all of Bangladesh.

2.3. Poverty exposure bias

The poverty exposure bias is estimated by comparing poverty levels within the geomorphic hotspots to those across all of Bangladesh, using high-resolution spatial poverty maps developed by Steele et al.[39]. These poverty maps were created through the combination of remote sensing, mobile phone operator call detail records, and traditional survey-based data from Bangladesh to provide highly granular maps of poverty for three commonly used indicators of living standards: (i) the Demographic and Health Surveys (DHS) Wealth Index (WI); (ii) an indicator of household expenditures (Progress out of Poverty index), and; (iii) household monetary income[1,39]. In this study, the DHS WI is extracted, as it measures household welfare, which is based on asset ownership (e.g., refrigerator, radio or bicycle), dwelling characteristics, and access to basic services, such as clean water, electricity and healthcare[1,39]. This type of information more robustly captures the multidimensional nature of poverty than income-based data[17], and better captures the wider welfare impacts of geomorphic hazards, such as asset losses, a disruption in educational and health services, and reduced consumption[15,40,41]. The WI values can be either positive or negative (ranging between – 1.165 and 2.185 for Bangladesh), with greater positive values indicating higher socio-economic status[1,39].

By overlaying all three layers (i.e., geomorphic hotspots, population, and poverty), the number of people within geomorphic hotspots across all poverty groups can be estimated. The poverty levels (taken as the WI) within the geomorphic hotspots are then interpolated between wealth index levels and normalised to the highest-level frequency of the population group. The resulting distribution curves of people living in poverty are then compared to the country as a whole to estimate whether there is an exposure bias for populations with a lower wealth index. This analysis is subsequently repeated at the administrative division level. In order to assess whether the exposure bias is statistically significant (p-value < 0.05), the non-parametric Mann-Whitney U statistical test is performed, as the underlying distributions are non-normal.

2.4. Future population exposure

Population projection models can be used to explore how the exposure to geomorphic hazards may change in the future. In this study, future population projections are taken from Van Huijstee et al.[42], who developed the 2UP model to simulate future population distribution on a global scale from 2010 until 2080, also distinguishing between rural and urban population changes. These spatially-explicit population projections have a relatively high resolution of 1km near the equator, providing the most detailed future population scenarios currently available for all Shared Socio-economic Pathways (SSPs)[42]. For the purpose of this study, SSP2 (“Middle of the Road”) is used, reflecting the “middle-ground” socio-economic development trajectory for Bangladesh. Thus, future population exposure is assessed at the country-wide scale, as well as within the identified geomorphic hotspots, for the short-term (2030), medium-term (2050) and long-term (2080). There is currently no model predicting future geomorphic change; hence, this exploration of future exposure assumes that geomorphic hotspots remain the same as observed over the past 35 years. Whilst in the future we can expect the precise location of geomorphic changes to evolve, the general hotspots of geomorphic change are likely to remain active over the coming decades[19].

3. Results

3.1. Hotspots of geomorphic change in Bangladesh

The national hotspots of geomorphic change in Bangladesh over the last 35 years are illustrated in Fig. 2, which were generated by applying the CRV analysis onto the DeepWaterMap model outputs.

Across all of Bangladesh, 28,300km^2 of land has undergone geomorphic change over the last three and a half decades. Of the 28,300km^2, 38% (10,800km^2) has been exposed to continuous erosion or waterlogging (blue), whilst 62% (17,500km^2) has primarily experienced accretion or drying up of surface water bodies (brown). When looking only at the more extreme ends of the CRV spectrum, the total land area that is more severely affected is 6,568km^2, 2,049km^2, and 782km^2, for the 25%, 10% and 5% ends of the CRV spectrum, respectively. As evident in Fig. 2, the fluvially-active area (i.e., areas within or nearby river channels) is the most geomorphically unstable, particularly within the braided Jamuna River corridor and the Meghna Estuary. In addition, the north-eastern Sylhet basin and the south-western poldered region are also experiencing widespread waterlogging or drying up. Both of these regions are subsiding landscapes; the south-western polders are subsiding due to the interruption of sedimentation within riverine floodplains as a result of embankment infrastructure[19,43,44], whilst the north-western Sylhet basin is subsiding predominantly due to reduced river flows (and thus sediment) within the Old Brahmaputra river due to underlying tectonic processes and upstream river developments[19].

3.2. Population exposed to geomorphic hazards

At present, just over 22 million people (13% of total population) live within geomorphically hazardous regions in Bangladesh, a figure that has grown by 5 million since 2000 (Fig. 3). From 2000 until 2005, the population exposed increased by 6%, which slowed to 2% between 2005 and 2010, and then once again increased to 6% from 2010 until 2015 (orange line in Fig. 3). However, between 2015 and 2020, the growth rate of people exposed to geomorphic hazards increased to 10%. When this is compared to Bangladesh as a whole, this sudden rise in population growth in the last five years is not evident; Bangladesh has experienced a relatively consistent population growth rate of between 7% and 8% over the last 20 years (grey line in Fig. 3). The fact that the growth in population within geomorphic hotspots is greater than background population growth rates over the last five years suggests that more people are being driven to live in high-risk areas and that Bangladesh's efforts to reduce population vulnerability to natural hazards ought to consider this increase in exposure.

When considering the spatial changes of population exposure over the last 20 years (Fig. 4),

it becomes evident that the Sylhet, Dhaka and Chittagong divisions have the greatest increases in exposure, whilst the southern coastal divisions of Khulna and Barisal have the least. This can be attributed to greater background population growth in Dhaka and Chittagong, and more widespread geomorphic change in the Sylhet basin.

3.3. Geomorphic hazards and poverty

Geomorphic hotspots are predominantly inhabited by the poorest portions of the population; of the 22 million people exposed to geomorphic hazards in Bangladesh, 86% are living in poverty (WI $\leq$ 0), with 40% living in extreme poverty (WI $\leq$ -1) (Table 1). When this is compared to Bangladesh overall (Table 1), it is evident that the extreme poverty quartile (WI $\leq$ -1) makes up 20–22% of the population, half of that observed within geomorphically hazardous areas of the country. This finding suggests that there is an exposure bias for poor people to geomorphic hazards (i.e., poorer people are more likely to live in highly geomorphically hazardous areas). These trends are diagrammatically represented in Fig. 5, which clearly illustrates this shift in the population's socio-economic structure between the population within geomorphically hazardous areas and Bangladesh as a whole. It is evident from Fig. 5 that Dhaka and Sylhet are the two predominant divisions where the poverty exposure bias is greatest. In order to test whether the overall exposure bias is statistically significant, the Mann-Whitney U test was performed. The resulting test statistic and p-value were found to be U=6116.5 and p = 0.022, respectively, which implies that the shift observed in Fig. 5 is statistically significant.

Table 1
Comparison of poverty exposure within geomorphic hotspots and all of Bangladesh.

Geomorphic hotspots					Bangladesh				
Poverty	% of Population (2000)	% of Population (2020)	Absolute increase	Growth rate	Poverty	% of Population (2000)	% of Population (2020)	Absolute increase	Growth rate
-1.2 – -0.5	41%	40%	1,619,917	1.24	-1.2 – -0.5	22%	20%	6,793,720	1.25
-0.5– 0.5	45%	46%	2,134,085	1.28	-0.5– 0.5	62%	59%	21,599,329	1.29
0.5– 1.5	12%	12%	691,461	1.36	0.5– 1.5	13%	16%	10,904,544	1.68
1.5– 2.2	2%	2%	233,291	1.79	1.5– 2.2	3%	5%	3,840,315	1.97

In addition, Table 1 illustrates that population growth rates for the two lower wealth quartiles are relatively similar between the hazardous areas and nation-wide; however, for the upper wealth quartiles there is a more substantial difference. The slower growth of the upper wealth quartiles observed within geomorphically hazardous regions likely suggests that people within these areas may find it more difficult to escape poverty.

When assessing the spatial distribution of poverty dynamics within the geomorphic hotspots across the eight administrative divisions (Fig. 6), it becomes evident that the northern divisions of Rangpur and Mymensingh have the highest proportion of exposed populations living in extreme poverty. This is likely linked to these divisions generally having the highest poverty rates, rather than disproportionate impacts of geomorphic hazards[45]. Interestingly, the spatial trends are also related to the location of cities relative to the geomorphic hazard hotspots (Dhaka and Chittagong), as cities are areas with better access to basic services and a greater concentration of assets, thus skewing the WI for the rest of the division.

3.4. Future population exposure to geomorphic hazards

Bangladesh's population is projected to continue to grow to just under 200 million people by 2050 and then gradually reduce thereafter[42,46]. In order to explore how future exposure to geomorphic hazards may unfold, the 2UP population growth estimates for SSP2[42] are combined with the geomorphic hotspots map. Given that geomorphic change has been occurring in relatively defined corridors (Fig. 2), this scenario analysis assumes that future geomorphic processes continue to take place within these corridors. By taking the population projections from the 2UP model, future exposure to geomorphic hazards may increase by up to 29% by 2050, of which 14% is likely to occur in urban areas, whilst 86% is expected to increase in rural areas. This finding emphasises that the currently disproportionate exposure to geomorphic hazards experienced by poorer and rural populations in Bangladesh will continue to grow over the coming decades.

4. Discussion

The Government of Bangladesh has an ambitious plan to eradicate most poverty by 2033, and completely by 2050, in line with the United Nations Sustainable Development Goals (SDGs)[18,24]. It also plans for the country to be resilient and prosperous in the face of climate change, with significant mobilisation and allocation of resources towards disaster risk reduction[24,47]. Previous studies have argued that disaster risk management and poverty alleviation go hand in hand[4,47]. Here, we demonstrate that the joint efforts in disaster risk and poverty reduction ought to also consider geomorphic hazards.

This study quantifies the dynamism of Bangladesh's landscapes, with vast areas undergoing geomorphic change at the annual and decadal scales. These geomorphic processes can be both episodic and chronic. The geomorphic hotspot modelling results in this study have shown that there are significant areas in Bangladesh that are prone to continuous and persistent geomorphic changes, both in terms of erosion and subsidence, and accretion and drying up of land. The erosional or subsiding processes can degrade or completely consume valuable floodplain lands, leading to losses of livelihoods, reduced agricultural productivity and income, food insecurity, unemployment, and ultimately social unrest and internal displacement[17]. Contrastingly, the drying up or accretion of land may provide benefits such as newly created land, but may also result in siltation of waterways, which has negative impacts on biodiversity, fishing livelihoods and navigation[19]. Unlike other hazards, such as flooding, there are limited options for coping with erosion hazards; if a household's land is removed by a river or the sea, temporary or permanent relocation is inevitable[22,48]. Migration in Bangladesh is a historical phenomenon; the country's census of 2011 states that 10% of the total population of Bangladesh are lifetime internal migrants[49]. A large proportion of internal migration is not permanent, but rather seasonal or temporary, predominantly as a response mechanism to environmental factors and shocks or due to seasonal or temporary employment opportunities elsewhere[49,50].

Charlands (river islands), where cyclical relocation is widespread, are a striking instance of a more-or-less constant process of internal migration which is driven by geomorphic change. There are approximately 6.5 million *chaura* people (*charland* dwellers) who cope with regular flooding and riverbank instability, of which approximately 65% live on the Jamuna River *chars*[22,28,51–53]. Population relocation is driven by landscape changes of fluctuating erosion and accretion patterns within the rivers[22,28]. When considering different *charland* communities across Bangladesh, erosion-prone households have been shown to experience relocation every five years on average, although some households experience displacement as much as three times within a single year of severe river erosion (for example in 1997-98)[28,51]. Resettlement is most commonly localised, with average distances of around 12km[51]. Typically, displaced landowners temporarily resettle on other areas of the same *char*, or on a nearby *char*, and then return to their land when it re-emerges from the river[28,51]. Many dwellings have, for instance, converted from traditional clay, straw and bamboo houses to tin sheds, as these are much easier to dismantle and shift in the case of erosion[28]. This localised re-settlement pattern is most likely linked to not being able to afford to move greater distances, as well as the hope that their land will re-emerge from the river, allowing them to return to their place of origin in the future[22].

Insecure land ownership and an uneven distribution of accessibility to land plays a significant role in driving inequalities to geomorphic risk[6,28,54]. Even land-rich households struggle finding suitable areas to relocate to when their homesteads are lost to erosion[28]. Moreover, given the high prices of land on the mainland, selling *charland* (which is, in itself, restricted due to limited ownerships rights) to acquire land on the more stable mainland is not feasible for many *charland* dwellers[28]. Oftentimes, in response to such land losses or agricultural unproductivity, farmers or fishers are forced to sell their productive assets, reduce their food consumption, stop children's education and take informal loans[6,55,56]. Thus, households living in these high-risk areas tend to have fewer alternative livelihood opportunities, fewer financial resources to spend on housing, and tend to also have a lack of access to regional and global markets, which combined, furthers their vulnerability to these geomorphic hazards[2,4,6].

The changing river courses therefore stimulate a process of involuntary migration, and can accentuate the process of impoverishment, resulting in enormous economic, social and psychological costs for the displaced populations[22]. The most severely impacted households may fall into poverty traps as a result of geomorphic shocks or more gradual riverine or coastal erosion, as the losses induced by these hazards repeatedly exceed the local recovery capacity, impeding longer-term future recovery and economic growth[6,18,57,58]. In response to this, the Bangladeshi government, with funding support from the UK and Australia, initiated the Chars Livelihoods Programme (CLP) in 2002, lasting until 2016, with the aim of substantially reducing extreme poverty for people living on the *chars* in Bangladesh[59]. As a result of the programme, 88% of targeted households escaped extreme poverty, which was achieved predominantly through promoting sustainable livelihoods and improving markets for the poor, better protecting communities from flooding and erosion, increasing access to water, sanitation and hygiene services, improving food security and supporting women's empowerment and social development[59]. The lessons learnt by the people facing these stresses is fundamental in successfully alleviating both geomorphic risks as well as poverty[22,55].

5. Conclusion

Natural hazards are interwoven with poverty dynamics in highly complex and reinforcing ways. Geomorphic processes, such as coastal and riverine erosion, are rarely at the forefront of policy debates and scholarly analysis of natural hazards. However, in geomorphically complex environments, such as large riverine and deltaic systems, geomorphic hazards can exacerbate environmental degradation, socio-economic marginalisation, and poverty. This study presents the first exploration of the links between exposure to geomorphic hazards and poverty, taking Bangladesh – one of the most geomorphically dynamic regions of the world – as a case study.

At present, over 22 million people are exposed to geomorphic hazards in Bangladesh, which has increased by 5 million people in the last 20 years. Of the 22 million people exposed, 86% (18 million) are living in poverty, with 40% (8.5 million) living in extreme poverty. The spatial exposure to geomorphic hazards is influenced by the location of cities (where population density is higher, but poverty tends to be proportionately lower) relative to geomorphic hotspots. Crucially, the percentage of people living in extreme poverty within geomorphically hazardous regions is double that of Bangladesh as a whole, though there has not been a significant increase in this proportion over the last 20 years. This statistically significant disparity suggests that the poorest portion of the population are disproportionately exposed to geomorphic hazards. With Bangladesh's increasing pressures of continuous rapid population growth and growing frequency in climatic shocks, more people will be exposed to geomorphic hazards, and the findings show that the poorer and more rural populations will continue to be the most severely affected.

Geomorphic hazards, in particular erosion, can result in temporary or permanent relocation of affected households, as the rivers or sea capture the homes and livelihoods of millions of people annually. The losses and continuous re-building of lives in equally high-risk areas can impede longer-term recovery and economic growth. These mutually reinforcing feedback loops, where geomorphic hazards can exacerbate poverty and poverty can exacerbate vulnerability to geomorphic hazards, can create vicious risk and poverty traps, and need to be jointly addressed for disaster risk reduction and poverty eradication efforts to be effective across deltaic nations.

Declarations

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Author contributions

A.P. conceptualised the research, undertook the geomorphic modelling and data analysis, and wrote the manuscript. T.T. contributed to the conceptualisation of the research, geomorphic modelling, and data analysis, and reviewed the manuscript. E.B. and J.W.H contributed to the conceptualisation and reviewed the manuscript prior to submission.

Competing interests

The authors declare no competing interests.

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Figures

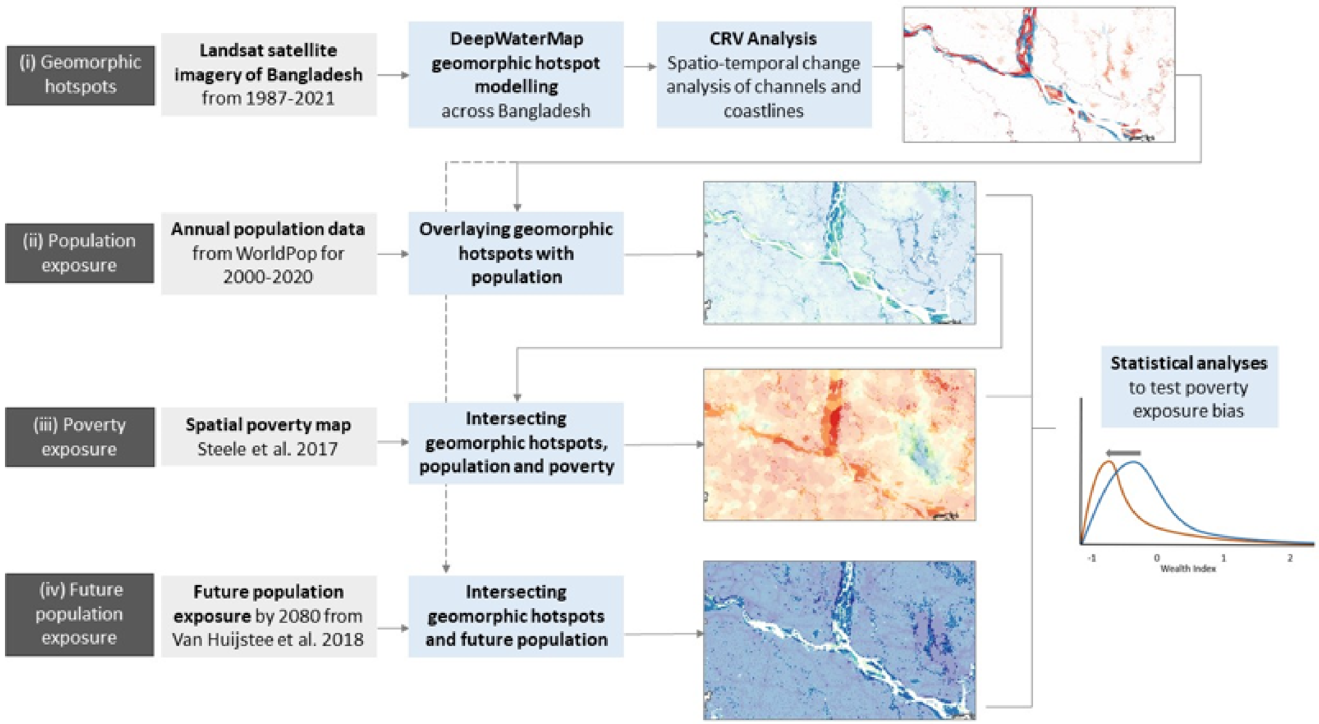
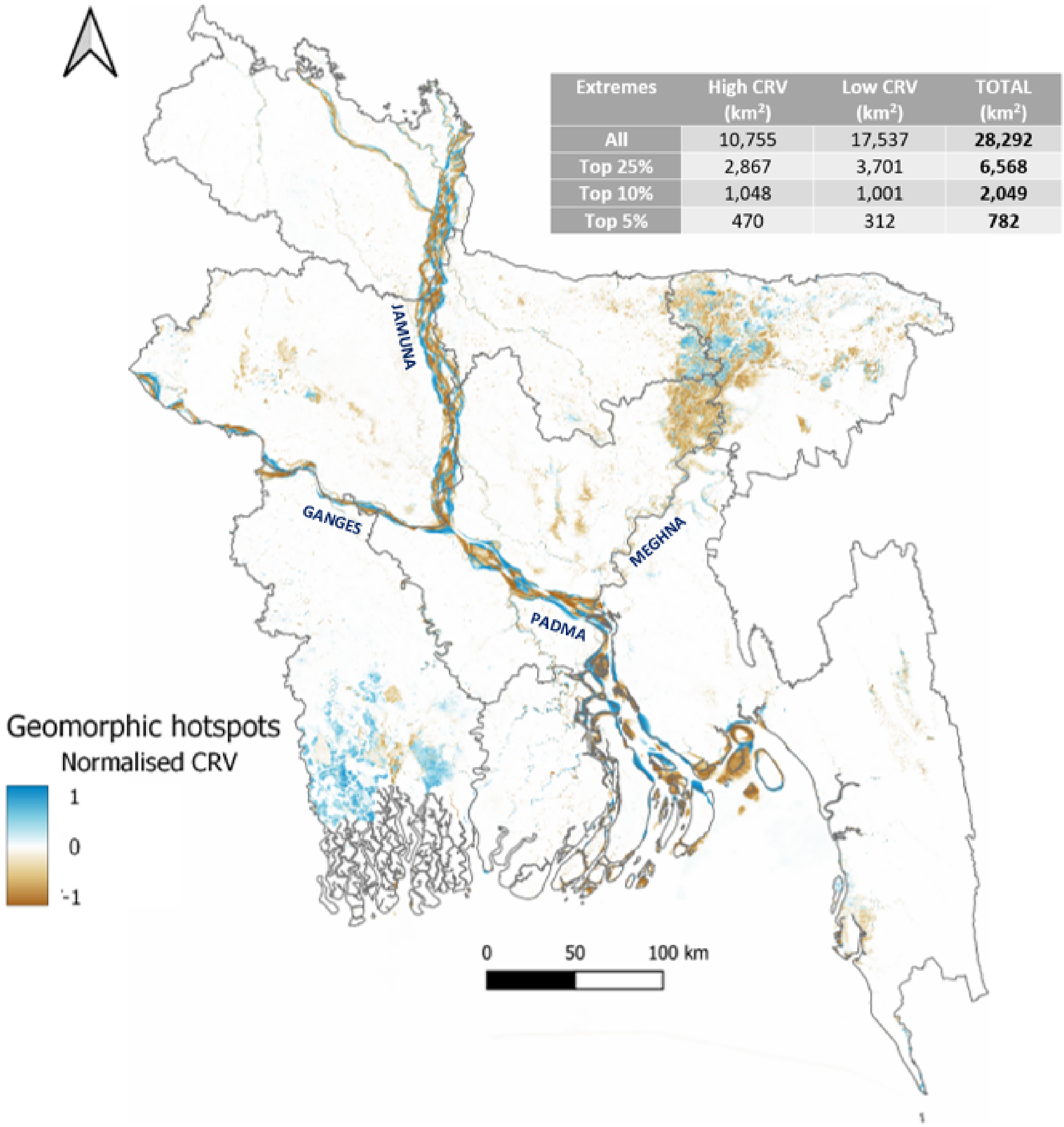


Figure 1

Flowchart visualising the method applied in this study. Dark grey boxes indicate the aim of the step, light grey boxes indicate data inputs, blue boxes represent methodological processes, and maps illustrate the key outputs. CRV: channelised response variance.



Extremes	High CRV (km^2)	Low CRV (km^2)	TOTAL (km^2)
All	10,755	17,537	**28,292**
Top 25%	2,867	3,701	**6,568**
Top 10%	1,048	1,001	**2,049**
Top 5%	470	312	**782**

Figure 2

Geomorphic change across Bangladesh from 1987-2022. Brown colours indicate decreases in channel presence (drying up or accreting) and blue areas represent increases in channel presence (wetting or erosion). The intensity of the colour represents the frequency of change over the 35-year period. The table details the areas for all geomorphic hotspots, as well as for the extreme ends (25%, 10% and 5%) of the CRV spectrum.

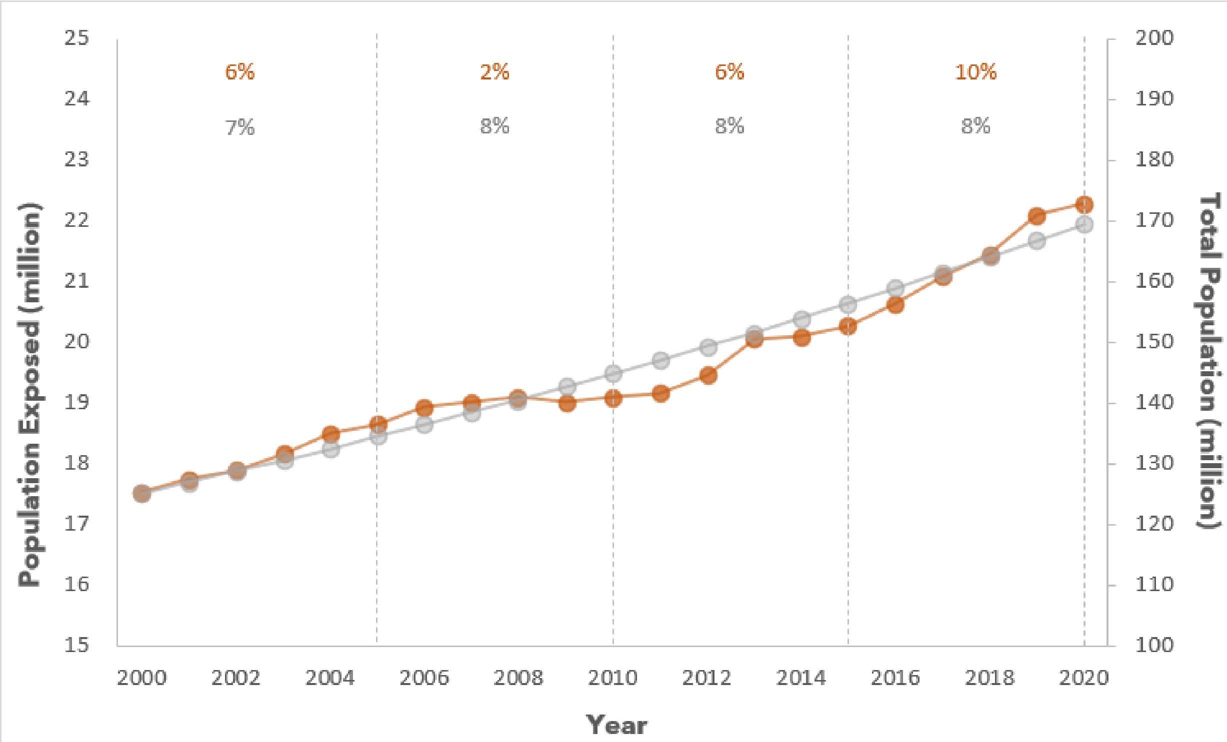


Figure 3

Number of people exposed to geomorphic hazards in Bangladesh over the last two decades (orange) and total population growth over the same time period (grey), based on WorldPop[37] population data.

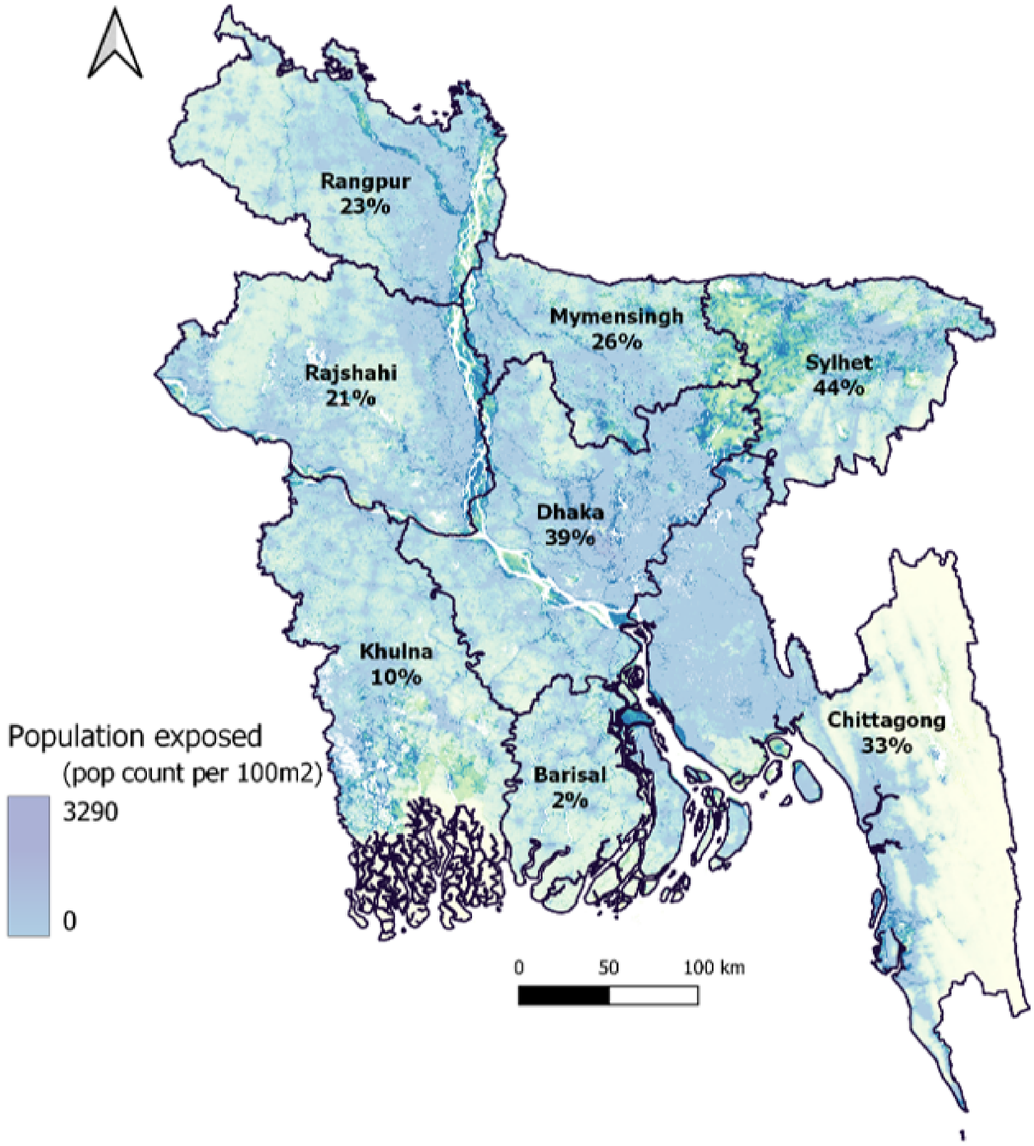


Figure 4

Spatial distribution of population exposed to geomorphic hazards in Bangladesh. The percentages highlight the overall increase in population exposed per administrative division over the last two decades.

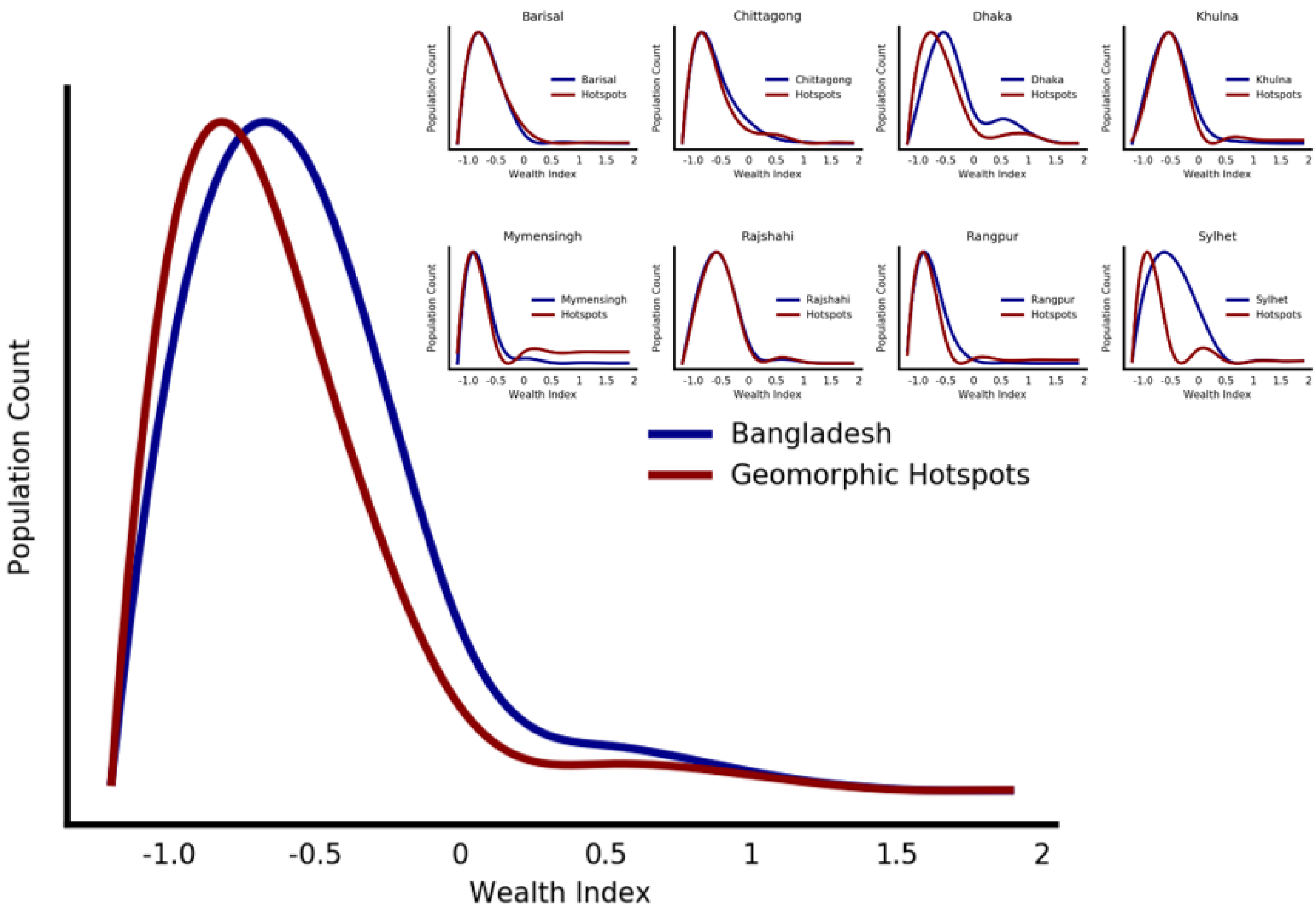


Figure 5

Normalised histograms showing the distribution of the population's socio-economic structure for 2020, comparing the population living within versus outside the geomorphic hotspots. Top right panel shows the same histograms for the eight administrative divisions.

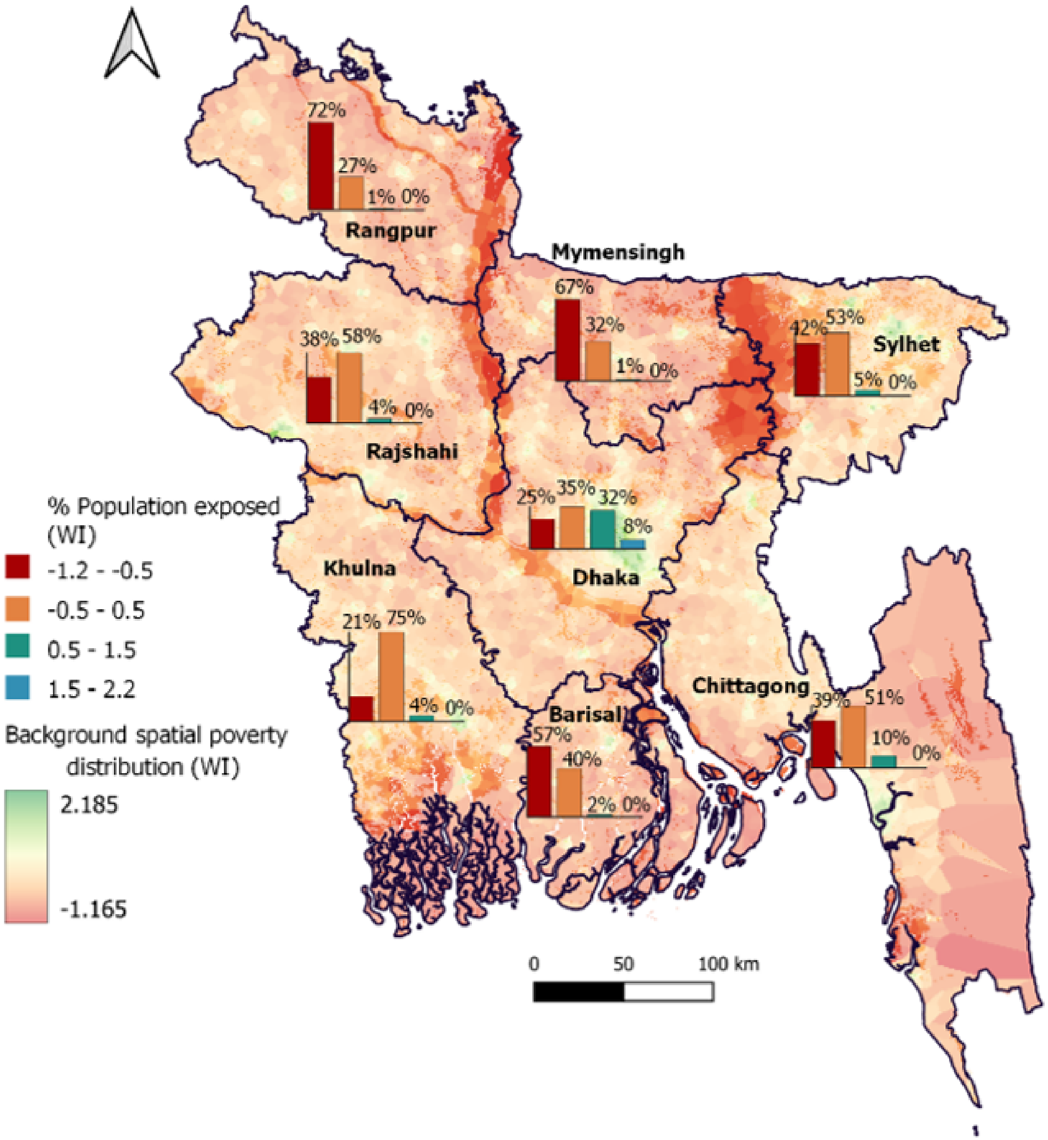


Figure 6

Mapping exposure to geomorphic hazards across the wealth quartiles. The poverty levels within geomorphic hotspots are highlighted with greater colour intensity (background more transparent). The bar charts illustrate the proportional percentage of population in geomorphic hotspots for each division for the year 2020. WI=Wealth Index.