

Disparities in exposure to hydrogeomorphic hazards in Bangladesh

Received: 18 May 2022

Accepted: 25 September 2025

Published online: 20 November 2025

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Natural hazards can impair socio-economic development. While population exposure to various natural hazards has been quantified, the exposure to hydrogeomorphic hazards – involving water-induced landscape changes – remains unknown. Using high-resolution hydrogeomorphic modelling, combined with population and wealth data, this study provides a national-scale spatial assessment of exposure to hydrogeomorphic hazards across population and wealth groups, taking Bangladesh as a case study. Bangladesh is an exceptionally geo-dynamic country, where multiple hazards coincide with a dense population (1300 people per km²) and a high poverty rate (20%). Here we show that over 22 million people, making up 13% of the population, live within hydrogeomorphically unstable regions. Of the 22 million, 86% are within the lowest wealth groups of the population. Given such a high level of disparity in exposure, hydrogeomorphic hazards must be incorporated into disaster risk management and poverty alleviation efforts in Bangladesh and beyond.

Exposure to natural hazards and poverty are interconnected in complex and reinforcing ways. Low-income and marginalised populations are typically more likely to live in hazard-prone areas, often with limited capacity to reduce their exposure by moving to safer locations or to a strongly built settlement^{1,2}. Thus, multiple studies have acknowledged that people living in poverty are particularly vulnerable to natural hazards^{3–7}, but that poverty can also be a key driver in increasing the vulnerability of households to such external shocks^{7–9}. 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^{6,7,10–15}. These poverty traps are exacerbated when individuals have climate-sensitive, resource-dependent livelihoods and limited access to up-to-date information on climate hazards and protective infrastructure^{4,9,15}.

The interactions between different natural hazards and poverty have been widely assessed, linking poverty with flooding^{4,5,7,16}, riverbank erosion^{17–20}, droughts^{6,7,12,13}, cyclones^{1,21}, extreme heat^{6,22}, saline

intrusion²³ and sea level rise²⁴. However, the interplay between hydrogeomorphic hazards and poverty have not yet been quantified. Hydrogeomorphic hazards may take several forms, including coastal erosion and deposition, river erosion and deposition, subsidence, siltation, landslides, and river avulsions²⁵. In this paper, the focus is on water-induced landscape changes that affect human and environmental processes in deltaic systems^{8,26}. These changes are expressed through four predominant processes: (i) riverine erosion and deposition; (ii) conversion of deltaic land to water bodies; (iii) wetting and drying of land due to land-use changes; and (iv) coastal erosion and accretion. These dynamics take place due to the complex interactions between background natural processes and extensive human interventions. It is important to note that hydrogeomorphic hazards are not inherently bad; they are natural processes of landscape evolution, and attempts to interrupt them are usually short-lived and have consequences elsewhere, but they can generate risks where they intersect with dense populations with limited capacity to adapt²⁷. Importantly, unlike other hazards, such as flooding, there are limited options for coping with hydrogeomorphic hazards. For example, if a household's

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land is removed by a river or the sea, temporary or permanent relocation is inevitable^{27–29}. In such circumstances, hydrogeomorphic processes have been acknowledged to be key drivers of socio-economic deprivation²⁵, particularly in densely populated and geomorphically complex landscapes.

Bangladesh is a prime example of this type of environment. The country is situated in a global hotspot for natural hazards and is also home to an exceptionally geomorphically complex and dynamic landscape: the Ganges-Brahmaputra-Meghna (GBM) delta. More than 80% of Bangladesh consists of floodplain land⁵ exposed to frequent and severe flooding and widespread erosion and hydrogeomorphic change²⁵. It is also one of the world's most densely populated countries³⁰, with over 165 million people living on just under 150,000 km² of land. Of the 165 million people, approximately 20.5% live below the national poverty line of less than US\$1.90 (United States Dollar) per day in purchasing power parity (as of 2019)³¹. Given the densely populated fertile floodplain lands, the migration of river channels due to sudden and gradual channel shifting, as well as increasingly exposed coastlines to erosion and inundation, means that valuable cultivable land is lost, settlements are destroyed, and hundreds of thousands of people are displaced annually^{20,28}.

Consequently, key policy documents for the GBM delta, such as the Bangladesh Delta Plan 2100, have acknowledged that hydrogeomorphic hazards, particularly river and coastal erosion, can act as key drivers in furthering poverty³². Although previous work in Bangladesh has assessed fluvially-induced channel changes^{18,33–36}, as well as

the vulnerability to erosion^{18–20,29,37–39}, and multiple coastal hazards^{1,40–42}, these studies did not focus on different hydrogeomorphic hazards at the national scale and did not explicitly combine these hazards with exposed populations and their associated levels of wealth.

This study addresses this gap by presenting a framework to quantify hydrogeomorphic risk that intersects hazard modelling with population exposure across different wealth groups (see Supplementary Fig. 1), with an application to Bangladesh. This is achieved through the (i) identification of hotspots of hydrogeomorphic changes at the national scale; (ii) assessment of population exposed to hydrogeomorphic hazards; and (iii) assessment of wealth levels of the exposed population. This study, therefore, presents a national-scale understanding of disparities in exposure to hydrogeomorphic hazards. The approach taken in this Bangladesh case study is applicable and relevant to other geomorphically dynamic deltaic nations in the world, where more than 500 million people live and where these interactions have similarly not been assessed^{43–45}.

Results

Hotspots of hydrogeomorphic change in Bangladesh

Across all of Bangladesh, 28,300 km² of land has undergone hydrogeomorphic change over the last three and a half decades, which equates to 20% of the country's land mass (Fig. 1). Of the 28,300 km², 38% (10,800 km²) has been exposed to erosion or wetting of land (e.g., waterlogging or extended inundation) (blue), while 62% (17,500 km²)

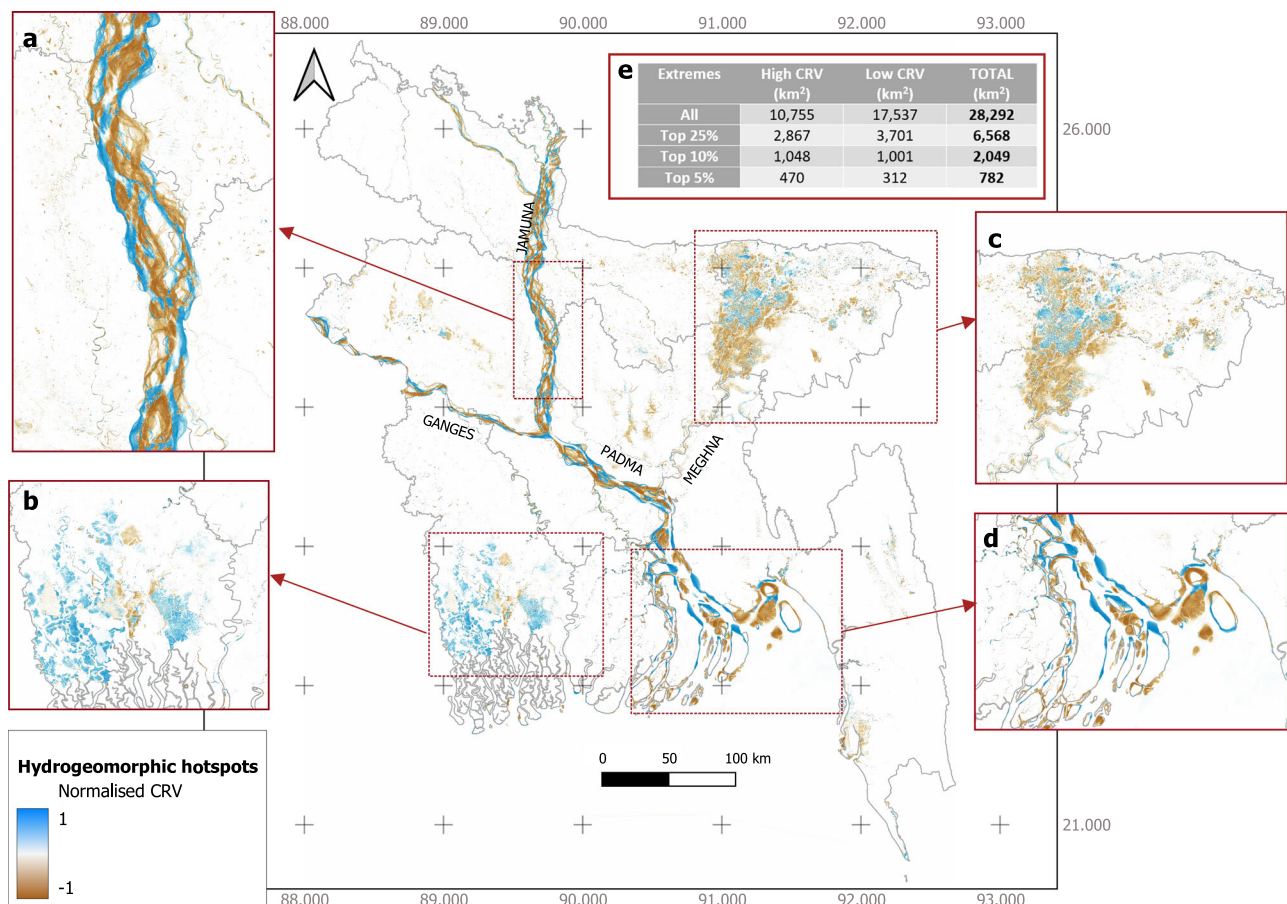


Fig. 1 | Hydrogeomorphic change across Bangladesh from 1987–2022. Brown colours indicate decreases in channel presence (accretion or drying up of land) and blue areas represent increases in channel presence (erosion or wetting of land). The intensity of the colour represents the frequency of change over the 35-year period. Inset maps illustrate the key hydrogeomorphic processes taking place: (a) riverine

erosion and accretion; (b) conversion of deltaic land to water bodies; (c) wetting and drying of land; and (d) coastal erosion and accretion. Panel (e) shows the areas for all hydrogeomorphic hotspots and for the extreme ends (25%, 10%, and 5%) of the CRV spectrum. Note, the scale bar is for the main country-wide map. CRV = Channelised Response Variance.

has primarily experienced accretion or drying up of surface water bodies (brown). The total land area that is severely and consistently affected is 6568 km², 2049 km², and 782 km², for the 25%, 10% and 5% most extreme ends of the Channelised Response Variance (CRV) spectrum (see “Methods”), respectively, which, in all cases, seems to be predominantly situated within and along the main river systems of the country.

As evident in Fig. 1, the CRV metric does not only identify where hydrogeomorphic changes are occurring, but also enables the distinction of different types of hydrogeomorphic processes taking place⁴⁶. The different processes evident in Bangladesh can broadly be categorised into four groups: (i) riverine erosion and accretion (Fig. 1a); (ii) conversion of deltaic land to water bodies (Fig. 1b); (iii) complex patterns of wetting and drying of land (Fig. 1c); and (iv) coastal erosion and accretion (Fig. 1d).

The river corridors of Bangladesh's major river systems (Fig. 1a), experience substantial hydrogeomorphic changes, particularly within the Jamuna River corridor. Approximately 3430 km² of land has eroded within the Ganges, Jamuna, and Padma river corridors, equivalent to 98 km² annually, whilst 5050 km² of land has been created (144 km² annually). Of this, approximately 55% of erosion and accretion has been taking place within the Jamuna River corridor. Along the Ganges River, the model results illustrate that over recent decades, the river eroded 767 km² of land, while accreting 1050 km². Finally, along the Padma River, approximately 1210 km² of land has been created in the last three and a half decades, whilst 788 km² has been eroded away by the river. It's evident from these figures that all three major river systems are currently creating more land than they erode; however, the magnitude of land loss is still profound.

In south-west Bangladesh (Fig. 1b), the modelling results illustrate an extensive area of waterlogging. Given that the model relies on dry season satellite imagery, it is unlikely that this is linked to seasonal inundation, which is also an issue in this part of Bangladesh^{47,48}. Instead, this waterlogging is most likely caused by the polderisation and widespread aquaculture development in the form of brackish water shrimp and fish cultivation^{4,46,49–51}. Particularly during the dry season, farmers pump brackish and saline water from surrounding rivers into their land for aquaculture production⁵².

In addition, the Sylhet basin in the north-eastern part of Bangladesh (Fig. 1c) is experiencing a complex combination of both wetting and drying up of land. In this region, land use has changed in recent years in the form of dry-season Boro rice cultivation, intentionally drying up natural wetlands⁵³, as well as embanked road construction⁵⁴, and localised subsidence^{55,56}. The interactions between these multiple different driving factors have resulted in a highly hydrogeomorphically complex landscape.

Finally, in the Meghna estuary, the modelling results present deposition rates as almost three times higher than erosion rates (Fig. 1d). This finding agrees with multiple previous studies, which have highlighted that this region experiences the greatest rates of land creation, with coastal erosion being more prevalent further away from the river mouth^{25,57,58}. The results also illustrate erosion along the western coastline of Bangladesh, reaching up to 2 km of erosion over the 35-year modelling period, equivalent to 57 m per year in parts of the western delta. Along this western coastline, the tides play a crucial role in pumping fluvial sediment from the Meghna estuary back towards south-western Bangladesh, ensuring the coastline has remained relatively stable despite the dramatic reduction in fluvial sediment delivery to this region since the construction of the Farakka barrage in 1975^{25,59–61}.

Population exposed to hydrogeomorphic change

At present, just over 22 million people (~13% of the total population) live within hydrogeomorphically unstable regions in Bangladesh, a figure that has grown by 5 million since 2000. Of the 22 million people,

4.3 million people are living within highly hydrogeomorphically unstable regions (25% of the CRV spectrum), and 1.7 million and 860,000 people live within the 10% and 5% most extreme cases of hydrogeomorphic instability, respectively. Fig. 2 illustrates the spatial distribution of population exposure to hydrogeomorphic hazards for the year 2020, with percentages in administrative divisions showing that the Sylhet, Dhaka and Chittagong divisions have the greatest increases in exposure since 2000, whilst the southern coastal divisions of Khulna and Barisal have the lowest. This can be attributed to greater background population growth in Dhaka and Chittagong, and more widespread recent hydrogeomorphic changes observed in the Sylhet basin. The main localised hotspots of greatest population exposure to hydrogeomorphic change can also be delineated. The three key areas with the most densely populated land susceptible to hydrogeomorphic change are along the Teesta River in the Rangpur Division, along the lower Jamuna River, near the city of Sirajganj, and on the outskirts of Dhaka city, highlighted by brown circles in Fig. 2.

Hydrogeomorphic change and wealth

Of the 22 million people exposed to hydrogeomorphic hazards in Bangladesh, 86% have low levels of wealth (Wealth Index (WI) ≤ 0), with 40% in the lowest wealth index group (WI ≤ −1) (see Table 1). When this is compared to Bangladesh as a whole (see Table 1), it is evident that the lowest wealth index group (WI ≤ −1) makes up 20–22% of the population, which is half of that observed within the hydrogeomorphically unstable parts of the country. This finding suggests an exposure bias of populations with lower wealth levels living in hydrogeomorphically unstable areas. This difference in exposure is diagrammatically represented in Fig. 3, which clearly illustrates the shift in the population's socio-economic structure between the population within hydrogeomorphically unstable areas compared to Bangladesh as a whole. In order to test whether this 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. 3 is statistically significant.

In addition, Table 1 illustrates that population growth rates (detailed in the final column) for the two lower wealth groups are relatively similar between populations exposed to hydrogeomorphic hazards and nationwide; however, for the higher wealth groups, there is a more substantial difference. The slower growth rate of wealthier populations observed within hydrogeomorphically hazardous regions could suggest that wealthier people may choose not to live in these unstable areas and move away, whilst the population that remains may face more challenges finding resources to migrate to safer locations. A similar trend is evident in the more extreme cases of hydrogeomorphic instability. For the 25%, 10% and 5% most extreme areas of hydrogeomorphic instability, the relative percentage change of population exposed in the lower WI groups (WI ≤ 0) has been increasing, whereas for the higher WI groups (WI > 0), the percentage change over the 20-year period has been negative (see Table 1 in the Supplementary Information). This suggests that, in areas with greater hydrogeomorphic risks, people with lower wealth levels continue to move towards highly unstable areas, while wealthier populations are moving away.

When assessing the spatial distribution of wealth within the hydrogeomorphic hotspots across the eight administrative divisions (Fig. 4), it becomes evident that the northern divisions of Rangpur and Mymensingh have the highest proportion of exposed populations with lowest relative levels of wealth. This is likely linked to these divisions generally having low levels of wealth (see wealth index map in Fig. 2 of the Supplementary Information), rather than disproportionate impacts of hydrogeomorphic hazards⁶². Interestingly, the spatial trends are also related to the location of cities relative to the hydrogeomorphic hazard areas (Dhaka and Chittagong), as cities are areas with better access to basic services and a greater concentration of

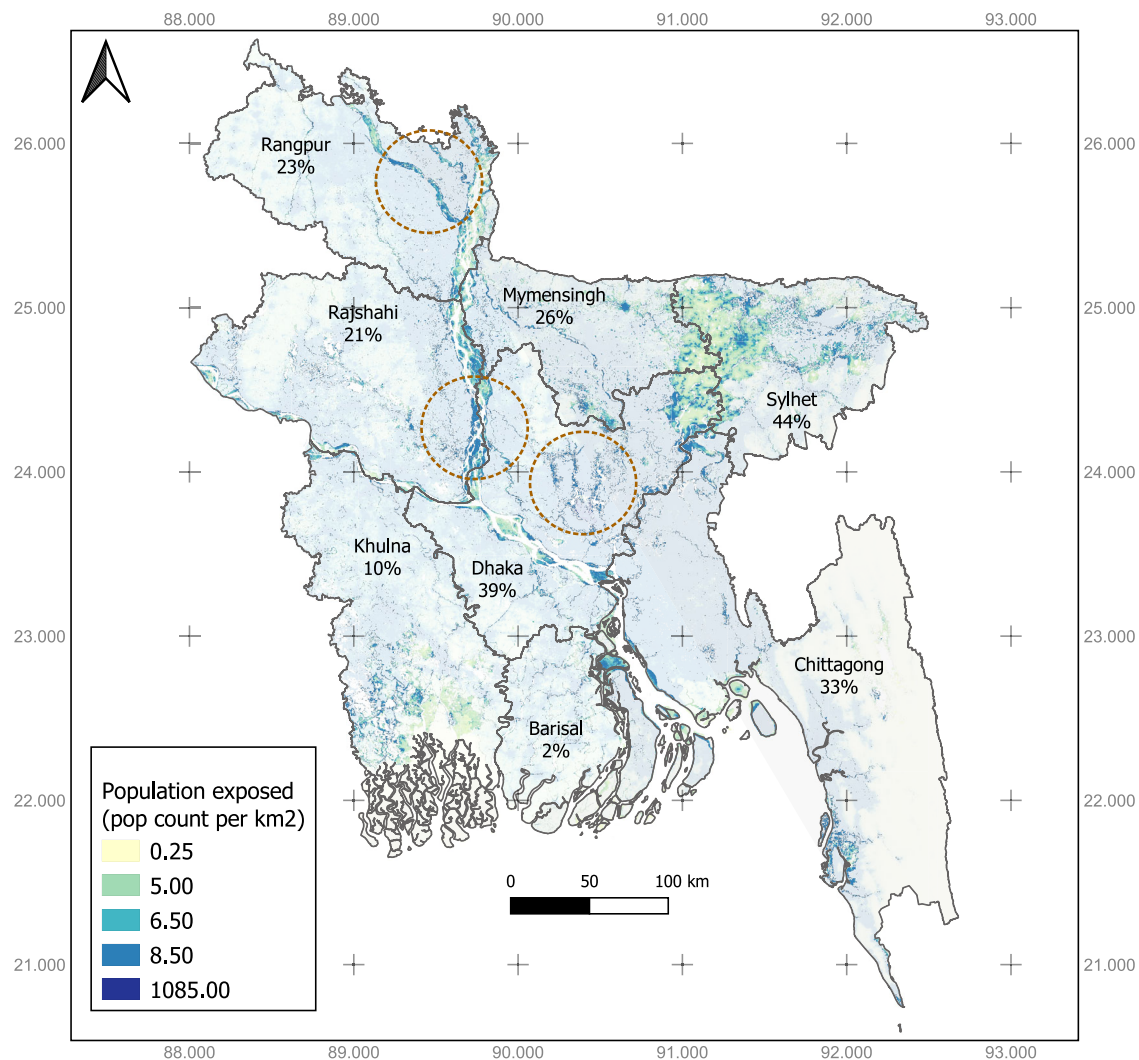


Fig. 2 | Spatial distribution of population exposed to hydrogeomorphic hazards in Bangladesh. The population within hydrogeomorphic hotspots is highlighted with greater colour intensity. The percentages highlight the overall

increase in population exposed per administrative division over the last two decades (2000–2020). The brown circles indicate the key regions of highest population density within areas of hydrogeomorphic instability.

Table 1 | Wealth distribution of populations exposed to hydrogeomorphic hazards compared to the population of Bangladesh as a whole

Hydrogeomorphic hotspots					Bangladesh				
Wealth Index	% of Population (2000)	% of Population (2020)	Absolute increase	Growth rate	Wealth Index	% 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

assets, thus skewing the WI for the rest of the division. The poverty map utilised in this study⁶³ includes highly granular data for urban centres, to ensure that urban poverty (e.g., informal settlements in and around Dhaka) is captured. Figs. 2 and 4 demonstrate that populations with lower wealth levels in both rural and urban areas, as well as wealthier populations in large urban centres such as Dhaka and Chittagong, are exposed to hydrogeomorphic instability.

Future population exposure to hydrogeomorphic hazards

In order to explore how future exposure to hydrogeomorphic hazards may unfold, the 2UP population growth estimates for Shared Socio-

economic Pathway 2 (SSP2)⁶⁴ are combined with the hydrogeomorphic hotspots map. Unfortunately, dynamical modelling of future hydrogeomorphic change has not been undertaken, which results in the assumption here that future hydrogeomorphic changes will continue to take place where there are current instabilities. Although this assumption introduces uncertainties, exploring future population exposure within these hotspots can help to identify areas that may experience increased hazard exposure due to population growth or migration.

By taking the population projections from the 2UP model, the findings show that future exposure to hydrogeomorphic hazards may

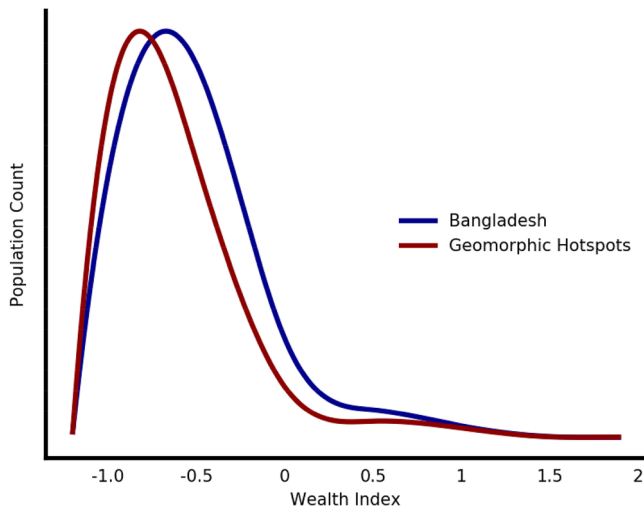


Fig. 3 | Exposure bias of population with low wealth. Normalised histogram showing the distribution of the population's socio-economic structure for 2020, comparing the population exposed to hydrogeomorphic hazards to Bangladesh as a whole. The population count (y-axis) has been normalised for visualisation purposes.

increase by up to 29% by 2050 as a result of population growth (which is lower than the 38% increase in population growth expected in Bangladesh by 2050, according to the 2UP model), of which 14% is likely to occur in urban areas and 86% is expected to increase in rural areas. This finding emphasises that the currently disproportionate exposure to hydrogeomorphic hazards experienced by rural populations with lower levels of wealth is likely to continue to grow over the coming decades.

Discussion

The hydrogeomorphic hotspot modelling results in this study have shown that 20% of Bangladesh's land area is prone to continuous and persistent hydrogeomorphic changes. The erosional processes along riverbanks and coastlines can degrade or completely consume valuable floodplain and coastal lands, leading to losses of livelihoods, reduced agricultural productivity and income, food insecurity, unemployment, and ultimately social unrest and internal displacement^{19,20,23,38,65}. Oftentimes, in response to these issues, rural resource-dependent populations are forced to sell their productive assets, reduce their food consumption, stop children's education, and take informal loans, which all deepen their vulnerability to these hazards^{9,66,67}. Unlike other hazards, riverbank and coastal erosion often result in temporary or permanent migration^{27,29}. Given the dynamic river systems in Bangladesh, land is constantly lost and created. Thus,

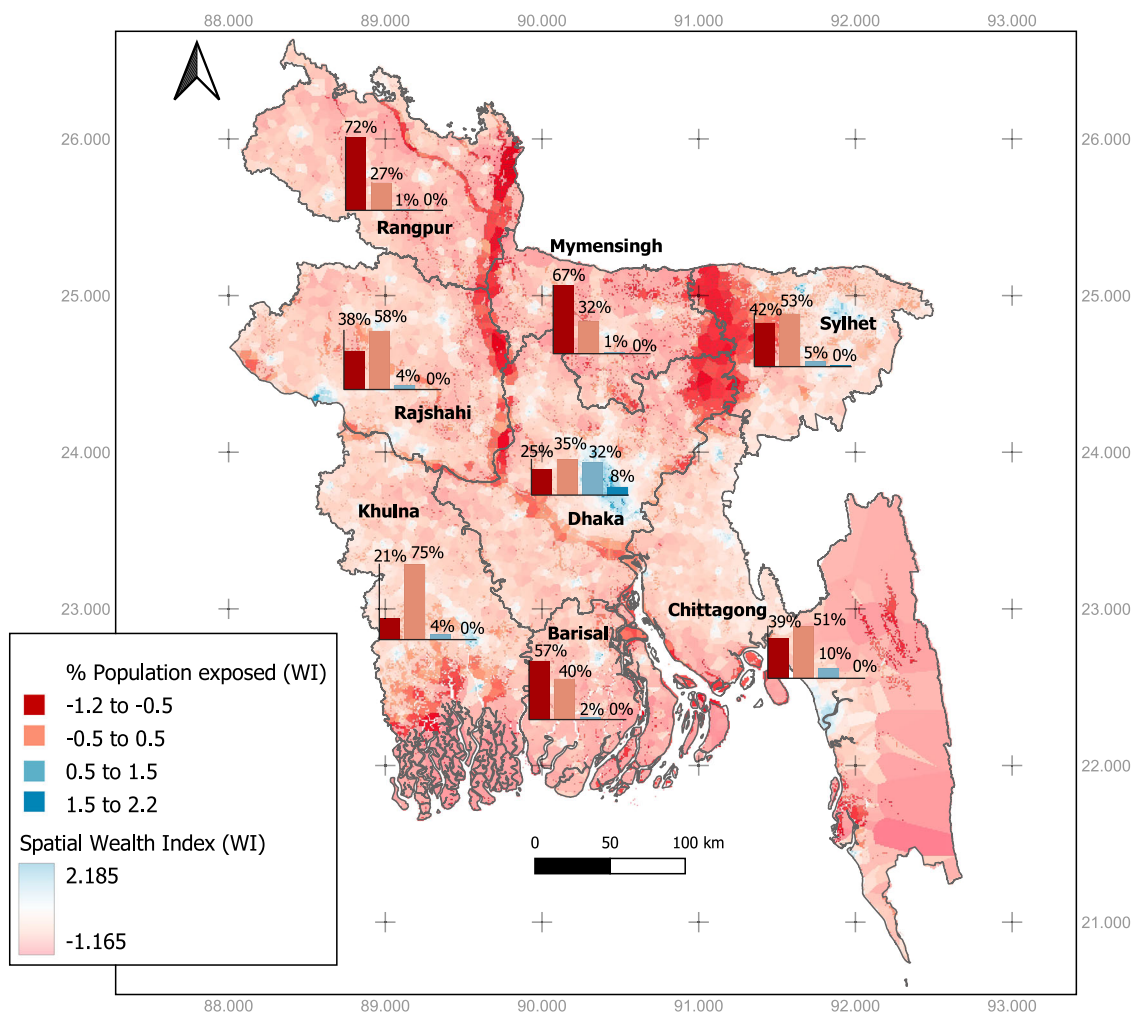


Fig. 4 | Wealth distribution of population exposed to hydrogeomorphic hazards. The wealth index of populations exposed to hydrogeomorphic hazards is highlighted with greater colour intensity (national wealth index more transparent

in the background). Red colours represent lower levels of wealth. The bar charts illustrate the proportional percentage of the population within hydrogeomorphic hotspots for each administrative division for the year 2020. WI = Wealth Index.

riverbank erosion differs from coastal erosion in that land may reappear after seasonal submergence or may be created in the vicinity of where it was eroded^{27,68,69}. Temporary displacement is therefore more common within and along riverbanks, whilst coastal erosion leads predominantly to permanent relocation⁷⁰.

By providing a national-scale spatial depiction of where hydrogeomorphic hazards intersect with densely populated populations with low levels of wealth, this study identifies the key areas in Bangladesh that are likely experiencing, or have experienced, hardships in the face of erosion hazards. These areas are predominantly along the upstream reaches of the Meghna River, as well as north of Sirajganj along the Jamuna River, along the Teesta and Darla rivers in the Rangpur Division, and in some coastal areas west of the river mouth. It is in these areas where targeted action to support populations affected by erosion hazards is needed in order to diminish or prevent potential livelihood disruptions, socio-economic setbacks, and possible poverty traps.

Extended waterlogging, such as evident in both south-west and north-eastern Bangladesh, also results in the loss of valuable floodplain land. This waterlogging is due to human modifications to the landscape that have maximised agricultural and aquacultural outputs^{71,72}. Poorly maintained infrastructure systems have resulted in drainage congestion, subsidence of embanked lands, saline intrusion in the south-west of Bangladesh, and environmental degradation^{48,71,73}. This extensive area of permanent waterlogging has rendered land unproductive, affecting millions of resource-dependent livelihoods each year, undermining poverty alleviation efforts, and exacerbating vulnerabilities to other hazards⁴.

Contrastingly, land accretion may provide multiple benefits associated with newly created fertile land. Given the widespread pressures for land to accommodate the continuously growing population of Bangladesh, the ability for fluvial sediment to accumulate and stabilise to form new land is of great importance and value to the country. In fact, the Bangladesh Delta Plan 2100 proposes to construct 11 cross-dams in the Meghna estuary area to encourage and accelerate land reclamation in the river mouth, as well as extract sediment from the river systems to raise the elevation of floodplain lands³². The high-resolution spatial information provided in this study on sediment deposition trends supports the Government of Bangladesh in identifying where these natural sedimentation processes can be tapped into to enhance land generation.

In addition, this study also sheds light on the areas where recently accreted land coincides with populations with lower levels of wealth. Newly accreted land takes some years to stabilise. However, due to widespread erosion and flood hazards within river corridors, newly accreted land is often inhabited by settlers from newly eroded land when it is not yet stable^{9,37,39,68,74,75}. Here, people-centric development, including formalised land tenure, is required to support the stabilisation of livelihoods and enhance the resilience of communities at the front lines of riverine hazards^{20,27,39}.

These existing challenges are likely to intensify in the future in the face of both population growth and climate change. Although not assessed in detail in this study, climate change is likely to intensify hydrogeomorphic processes, particularly fluvial dynamics, potentially expanding the extent and modifying the characteristics of identified hotspots and shifting the size and location of populations. This could lead to the emergence of new areas prone to hydrogeomorphic hazards or increased susceptibility in existing ones. The mobility of communities residing in hydrogeomorphically unstable regions may become increasingly constrained, as surrounding areas might become unsuitable for relocation due to climate-related factors like sea-level rise or heightened flood risk. Looking ahead, future work should investigate the influence of climate change on population exposure to hydrogeomorphic hazards in the intermediate (2050) and long-term (2080–2100), through, for example, predictive coupled human and

hydrogeomorphic dynamical systems models. This would provide invaluable insights into the complex interplay between climate change, socio-economic vulnerabilities, and the spatial distribution of these hidden hazards.

A focus on the long-term evolution of hydrogeomorphic hazards and exposure would support the Government of Bangladesh in its ambitious plan to eradicate most poverty by 2033, and completely by 2050, in line with the United Nations Sustainable Development Goals (SDGs)^{24,32}. The Government also plans for the country to be resilient and prosperous in the face of climate change, with substantial mobilisation and allocation of resources towards disaster risk reduction^{32,76}. Previous studies have argued that disaster risk management and poverty alleviation go hand in hand^{7,76}. Here, we demonstrate that the joint efforts in disaster risk and poverty reduction ought to also consider and incorporate hydrogeomorphic hazards.

To conclude, this study has found that over 22 million people are currently exposed to hydrogeomorphic hazards in Bangladesh, of which 86% (18 million people) have low levels of wealth and 40% (8.5 million people) are within the lowest wealth population group. The statistically significant disparity suggests that populations with lower levels of wealth are disproportionately exposed to hydrogeomorphic hazards. Bangladesh's increasing pressures of continuous and rapid population growth, combined with a shortage of available land, and the growing frequency and magnitude of climatic shocks, will likely result in more people being exposed to hydrogeomorphic hazards in the future, with low-income and rural populations expected to be more severely affected. This calls for disaster risk reduction and poverty eradication efforts to be addressed in unison⁷⁷, with the incorporation of hydrogeomorphic hazards, in order to set deltaic nations like Bangladesh towards a path of sustainable growth.

Methods

The concept of hazard 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 hazards^{68,74,78,79}. This study examines whether there is an exposure bias of populations with lower levels of wealth towards hydrogeomorphic instabilities in Bangladesh by intersecting high-resolution hydrogeomorphic modelling with population and poverty data. An exposure bias is measured as the number of exposed populations to hydrogeomorphic hazards with lower wealth levels compared to all people exposed across the country^{7,80}. Previous studies have shown that populations with lower wealth levels are subject to exposure bias from flood hazards⁷, and cyclones¹, but the extent of exposure bias to hydrogeomorphic hazards has not been quantified.

The methodology is broken down into four main steps, as outlined in the flowchart below (Fig. 5), with quantitative statistical analyses undertaken in each step, including: (i) generating a national hydrogeomorphic hotspot map for Bangladesh; (ii) assessing population exposed to hydrogeomorphic changes nationally and regionally; (iii) assessing how hydrogeomorphic changes may impact different wealth groups; and (iv) exploring how population exposure to hydrogeomorphic instabilities may change in the future. Each of these steps is discussed in more detail in the following sections.

Hydrogeomorphic hotspot analysis

Until recently, there had not been an automated approach of mapping hydrogeomorphic changes at a large scale. However, Jarriel et al.⁴⁶ 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 presence⁴⁶. Their model builds on previous work by Isikdogan et al.^{81,82} and Passalacqua⁸³, who developed the first automatic extraction of channel networks from satellite imagery. This approach eliminates the laborious process of

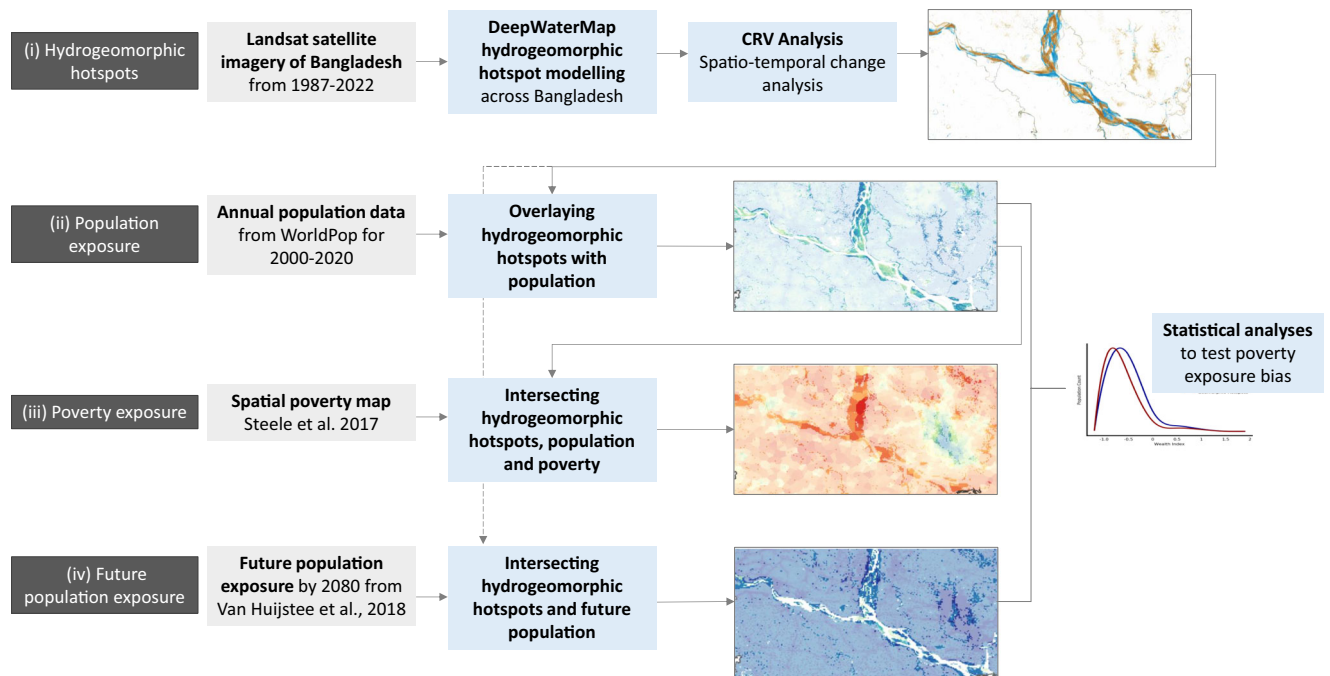


Fig. 5 | Methodological flowchart to map disparities in exposure to hydrogeomorphic hazards. Dark grey boxes indicate the aim of the step, light grey boxes indicate data inputs, blue boxes represent methodological processes, and maps illustrate the key outputs. CRV = channelised response variance.

manual inspections and delineation, and enables monitoring of near-live changes in complex channel networks at large spatial scales^{81,82}.

Here, we apply the openly available DeepWaterMap model to Bangladesh from 1987 to 2022. Nation-wide satellite imagery is extracted from Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI using Google Earth Engine, at a resolution of 1 arc second (approximately 30 m x 30 m at the equator). Images from the dry season (October until March) are chosen, as there is less cloud cover and channels are at their lowest stage⁴⁶. For each of the 35 years assessed, one composite image is created by taking the median value of all cloud-free pixels^{46,81}. This approach of averaging the input satellite data across the dry season constrains the effects of changes in channel levels, avoids misinterpreting channel changes due to flooding, and dampens the unavoidable fluctuations in tidal levels⁴⁶.

Once 35 new images are created – one composite image per dry season per year – they are 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 between⁴⁶. 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 time⁴⁶. High positive CRV values illustrate hotspots of increasing water presence (river or coastal erosion or longer-term wetting or inundation of land) over time, whilst high negative CRV values represent key areas that are decreasing in water presence (river or coastal deposition or drying up of land). The two extremes on the CRV spectrum, therefore, provide an indication of where the most frequent and severe hydrogeomorphic changes are observed. The lowest 5% of values from the CRV assessment have been removed to minimise potential errors introduced from image classification, but all other pixels were considered as experiencing hydrogeomorphic change. In this study, we also explore the 25, 10 and 5% most extreme areas of hydrogeomorphic instability in Bangladesh.

The raster images of tracked hydrogeomorphic changes (CRV) over the 35-year period can then be further analysed in a Geographic

Information System (GIS). Here, GIS is used to assess and visualise the outputs of the CRV results and calculate the overall hydrogeomorphically unstable land area, as well as for areas undergoing specific hydrogeomorphic changes.

Population exposure to hydrogeomorphic hazards

WorldPop⁸⁴ data for Bangladesh is used to map the population exposed to hydrogeomorphic 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 technique⁸⁵. This open-access dataset provides annual spatial population data from 2000 until 2020, at a resolution of 3 arc seconds (approximately 100 m x 100 m), available at the country level. Using GIS, this spatial population layer for each year is intersected with the hydrogeomorphic hotspot map from the above CRV model to assess the proportion of the Bangladeshi population living within these hydrogeomorphically unstable areas. Where hydrogeomorphic changes cut partially across a population grid (due to differences in spatial 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 regional trends in changing population exposure from 2000 until 2020.

Exposure bias

The exposure bias is estimated by comparing the wealth levels of exposed populations to hydrogeomorphic changes to wealth levels across all of Bangladesh, using high-resolution wealth distribution maps developed by Steele et al.⁶³. These 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 wealth for commonly used indicators of living standards, such as the Demographic and Health Surveys (DHS) Wealth Index (WI)^{4,63}. Their study selects suitable predictors for modelling wealth by transforming and preprocessing mobile phone data and

remote sensing covariate data. They use statistical modelling techniques, considering different combinations of covariates, employ non-spatial generalised linear models, and apply hierarchical Bayesian Geostatistical Models to predict wealth metrics at unsampled locations. These models account for the spatial autocorrelation and incorporate a spatially varying random effect, based on Voronoi polygons⁶³. Model performance is evaluated using out-of-sample validation statistics, and prediction maps with associated uncertainties are generated. It should be noted that this is a static dataset of wealth – a concept that is highly dynamic – with a basis from census data captured in 2011, and surveys undertaken in 2014⁶³. Nevertheless, this dataset still currently provides the most granular and detailed information on wealth distribution across Bangladesh.

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, healthcare, and education^{4,63}. This type of information more robustly captures the multidimensional nature of wealth, compared to income-based data^{23,86}, and better captures the wider welfare impacts of hydrogeomorphic hazards, such as asset losses, a disruption in educational and health services, and reduced consumption^{3,21,87,88}. The WI values can be positive, negative, or zero (ranging between −1.165 and 2.185 for Bangladesh), with greater positive values indicating higher socio-economic status^{4,63}. The WI is based on relative wealth and takes many factors into account that go beyond income-based indicators; therefore, it cannot be mapped onto traditional definitions of poverty thresholds (e.g., less than US\$1.90 per day in purchasing power parity). Consequently, this study uses higher and lower wealth population groups, defined by the WI, to assess disparities in exposure to hydrogeomorphic hazards.

By intersecting all three layers (i.e., hydrogeomorphic hotspots, population, and wealth) in GIS, the number of people living within hydrogeomorphic hotspots, and their levels of wealth, can be estimated. To fill in data gaps and areas without direct WI measurements, interpolation techniques were employed to estimate levels of wealth between the WI classifications. The interpolated wealth levels were then normalised by adjusting them to the highest-level frequency observed within the corresponding WI population group. This normalisation ensures that the estimated wealth distribution better reflects the wealth of the population across different wealth index levels, with the group having the highest frequency serving as the reference. The resulting wealth distribution of people exposed to hydrogeomorphic hazards is then compared to the wealth distribution of the country to estimate whether there is an exposure bias of populations with lower levels of wealth towards hydrogeomorphic hazards. 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.

Future population exposure

Population projection models can be used to explore how the exposure to hydrogeomorphic hazards may change in the future. In this study, future population projections are taken from Van Huijstee et al.⁶⁴, 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 1 km near the equator, providing detailed future population scenarios for all SSPs⁶⁴. For the purpose of this study, SSP2 (Middle of the Road) is used, reflecting the middle-ground socio-economic development trajectory for Bangladesh. Using this scenario, Bangladesh's population is projected to continue to grow to just under 200 million people by 2050 and then gradually reduce thereafter^{64,89}, with the greatest population growth predicted to occur in urban centres.

Future population exposure is assessed following the same approach as current population exposure. The assessment is undertaken at the country-wide scale, as well as within the identified hydrogeomorphic hotspots, for the short-term (2030), medium-term (2050) and long-term (2080), aligning with standard planning horizons in development frameworks and demographic projection intervals. Future trends in hydrogeomorphic change have not yet been projected; hence, this exploration of future exposure assumes that hydrogeomorphic hotspots remain the same as observed over the past 35 years. While in the future we can expect the precise location of hydrogeomorphic changes to evolve, the general hotspots of hydrogeomorphic change are likely to remain active over the coming decades²⁵. Although this assumption introduces uncertainties, exploring future population exposure within these hotspots can help identify areas that may experience increased hazard exposure due to population growth or migration.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All datasets used in this study are publicly available. The DeepWaterMap model is available under the following link and is based on satellite imagery from Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI: <https://www.nature.com/articles/s41598-020-69688-3#Ack1> <https://github.com/isikdogan/deepwatermap>; WorldPop Population data for Bangladesh from 2000-2020: <https://hub.worldpop.org/geodata/country?iso3=BGD>; Poverty data from Steele et al., 2017: <https://data.humdata.org/dataset/bangladesh-1km-resolution-poverty-estimates-mapping-poverty-using-mobile-phone-and-satellite-data>; Future population projections from Van Huijstee et al., 2018: <https://www.pbl.nl/en/publications/towards-an-urban-preview-modelling-future-urban-growth-with-2up>.

References

1. Akter, S. & Mallick, B. The poverty–vulnerability–resilience nexus: Evidence from Bangladesh. *Ecol. Econ.* **96**, 114–124 (2013).
2. Karim, A. & Noy, I. Poverty and natural disasters — a qualitative survey of the empirical literature. *Singap. Econ. Rev.* **61**, 1640001 (2016).
3. Karim, A. Knowledge, perception or disaster experience? The new determinants of household disaster preparedness behaviour in Bangladesh. *J. Int. Dev.* **36**, 2557–2580 (2024).
4. Adnan, M. S. G., Abdullah, A. Y. M., Dewan, A. & Hall, J. W. The effects of changing land use and flood hazard on poverty in coastal Bangladesh. *Land Use Policy* **99**, 104868 (2020).
5. Brouwer, R., Akter, S., Brander, L. & Haque, E. Socioeconomic vulnerability and adaptation to environmental risk: A case study of climate change and flooding in Bangladesh. *Risk Anal.* **27**, 313–326 (2007).
6. Hallegatte, S. & Rozenberg, J. Climate change through a poverty lens. *Nat. Clim. Change* **7**, 250–256 (2017).
7. Winsemius, H. C. et al. Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts. *Environ. Dev. Econ.* **23**, 328–348 (2018).
8. Alcántara-Ayala, I. Geomorphology, natural hazards, vulnerability and prevention of natural disasters in developing countries. *Geomorphology* **47**, 107–124 (2002).
9. Leichenko, R. & Silva, J. A. Climate change and poverty: vulnerability, impacts, and alleviation strategies. *WIREs Clim. Change* **5**, 539–556 (2014).
10. Borgomeo, E., Hall, J. & Salehin, M. Avoiding the water-poverty trap: insights from a conceptual human-water dynamical model for coastal Bangladesh. *Int. J. Water Resour. Dev.* **34**, 900–992 (2017).

11. Carter, M. R. & Barrett, C. B. The economics of poverty traps and persistent poverty: An asset-based approach. *J. Dev. Stud.* **42**, 178–199 (2006).
12. Carter, M. R., Little, P. D., Mogue, T. & Negatu, W. Poverty traps and natural disasters in Ethiopia and Honduras. in *Social Protection for the Poor and Poorest: Concepts, Policies and Politics* (eds. Barrientos, A. & Hulme, D.) 85–118 (Palgrave Macmillan UK, London, 2008).
13. Dercon, S. & Christiaensen, L. Consumption risk, technology adoption and poverty traps: Evidence from Ethiopia. *J. Dev. Econ.* **96**, 159–173 (2011).
14. Dercon, S. & Shapiro, J. S. *Does Poverty Entrap?* (2005).
15. Lázár, A. N., Adams, H., Adger, W. N. & Nicholls, R. J. Modelling household well-being and poverty trajectories: An application to coastal Bangladesh. *PLOS ONE* **15**, e0238621 (2020).
16. Karim, A. The household response to persistent natural disasters: Evidence from Bangladesh. *World Dev.* **103**, 40–59 (2018).
17. Tha, T., Piman, T., Bhatpuria, D. & Ruangrassamee, P. Assessment of riverbank erosion hotspots along the mekong river in Cambodia using remote sensing and Hazard exposure mapping. *Water* **14**, 1981 (2022).
18. Bhuiyan, M. A. H., Islam, S. M. D.-U. & Azam, G. Exploring impacts and livelihood vulnerability of riverbank erosion hazard among rural household along the river Padma of Bangladesh. *Environ. Syst. Res.* **6**, 25 (2017).
19. Islam, T. et al. Socio-economic vulnerability of riverbank erosion of displacees: Case study of coastal villages in Bangladesh. *Indian J. Ecol.* **46**, 34–38 (2019).
20. Islam, M. F. & Rashid, A. B. Riverbank erosion displacees in Bangladesh: need for institutional response and policy intervention. *Bangladesh J. Bioeth.* **2**, 4–19 (2011).
21. Verschuur, J., Koks, E. E., Haque, A. & Hall, J. W. Prioritising resilience policies to reduce welfare losses from natural disasters: A case study for coastal Bangladesh. *Glob. Environ. Change* **65**, 102179 (2020).
22. Jones, B. et al. Future population exposure to US heat extremes. *Nat. Clim. Change* **5**, 652–655 (2015).
23. Amoako Johnson, F. & Hutton, C. W. A Geospatial Analysis of the Social, Economic and Environmental Dimensions and Drivers of Poverty in South-West Coastal Bangladesh. in *Ecosystem Services for Well-Being in Deltas: Integrated Assessment for Policy Analysis*. (Springer International Publishing, Cham 2018).
24. Lázár, A. N., Nicholls, R. J., Hall, J. W., Barbour, E. J. & Haque, A. Contrasting development trajectories for coastal Bangladesh to the end of century. *Reg. Environ. Change* **20**, 93 (2020).
25. Paszkowski, A., Goodbred, S., Borgomeo, E., Khan, M. S. A. & Hall, J. W. Geomorphic change in the Ganges–Brahmaputra–Meghna delta. *Nat. Rev. Earth Environ.* **2**, 763–780 (2021).
26. Gares, P. A., Sherman, D. J. & Nordstrom, K. F. Geomorphology and natural hazards. in *Geomorphology and Natural Hazards* (ed. Morisawa, M.) 1–18 (Elsevier, Amsterdam, 1994).
27. Paszkowski, A., Laurien, F., Mechler, R. & Hall, J. Quantifying community resilience to riverine hazards in Bangladesh. *Glob. Environ. Change* **84**, 102778 (2024).
28. Haque, C. E. & Zaman, M. Q. Coping with riverbank erosion hazard and displacement in Bangladesh: Survival strategies and adjustments. *Disasters* **13**, 300–314 (1989).
29. Rahman, M. A. T. M. T., Islam, S. & Rahman, S. H. Coping with flood and riverbank erosion caused by climate change using livelihood resources: a case study of Bangladesh. *Clim. Dev.* **7**, 185–191 (2015).
30. Countries by Population Density 2025 *World Population Review* <https://worldpopulationreview.com/country-rankings/countries-by-density> (2025).
31. ADB. Poverty: Bangladesh. *Asian Development Bank* <https://www.adb.org/countries/bangladesh/poverty> (2022).
32. General Economics Division. *Bangladesh Delta Plan 2100* (2018).
33. Dewan, A. et al. Assessing channel changes of the Ganges-Padma River system in Bangladesh using Landsat and hydrological data. *Geomorphology* **276**, 257–279 (2017).
34. Sarker, M. H., Thorne, C. R., Aktar, M. N. & Ferdous, M. R. Morphodynamics of the Brahmaputra–Jamuna River, Bangladesh. *Geomorphology* **215**, 45–59 (2014).
35. Takagi, T. et al. Channel braiding and stability of the Brahmaputra River, Bangladesh, since 1967: GIS and remote sensing analyses. *Geomorphology* **85**, 294–305 (2007).
36. Ophra, S. J., Begum, S., Islam, R. & Islam, M. N. Assessment of bank erosion and channel shifting of Padma River in Bangladesh using RS and GIS techniques. *Spat. Inf. Res.* **26**, 599–605 (2018).
37. Sarker, M. H., Huque, I. & Alam, M. Rivers, chars and char dwellers of Bangladesh. *Int. J. River Basin Manag.* **1**, 61–80 (2003).
38. Hassan, A., Siddik, A., Akhtar, M. P. & Rahman, M. H. River bank erosion and associated impacts on livelihood: A case study of Harinatpur, Barishal. *Barishal Univ. J.* **1.1-2**, 215–224 (2018).
39. Kabir, M. E. & Kamruzzaman, P. Exploring the drivers of vulnerability among disadvantaged internal migrants in riverbank erosion prone areas in North-West Bangladesh. *J. South Asian Dev.* **17**, 57–83 (2022).
40. Islam, S. N., Reinstädler, S. & Gnauck, A. Coastal environmental degradation and ecosystem management in the Ganges deltaic region in Bangladesh. *Int. J. Ecol. Econ. Stat.* **37**, 59–81 (2016).
41. Barbour, E. J. et al. The unequal distribution of water risks and adaptation benefits in coastal Bangladesh. *Nat. Sustain* **5**, 294–302 (2022).
42. Adshead, D. et al. Climate threats to coastal infrastructure and sustainable development outcomes. *Nat. Clim. Change* **14**, 344–352 (2024).
43. Darby, S. E., Dunn, F. E., Nicholls, R. J., Rahman, M. & Riddy, L. A first look at the influence of anthropogenic climate change on the future delivery of fluvial sediment to the Ganges–Brahmaputra–Meghna delta. *Environ. Sci. Process. Impacts* **17**, 1587–1600 (2015).
44. Nicholls, R. J. et al. Integrated assessment of social and environmental sustainability dynamics in the Ganges–Brahmaputra–Meghna delta, Bangladesh. *Estuar. Coast. Shelf Sci.* **183**, 370–381 (2016).
45. Becker, M. et al. Coastal Flooding in Asian Megadeltas: Recent Advances, Persistent Challenges, and Call for Actions Amidst Local and Global Changes. *Rev. Geophys.* **62**, e2024RG000846 (2024).
46. Jarriel, T., Isikdogan, L. F., Bovik, A. & Passalacqua, P. System wide channel network analysis reveals hotspots of morphological change in anthropogenically modified regions of the Ganges Delta. *Sci. Rep.* **10**, 12823 (2020).
47. Adnan, M. S. G., Haque, A. & Hall, J. W. Have coastal embankments reduced flooding in Bangladesh?. *Sci. Total Environ.* **682**, 405–416 (2019).
48. Auerbach, L. W. et al. Flood risk of natural and embanked landscapes on the Ganges–Brahmaputra tidal delta plain. *Nat. Clim. Change* **5**, 153–157 (2015).
49. Mukhopadhyay, A. et al. Land cover and land use analysis in coastal Bangladesh. in *Ecosystem services for well-being in deltas: Integrated assessment for policy analysis* 367–381 (2018).
50. Khan, M. M. H. et al. Natural disasters and land-use/land-cover change in the southwest coastal areas of Bangladesh. *Reg. Environ. Change* **15**, 241–250 (2015).
51. Rahman, M. T. U. et al. Temporal dynamics of land use/land cover change and its prediction using CA-ANN model for southwestern coastal Bangladesh. *Environ. Monit. Assess.* **189**, 565 (2017).
52. Akter, S., Ahmed, K. R., Marandi, A. & Schüth, C. Possible factors for increasing water salinity in an embanked coastal island in the southwest Bengal Delta of Bangladesh. *Sci. Total Environ.* **713**, <https://doi.org/10.1016/j.scitotenv.2020.136668> (2020).

53. Rai, R., Zhang, Y., Paudel, B., Li, S. & Khanal, N. R. A Synthesis of studies on land use and land cover dynamics during 1930–2015 in Bangladesh. *Sustainability* **9**, 1866 (2017).
54. Gupta, S., Islam, S. & Hasan, M.dM. Analysis of impervious land-cover expansion using remote sensing and GIS: A case study of Sylhet sadar upazila. *Appl. Geogr.* **98**, 156–165 (2018).
55. Goodbred, S., Kuehl, S., Steckler, M. & Sarker, M. Controls on facies distribution and stratigraphic preservation in the Ganges-Brahmaputra delta sequence. *Sediment. Geol.* **155**, 301–316 (2003).
56. Sarker, M. H. Morphological response of the Brahmaputra-Padma-Lower Meghna river system to the Assam earthquake of 1950. (University of Nottingham, 2009).
57. Sarwar, M. G. M. & Woodroffe, C. D. Rates of shoreline change along the coast of Bangladesh. *J. Coast. Conserv.* **17**, 515–526 (2013).
58. Rahman, A. F., Dragoni, D. & El-Masri, B. Response of the Sundarbans coastline to sea level rise and decreased sediment flow: A remote sensing assessment. *Remote Sens. Environ.* **115**, 3121–3128 (2011).
59. Bomer, E. J., Wilson, C. A., Hale, R. P., Hossain, A. N. M. & Rahman, F. M. A. Surface elevation and sedimentation dynamics in the Ganges-Brahmaputra tidal delta plain, Bangladesh: Evidence for mangrove adaptation to human-induced tidal amplification. *Catena* **187**, <https://doi.org/10.1016/j.catena.2019.104312> (2020).
60. Hale, R., Bain, R., Goodbred, S. & Best, J. Observations and scaling of tidal mass transport across the lower Ganges-Brahmaputra delta plain: Implications for delta management and sustainability. *Earth Surf. Dyn.* **7**, 231–245 (2019).
61. Rogers, K. G., Goodbred, S. L. & Mondal, D. R. Monsoon sedimentation on the ‘abandoned’ tide-influenced Ganges-Brahmaputra delta plain. *Estuar. Coast. Shelf Sci.* **131**, 297–309 (2013).
62. Barman, R. P. & Islam, M. Root causes and consequences of extreme poverty in Northern Bangladesh. *ABC Res. Alert* **8**, 139–146 (2020).
63. Steele, J. E. et al. Mapping poverty using mobile phone and satellite data. *J. R. Soc. Interface* **14**, 20160690 (2017).
64. Van Huijstee, J., Van Huijstee, B., Van Bommel, A., Bouwman, A. & Van Rijn, F. *Towards an Urban Preview* (2018).
65. Das, T. et al. Impact of Riverbank Erosion: A case study. *Australas. J. Disaster Trauma Stud.* **21**, 73–81 (2017).
66. Ayeb-Karlsson, S., van der Geest, K., Ahmed, I., Huq, S. & Warner, K. A people-centred perspective on climate change, environmental stress, and livelihood resilience in Bangladesh. *Sustain. Sci.* **11**, 679–694 (2016).
67. Khan, M. I., Kundu, G. K., Akter, M. S., Mallick, B. & Islam, M. M. Climatic impacts and responses of migratory and non-migratory fishers of the Padma River, Bangladesh. *Soc. Sci.* **7**, 254 (2018).
68. Lein, H. The poorest and most vulnerable? On hazards, livelihoods and labelling of riverine communities in Bangladesh. *Singap. J. Tropical Geogr.* **30**, 98–113 (2009).
69. Islam, S. N., Singh, S., Shaheed, H. & Wei, S. Settlement relocations in the char-lands of Padma River basin in Ganges delta, Bangladesh. *Front. Earth Sci.* **4**, 393–402 (2010).
70. Barua, P., Rahman, S. & Mitra, A. Coastal Erosion pattern and rehabilitation of climate displaced communities of 3 coastal Islands in and around the South-Eastern Coast of Bangladesh. *Glob. J. Earth Sci. Eng.* **11**, 68–100 (2024).
71. Nowreen, S., Jalal, M. R. & Khan, M. S. A. Historical analysis of rationalizing South West coastal polders of Bangladesh. *Water Policy* **16**, 264–279 (2014).
72. Dewan, C., Mukherji, A. & Buisson, M.-C. Evolution of water management in coastal Bangladesh: from temporary earthen embankments to depoliticized community-managed polders. *Water Int.* **40**, 401–416 (2015).
73. Hoque, M. & Alam, M. Subsidence in the lower deltaic areas of Bangladesh. *Mar. Geod.* **20**, 105–120 (1997).
74. Wisner, B., Blaikie, Piers, Cannon, T. & Davis, I. *At Risk: Natural Hazards, People’s Vulnerability and Disasters*. (Routledge, London; New York, 2003).
75. Haque, R., Parr, N. & Muhidin, S. Climate-related displacement, impoverishment and healthcare accessibility in mainland Bangladesh. *Asian Popul. Stud.* **16**, 220–239 (2020).
76. Karim, A. & Noy, I. Risk, poverty or politics? The determinants of subnational public spending allocation for adaptive disaster risk reduction in Bangladesh. *World Dev.* **129**, 104901 (2020).
77. Eslami, S. et al. A systems perspective for climate adaptation in deltas. *Nat. Clim. Chang.* **15**, 687–691 (2025).
78. Adger, W. N. Vulnerability. *Glob. Environ. Change* **16**, 268–281 (2006).
79. IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (2021).
80. Hallegatte, S., Vogt-Schilb, A., Rozenberg, J., Bangalore, M. & Beaudet, C. From poverty to disaster and back: a review of the literature. *EconDisCliCha* **4**, 223–247 (2020).
81. Isikdogan, F., Bovik, A. & Passalacqua, P. RivaMap: An automated river analysis and mapping engine. *Remote Sens. Environ.* **202**, 88–97 (2017).
82. Isikdogan, F., Bovik, A. & Passalacqua, P. Automatic Channel Network Extraction From Remotely Sensed Images by Singularity Analysis. *IEEE Geosci. Remote Sens. Lett.* **12**, 2218–2221 (2015).
83. Passalacqua, P., Lanzoni, S., Paola, C. & Rinaldo, A. Geomorphic signatures of deltaic processes and vegetation: The Ganges-Brahmaputra-Jamuna case study. *J. Geophys. Res. Earth Surf.* **118**, 1838–1849 (2013).
84. Tatem, A. J. WorldPop, open data for spatial demography. *Sci. Data* **4**, 170004 (2017).
85. Stevens, F. R., Gaughan, A. E., Linard, C. & Tatem, A. J. Dis-aggregating census data for population mapping using random forests with remotely-sensed and ancillary data. *PLOS ONE* **10**, e0107042 (2015).
86. Kolstad, I., Karim, A., Lujala, P. & Wiig, A. Expert adoption of composite indices: a randomized experiment on migrant resettlement decisions in Bangladesh. *Nat. Hazards* **119**, 261–297 (2023).
87. Markhvida, M., Walsh, B., Hallegatte, S. & Baker, J. Quantification of disaster impacts through household well-being losses. *Nat. Sustain* **3**, 538–547 (2020).
88. Meyer, V. et al. Review article: Assessing the costs of natural hazards – state of the art and knowledge gaps. *Nat. Hazards Earth Syst. Sci.* **13**, 1351–1373 (2013).
89. World Population Review. Bangladesh Population 2021 (Demographics, Maps, Graphs). <https://worldpopulationreview.com/countries/bangladesh-population> (2021).

Acknowledgements

This research was funded in part by the engineering and consultancy practice Buro Happold, and is an output from the REACH programme funded by UK Aid from the UK Foreign, Commonwealth and Development Office (FCDO) for the benefit of low- and middle-income countries (Programme Code 201880). However, the views expressed, and information contained in it are not necessarily those of or endorsed by Buro Happold or FCDO, which accept no responsibility for such views or information or for any reliance placed on them.

Author contributions

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

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41467-025-64920-y>.

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Peer review information *Nature Communications* thanks Kathy Lüdge and the other anonymous reviewer(s) for their contribution to the peer review of this work. A peer review file is available.

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