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Climate threats to coastal infrastructure and sustainable development outcomes

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Climate hazards pose increasing threats to development outcomes across the world's coastal regions by impacting infrastructure service delivery. Using a high-resolution dataset of 8.2 million households in Bangladesh's coastal zone, we assess the extent to which infrastructure service disruptions induced by flood, cyclone and erosion hazards can thwart progress towards the Sustainable Development Goals (SDGs). Results show that climate hazards potentially threaten infrastructure service access to all households, with the poorest being disproportionately threatened in 69% of coastal subdistricts. Targeting adaptation to these climatic threats in one-third (33%) of the most vulnerable areas could help to safeguard 50–85% of achieved progress towards SDG 3, 4, 7, 8 and 13 indicators. These findings illustrate the potential of geospatial climate risk analyses, which incorporate direct household exposure and essential service access. Such high-resolution analyses are becoming feasible even in data-scarce parts of the world, helping decision-makers target and prioritize pro-poor development.

Climate hazards are projected to have a disproportionate impact on poor and vulnerable people and communities[1]. This is a consequence, among others, of poorer people living in more exposed locations ('exposure bias')[2,3]. The exposure and vulnerability of poor communities can become exacerbated over time through cycles of repeated climate impacts[4,5], which can prevent the accumulation of assets and chronically impact health, education and employment opportunities, and drive temporary or permanent out-migration of people and their resources. This type of 'poverty trap' may lead to chronic declines in welfare at a range of scales, which has been documented across regions[6–8] including in coastal Bangladesh[9], which is on the 'frontline' of climate change and its associated effects—the focus area of this study.

Given the potential for climate extremes to adversely impact people and their wider development opportunities, national development plans may be thrown off course by climate impacts[10,11]. Targeted interventions focused on the most vulnerable can help to alleviate these harmful dynamics. However, given inevitably scarce resources and the potential for misallocation, these interventions need to be informed by spatial analyses on climate risks and vulnerabilities, as well as their interactions across socioeconomic systems[12–14]. Thus far, however, the linking of high-resolution spatial vulnerability mapping with hazard, exposure and sustainable development objectives is incomplete.

Social vulnerability has been mapped geospatially and integrated with flood risk management assessment at the local and municipal scales[15,16], as well as at the national and global scales[1]. However, the impacts of climate hazards, especially flooding, erosion and other geomorphological changes, can (1) be sensitive to the exact location of vulnerable households, requiring high-resolution geolocated household-level data; and (2) depend not only on households' locations but also on their access to essential services, such as hospitals and electricity, which are fundamental to the achievement of the Sustainable Development Goals (SDGs). Currently, there is a lack of reliable high-resolution data to distinguish local and regional vulnerability differences[17,18]. This lack of detailed information can explain

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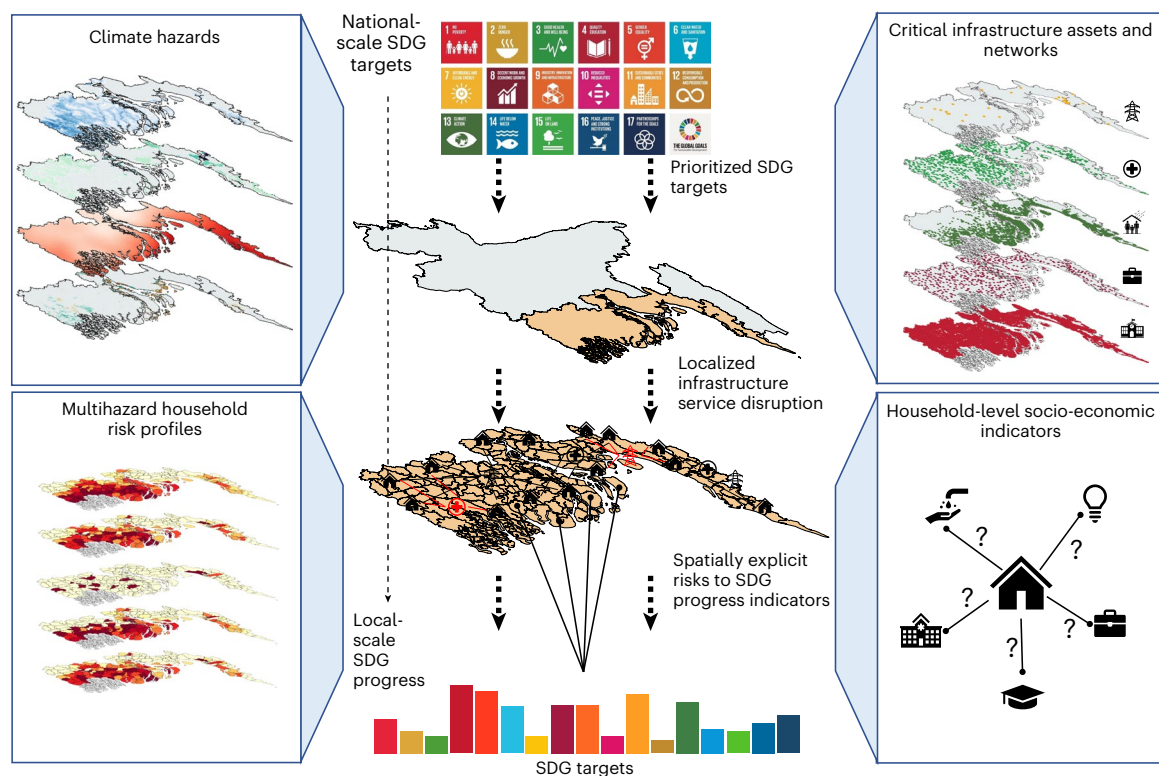
Fig. 1 | A multihazard spatial assessment of households' critical infrastructure exposure with potential implications for achieving priority SDG indicators in Bangladesh's coastal region. Key climate hazards (top left) are intersected with critical infrastructure asset and network data (top right). Climate risk profiles quantifying the extent of potential household disruption of various infrastructure services are determined at the upazila scale (local subdistrict) (bottom left). Household-level socioeconomic data are used to assess current development progress and future impacts of climate threats on the government's priority SDG indicators (bottom right).

the discrepancies in estimates of climate risks, for example, in river floodplains[19] and coastal zones[20], which can undermine efforts to target adaptation towards the most vulnerable.

The SDGs endeavour to provide a complete and universally applicable assessment framework for development progress. Several studies have examined at an aggregated scale how cross-cutting development interventions (for example, in infrastructure systems, green energy, climate action and other areas[21–23]) can contribute to several SDGs. It is also recognized that appropriate and measurable indicators are needed to drive more-targeted development planning and adaptation strategies within the SDG framework[24–26]. Recent national-scale applications of such approaches demonstrate how resilience needs can be identified across a nation's built and natural assets, and how strategic interventions can be evaluated in relation to a national development vision informed by the SDGs[27–29].

Local risks to development progress in coastal Bangladesh

Here we illustrate how geolocated household data can be used in data-scarce locations to obtain new insights about climatic threats to sustainable development. We assess these vulnerabilities through the lens of infrastructure service delivery and its role in achieving the SDGs in coastal Bangladesh[30]. Bangladesh is situated in a global hotspot of climate hazards, with more than 80% of its land area consisting of floodplain lands[31]. Frequent and intense fluvial, pluvial and tidal flooding, cyclonic winds and associated storm surges, and widespread riverbank and coastal erosion impact the country on an annual basis[32–34]. The repeated damages and disruptions to infrastructure networks as a result of these multiple hazards place a heavy burden on the country's economic growth, social resilience and progress towards achieving the SDGs[35]. In coastal Bangladesh, particularly in rural areas, inadequate

infrastructure services hamper human development and slow down resilience efforts in the face of hazard impacts[36]. However, the understanding of household-level infrastructure service disruption resulting from the threats of climatic hazards remains limited, with previous efforts mainly focusing on constructing risk[37] and resilience metrics to assess hazard threats to infrastructure. In Bangladesh, the SDG Working Committee of the Prime Minister's Office, supported by all relevant government ministries, has defined 39 priority indicators (NPTs) to measure progress towards key SDG targets (https://sdg.gov.bd/), which have informed the geospatial analysis in this study. Directly addressing five of these indicators, we bring together national-scale geospatial data on climate hazards and infrastructure assets with high-resolution household data to assess localized risks to SDG achievement by means of disruptions to infrastructure service provision caused by one or multiple climate hazards (see Methods). Notably, we assess household access to these essential services, quantifying not only the exposure of households but also potential disruption to services upon which they depend.

We first assess the exposure of coastal Bangladesh's infrastructure service provision to climate hazards by intersecting river and coastal flooding, cyclone and erosion hazard maps (for the present day, as well as for future scenarios of river and coastal flooding) with critical infrastructure asset and network data relevant to subsequent assessments of SDG attainment (Fig. 1, top left and right; see Methods). The exposure analysis makes use of a synthetic household dataset that associates realistic socioeconomic household characteristics (such as electrification, employment and educational achievement) with the location of households (for example, using population density maps), which have been validated by independent household surveys[38]. Further survey data and geospatial analysis is used to develop a spatial proxy of socioeconomic household 'wealth' groups (which are

divided into quintiles; see Methods) and their levels of infrastructure access in the coastal zone of Bangladesh. We analyse the whole coastal region of Bangladesh (150 subdistricts, locally termed as 'upazilas', across 19 coastal districts, with a total population of ~35 million people[39]) and assess infrastructure service delivery for individual households, developing climate risk profiles that quantify the extent of household exposure to multiple hazards (Fig. 1, bottom left).

Woven throughout this process is Bangladesh's sustainable development vision. We downscale current performance against relevant national targets to the local (upazila) level and utilize household-level data on socioeconomic characteristics and access to services to reveal the spatial landscape of current progress towards the selected targets (Fig. 1, bottom right). By linking asset service delivery at the household level and their exposure to various hazard scenarios, we can assess the potential impacts of hazards on SDG progress in relation to some of the government's overall development targets.

Household service 'exposure bias' to climate hazards

This analysis focuses on the disruption to cyclone shelters, education facilities, market centres, healthcare facilities and electricity substations, selected for their relevance to the subsequent analysis on SDG target achievement (Supplementary Fig. 1 also includes the road network). For coastal and riverine flooding, we consider a household disrupted if its nearest asset is exposed to more than 1 m of flooding (see Methods). All 8.2 million households in the coastal region of Bangladesh are exposed to some disruption of essential infrastructure services caused by climate hazards. For a baseline 1-in-50-year hazard, coastal flooding (including storm surges), riverine flooding and cyclones (wind damage) are expected to disrupt on average 39.5%, 22.7% and 94.5%, respectively, of the coastal population across all infrastructure services. Erosion is estimated to have disrupted 56% of the coastal population across all infrastructure services cumulatively since 1987. It is important to note that these climate hazards (for example, cyclonic winds and floods) can occur simultaneously, leading to more severe compound impacts, which are not considered in this study.

For combinations of each hazard and asset type, we calculate the proportion of households in each upazila and wealth quintile exposed to potential disruptions to services in the event of a 1-in-50-year hazard for a present-day scenario and in the case of flooding for the year 2030 under Representative Concentration Pathway (RCP) 4.5. Figure 2 displays coastal flooding exposure for the 1-in-50-year event for 2030 (RCP 4.5), showing the expected proportion of households disrupted in the median socioeconomic quintile (left), and the statistically significant poverty bias (middle) and wealth bias (right) relative to this median quintile. As evident, the main effects of coastal flooding are concentrated in the low-lying Khulna and Barisal divisions and in the coastal southern half of the Chittagong division. The prevalence of coastal flooding in the southern part of Chittagong reflects the strong winds and waves in this region, both with south westerly directions[40,41] which pushes water directly onshore.

Across the entire coastal region, a mild but consistent pattern shows that poor households are more exposed to infrastructure service disruptions from coastal flooding than wealthier socioeconomic groups. For cyclone shelters, market centres, education and health facilities, we see a statistically significant poverty bias. In the case of education facilities, the poor population is 1.07 times and 1.13 times more likely to be exposed to education disruption than the median or wealthiest groups, respectively. We see similar risk ratios for health facilities (1.07), market centres (1.02) and cyclone shelters (1.24) between the poorest and wealthiest population groups. In the case of substations, however, this risk ratio is 0.989, indicating that the wealthiest group is 1.01 times more likely to be affected by disruption to electricity substations due to coastal flooding. This wealth bias is probably due to substations in the Patiya and Hathazari upazilas in the

Chittagong division being particularly exposed to flooding near the Karnaphuli river, which predominantly serve wealthier households (60–70%) (Supplementary Fig. 1e).

When assessing exposure to any climate hazard disrupting any infrastructure service, a statistically significant poverty bias is observed in 104 upazilas, equivalent to 69% of the coastal region of Bangladesh. Focusing on coastal flooding alone, a poverty bias in disruptions affecting at least one of the five asset types is observed in 35 (23.33%) of the 150 coastal upazilas. Twelve and two upazilas respectively exhibit poverty bias for two or three asset types. The upazilas showing poverty bias across three asset types are Chakaria (southeast Chittagong) and Jhalokati Sadar (northwest Barisal), showing poverty bias for education and market centres, as well as cyclone shelters (Chakaria) and health facilities (Jhalokati Sadar). Across the five infrastructure asset types, disruptions to education facilities show the most widespread poverty bias, with 17 upazilas largely centred in low-lying regions around the Meghna River but also in the Khulna and Chittagong divisions showing poverty biases between 1.008 (Bhandaria) and 1.4 (Kotwali). It is in these critical upazilas where most action is needed to strengthen the service that existing infrastructure systems provide, as well as where the connectivity and accessibility to improved services must be most urgently enhanced to withstand future coastal flood events. The largest absolute number of poorer households expected to be disrupted in any upazila (wealth quintiles 1–3) is in Patuakhali Sadar, where 381,680 households are exposed to substation disruptions due to coastal flooding.

Safeguarding SDG target achievement

Next, we consider the SDG progress that has been achieved across several of Bangladesh's national priority indicators and how infrastructure service disruption as a result of climatic hazards may negatively affect it. Using household-level data, we can estimate current SDG achievement at the local level for five indicators directly linked to infrastructure services provided to households for each of the sectors included in this study (see 'Household infrastructure service accessibility and the SDGs' in Methods). In the absence of appropriate resilience measures, areas that currently have higher levels of SDG achievement are at greater risk of declines in this progress due to hazard impacts on infrastructure services. Areas with lower levels of SDG progress also benefit from an understanding of the spatial nature of hazard exposure in relation to local populations lacking appropriate infrastructure services.

SDG target achievement 'at risk' is shown in Fig. 3, with darker-shaded upazilas facing more potential disruption to achieved SDG progress due to the hazard. Coastal flooding has the greatest potential disruptive impact on SDG 7 (electrification) progress (as the dominant hazard in 51 upazilas), with river flooding particularly impacting SDGs 3 (health) and 4 (education) (dominant in 41 and 40 upazilas, respectively). Erosion hazards impact especially SDG 3 (dominant in 55 upazilas). Potential cyclone disruption to infrastructure services is particularly widespread across the region, showing impacts on health (SDG 3), education (SDG 4), electrification (SDG 7) and economic (SDG 8) indicators in most upazilas. While shelters are built to withstand cyclonic wind gusts, they are also exposed to coastal flooding and erosion hazards; thus, SDG 13 (limiting climate change impacts) progress remains particularly vulnerable throughout many upazilas bordering the coast. Outcomes related to household electrification, health and school access are exposed to varying levels of risk to coastal and river flooding and erosion, depending on the local SDG performance already achieved.

Figure 4 illustrates that policymakers aiming to prioritize resilience measures can begin to see notable impacts when focusing on only a few key areas, although these vary according to the hazard. For each of the four hazards, upazilas are ranked in descending order by their average SDG progress at risk across each of the five targets assessed here. SDG progress at risk refers to the extent to which regional target
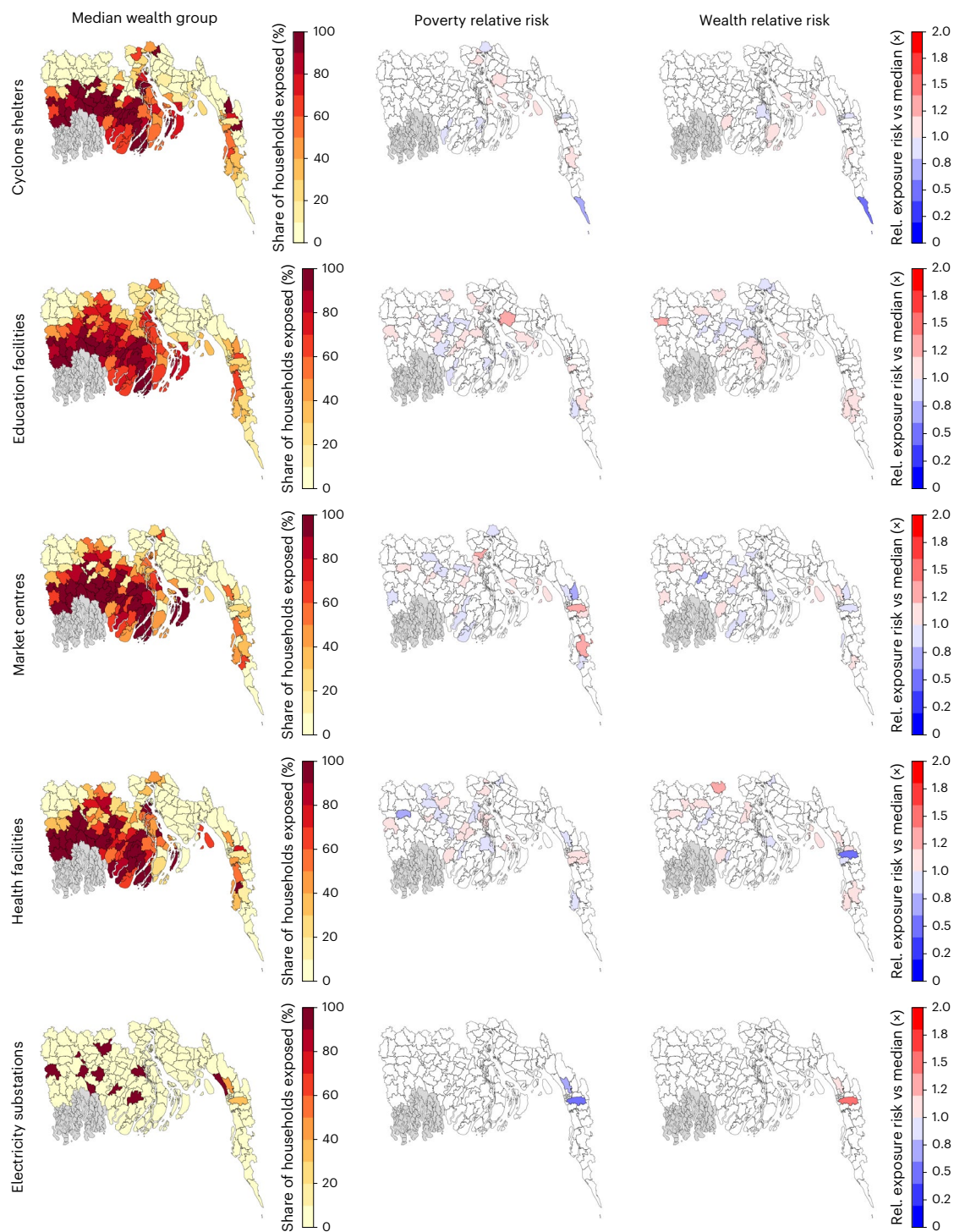
Fig. 2 | Share of households whose services are exposed to coastal flooding in relation to the median wealth quintile, identified at the upazila level. For each of the five infrastructure service types, the panels show the spatial distribution of service exposure to a 1-in-50-year coastal flood event under a 2030 RCP 4.5 scenario in terms of proportion of households affected per upazila (see Supplementary Fig. 1 for equivalent results for other hazards, including the road network). The left panel shows the proportion of households in the median wealth quintile exposed to coastal flooding through service disruption. The centre and right panels show the relative risk (risk ratio) of household exposure for the poorer (centre) and wealthier (right) quintiles relative to the median quintile. Relative risks are only shown for upazilas where the difference between exposure proportions between quintiles was found to be statistically significant at the 95% confidence level.

achievement would decline if hazards were to disrupt infrastructure services. For coastal flood hazards, measures to enhance the resilience of infrastructure services could safeguard 15–20% of SDG progress when only 10 upazilas (6.6% of the coastal region) are targeted, depending on the SDG; when 50 upazilas (33%) are targeted, this SDG safeguarding rises to approximately two-thirds (60–70%). In 117 upazilas (78%), over 99% of current progress across all targets can be protected. Without such safeguards, measured SDG progress in the region could see a substantial decline due to infrastructure service exposure to climatic hazards.
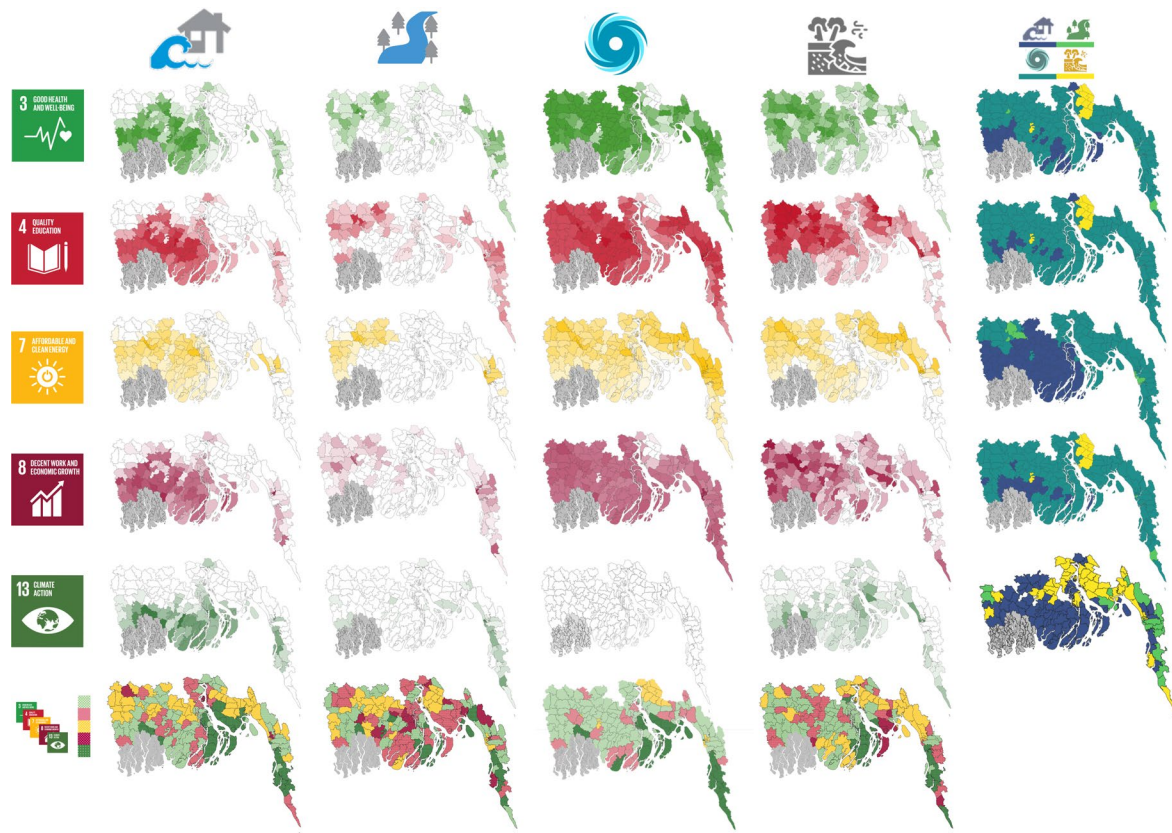
Fig. 3 | Extent of climate threats to representative SDG progress indicators in 150 upazilas across Bangladesh's 19 coastal districts. Darker shades indicate greater levels of SDG achievement at risk. The cumulative column (far right) shows the dominant hazard most affecting the representative SDG indicator in each upazila. The cumulative row (bottom) denotes the SDG most threatened by each type of hazard, based on its current progress level and magnitude of potential exposure to the hazard. Note: cyclone shelters are purpose-built to withstand cyclone winds, hence their exposure to cyclones is not considered a threat to progress towards the SDG 13 indicator (directly affected persons); they are, however, considered vulnerable to impacts of coastal and river flooding and erosion.

For river flooding, corresponding numbers are 21–30% (10 upazilas) and 76–85% (50 upazilas), while 99% is achieved with resilience measures in 114 upazilas. Cyclone resilience across the relevant infrastructures safeguards 15–19% of SDG progress (10 upazilas) and 50–56% (50 upazilas), while nearly all (149) require some intervention to achieve 99% protection. Coastal erosion resilience can safeguard 19–21% (10 upazilas), 52–60% (50 upazilas) and 99% with measures in 141 upazilas. We also note differences in cumulative protection between infrastructure types due to spatial variations in hazard exposure. Electricity access (SDG 7), for example, requires more widespread resilience planning to protect against coastal flooding than against river flooding, which is more spatially limited in its potential disruption of substations.

To fully achieve the government's SDG targets, new infrastructure will also have to be built across the coastal region and the rest of Bangladesh to reach populations that are underserved, not connected or unable to benefit from infrastructure services due to a lack of proximity. Estimates from our household dataset suggest that the share of these households can be substantial in the coastal region, reflected in survey responses and/or with households geolocated outside the distance thresholds required to reasonably access services from the nearest asset. For example, 46% of households report no access to electricity across the region, while 18% are further than 5 km from their nearest healthcare facility. Aggregating household access rates across the 150 upazilas, we observe locations across the region where resilient new infrastructure should be targeted to reach these underserved populations.

Although this infrastructure is yet to be built, intersecting these areas with high-resolution spatial hazard data can inform the spatial planning of assets to achieve national SDG priorities (shown for coastal flooding hazards in Fig. 5). Notably, we can visualize where these new infrastructures will be less at-risk (darker grey) and where resilience measures should be prioritized (darker blue) to ensure effective service delivery from the built asset to households. In the case of cyclone shelters, this also indicates that cyclone and associated coastal flood exposure extend into parts of the region where fewer shelters are recorded. For all other infrastructure service provision, low accessibility intersects with high exposure in the Meghna Estuary and the south-western upazilas of coastal Bangladesh.

Sustainable development achievement in coastal Bangladesh

Patterns of exposure to climate hazards in coastal Bangladesh are complex, but by using high-resolution geospatial analysis, we can begin to identify where poorer households' access to essential services is disproportionately impacted by climate-related hazards. The tendency for poorer households to be more exposed in parts of coastal Bangladesh reflects several interacting factors, including typically highly resource-dependent livelihoods, insecure land ownership and an uneven distribution of accessibility to land, less capacity to migrate to cities where incomes are on average higher, land degradation linked to previous hazards and a lack of protective infrastructure, among others[42,43]. For instance, gradual increases in soil salinity and/or chronic waterlogging have impacted agricultural production, damaging the livelihoods of the marginal coastal population[44]. A limited capacity to relocate may reinforce this continued exposure to a greater intensity of climate hazards, which continues to pose challenges for development. In addition, disparities in the provision of infrastructure services across more and less exposed areas in this region during different phases of
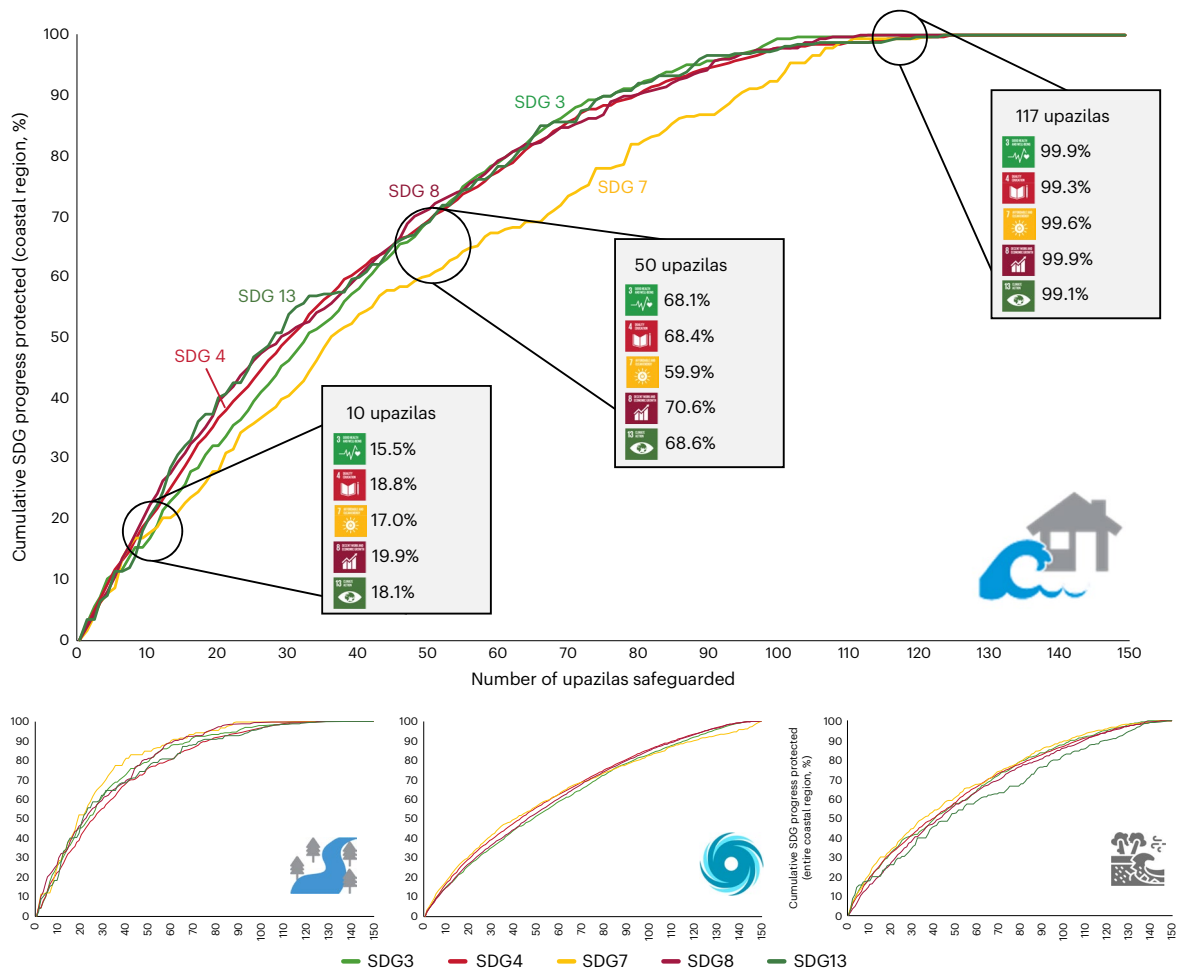
Fig. 4 | Cumulative progress towards safeguarding current SDG achievement from four hazards across Bangladesh's coastal region. Top: progress towards safeguarding current SDG achievement from coastal flooding. Bottom: progress towards safeguarding current SDG achievement from river flooding, cyclones and erosion hazards. For the bottom panels, labels for the *x* and *y* axes are the same as those of the top panel. Upazilas are ranked along the horizontal axis according to their SDG progress at risk in descending order. The vertical axis shows the additional benefit, in terms of average SDG progress in the region, of resilience measures to protect hazard-exposed infrastructure service provision in each additional upazila across the five subsectors considered in these results. Each upazila's contributions to overall (regional) SDG progress has been weighted by population. By targeting a limited number of upazilas along the *x* axis, policymakers can expect to see a disproportionately positive improvement in SDG progress, depending on the specific indicator and climate hazard considered. As we do not factor in resilience measures that may already have been implemented, this quantification of SDG progress at risk is based on a worst-case scenario where all exposed assets are considered to cause household disruptions.

climate extremes—before, during and after such events—act as impediments to the resilience of coastal communities[36].

Where national resources are limited, the results presented in this study provide means for investment prioritization, extending previous methodological development for infrastructure prioritization based on similar but less extensive household data in the same region[45]. For instance, our results indicate that market centres' exposure to coastal flooding, cyclones and erosion may be an obstacle to achieving SDG 8 and would be further exacerbated by disruptions to the road network. Improving access to market centres by constructing new roads or enhancing existing ones could promote economic activity in the coastal region and lessen poverty[46]. In addition, purpose-built cyclone shelters are highly important to larger areas of the coastal region and should be located within short distances to settlements to be effective. We have quantitatively shown that the programme of constructing cyclone shelters has been targeting the poorest and most disadvantaged populations, and accordingly is widely regarded for its effectiveness in reducing cyclone fatalities[47]. It is important to note, however, that the results presented in this study should be interpreted with care since local realities are highly nuanced.

Different infrastructure assets may be able to withstand differing levels of hazard exposure, while disruption magnitude may be caused by various structural factors and may reverberate further along the network than the local area. New and evolving resilience metrics and risk mitigation approaches for different types of infrastructure, such as roads[48], electricity grids[49] and water supply[50], can inform solutions and investments at the local scale.

To address the identified exposure biases, a range of resilience measures targeted to the unique characteristics of local populations should be developed and planned at local levels. This can benefit from quantitative analyses such as these, alongside more in-depth qualitative assessments within local communities. A knowledge of existing resilience-enhancement measures at each asset, local or community level and an understanding of their ability to protect households from disruptions will complement the upazila prioritization approach used here.

High-resolution measurement of spatial SDG attainment
Typically, SDG achievement is reported nationally, with performance aggregated across a country's diverse geographical and
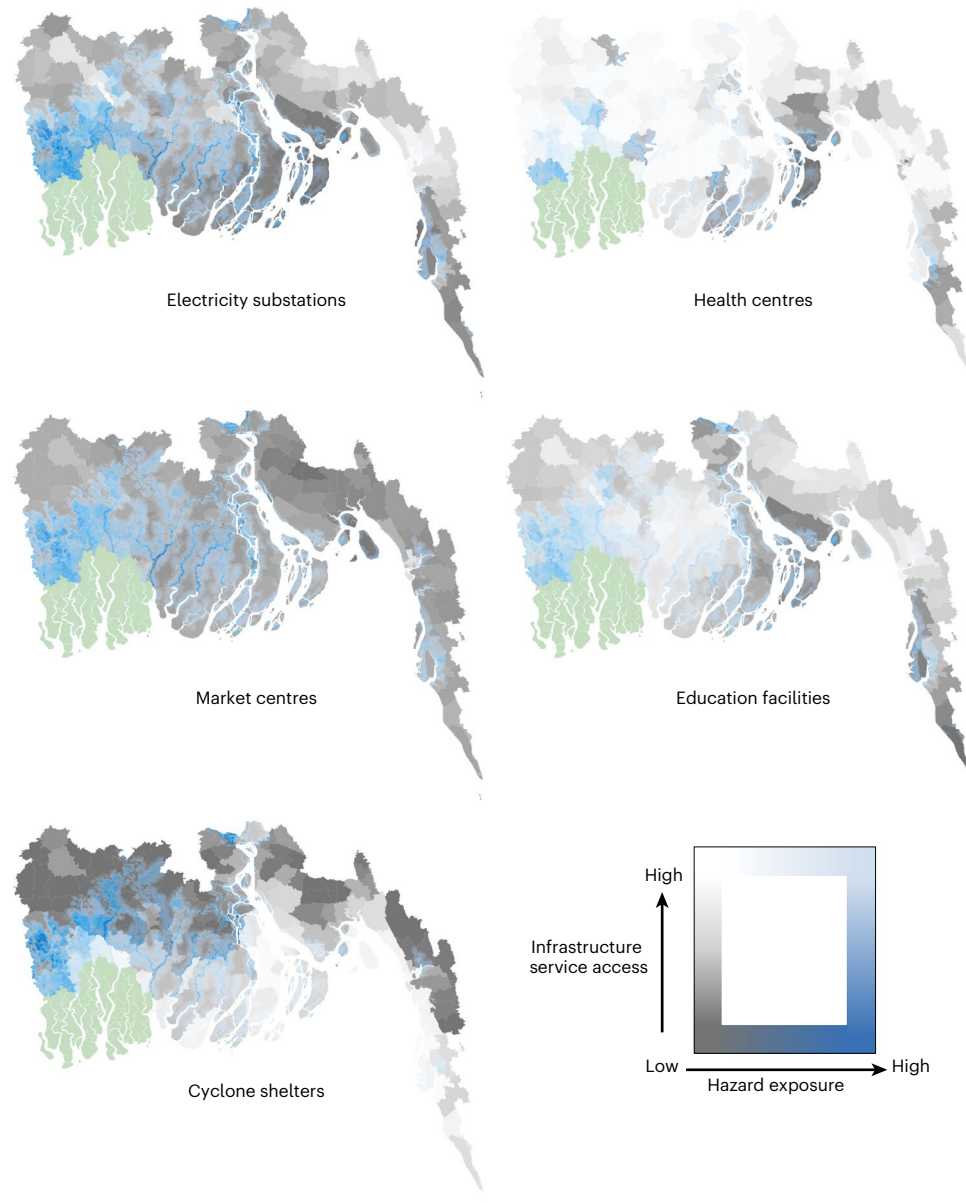
Fig. 5 | Prioritizing spatial localization of new infrastructure to target underserved populations. Intersecting coastal flood hazard exposure (30 × 30 m resolution) with existing infrastructure service access, determined by household survey responses or proximity thresholds aggregated by upazila. Dark blue areas show where infrastructure access is low and hazard exposure is high (that is, the critical areas), while white areas show where both infrastructure access and hazard exposure are of less critical concern. Dark shades of grey indicate where households have low levels of access to infrastructure services but are not highly exposed to coastal flooding and light blue areas indicate where there is high exposure to coastal flooding but household access to services is high. The Sundarbans Reserve Forest is shown in green. Equivalent maps for river flooding, cyclones and erosion are included in Supplementary Fig. 2.

socioeconomic strata. Mechanisms for SDG target-setting can often be vague and not amenable to downscaling at the local level[51]. This study demonstrates the future potential of bottom-up measurement of SDG progress that can be directly linked to climate hazards to assess and improve upon key sustainable development indicators.

In this and other contexts, additional SDG targets can be incorporated in the same way with adequate provision of geospatial data on other relevant infrastructures, extending to water treatment plants, distribution networks and access points (for example, wells and boreholes) (SDG 6), road and rail networks (SDGs 9 and 11), waste treatment facilities (SDG 12), and civil and government buildings (SDG 16). Climate-related hazards that are more relevant in other parts of the world (for example, droughts, wildfires and storms) can be integrated or substituted into this assessment approach, as disruptions are being measured by critical asset exposure.

Mainstreaming spatial hazard analysis into policy

There is great potential for data-driven geospatial analysis to inform adaptation investment decisions at the local level. While high-resolution household data are difficult to obtain in many contexts, emerging methods around spatial microsimulation and dasymetric modelling[52], complemented by increasingly advanced satellite technology and remote sensing, can provide decision-makers with a precise toolkit to inform infrastructure and development decisions.

To reach its full potential in a national policy planning context however, this type of analysis must be integrated into existing government systems and processes. In the case of Bangladesh, the Mujib Climate Prosperity Plan serves as a national roadmap for climate resilience seeking to counteract climate-induced damage and losses, strengthening employment, promoting well-being and securing energy independence while supporting delivery of the 2030 Sustainable Development Agenda.

A comprehensive streamlining process with identified entry points in relevant government agencies and ministries should be undertaken in parallel for this type of analysis to be most effective.

The delivery date for the Sustainable Development Goals is rapidly approaching; however, major achievement gaps remain across most countries. These gaps are at risk of growing as climate hazards intensify in many parts of the world. Existing national targets do not always adopt a pro-poor approach to achieving the SDGs or consider exposure bias in vulnerable communities. As a result, these populations are at a higher risk of failing to reach target thresholds, even as national development progress improves overall. We show that novel geospatial data techniques can assist policymakers in understanding localized climate hazard threats to the achievement of national SDG targets through their impacts on vulnerable populations. This approach is particularly relevant in other similarly data-scarce parts of the world, where decision-makers can target and prioritize pro-poor development, accelerating informed sustainable development at scale.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-024-01950-2.

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Methods

The study was conducted according to the following methodological components: (1) creation of a database[53] including (i) relevant climate hazard scenario data from national or global datasets and (ii) point and network data for critical infrastructure and social sector locations; (2) use of high-resolution household survey data to identify dependence on infrastructure assets at a granular scale through nearest-neighbour analysis; (3) assignment of households to wealth quintiles based on household survey responses; (4) calculation of statistically significant exposure biases across different wealth quintiles; and (5) calculation of SDG progress downscaled to the local administrative level through household survey responses and proximity to services, and identification of climate threats to progress based on asset exposure.

Spatial database of climate hazard and infrastructure risks

The study area was defined as the 19 districts comprising Bangladesh's coastal region, which were further divided into 150 smaller administrative regions, known as upazilas, based on a recent World Bank report[39].

Climate hazards. For coastal and riverine flooding, data from the World Resources Institute 'Aqueduct Floods' online platform was obtained[54], which include both tidal inundation as well as storm-surge-induced coastal flooding. The dataset measures flood risks for the baseline year (1980) and projections to 2030, 2050 and 2080. These scenarios are provided for return periods for 2, 10, 25, 50 and 100 years for Representative Concentration Pathways (RCPs) 4.5 (realistic) and 8.5 (extreme) at a resolution of 30 arc seconds (about 1 km × 1 km). For cyclone hazards, maximum wind gusts (in m s^{-1}) are based on a probability distribution derived from ensemble resimulations of 12 historical cyclones from return period event maps at a resolution of 4.4 km[40]. For erosion hazards, an erosion map was created using the DeepWaterMap model[55,56], which is based on satellite imagery from the past 35 years and has a resolution of 30 m × 30 m. The DeepWaterMap model automatically distinguishes land from water, and thus tracks morphological changes over time; ref. 55 provides further information on the model and its validation in coastal Bangladesh. Here we extract all pixels that have experienced erosion at any point in the last 35 years. Given the focus on past cyclones and erosion events, these two datasets do not entail future hazard scenarios. Although there is a discrepancy in the scenarios and timeframes covered by the different climate hazard datasets, at present there are no models that simulate cyclonic wind gusts and erosion trends for the same scenarios and timeframes as river and coastal flooding. Thus, for the purpose of this multihazard assessment, analyses were undertaken for all four hazards, but their differing temporal resolutions are caveated where appropriate. Finally, despite not undertaking an uncertainty analysis of these hazard layers, we ensured that all input data have previously been validated; for example, the cyclone hazard layer was validated using past cyclone events[40], the erosion layer was validated in coastal Bangladesh[55], synthetic household data were validated against household surveys[38].

Infrastructure data. Point and network data for the energy sector as well as critical social infrastructure assets were obtained from a mix of publicly available and Bangladesh Government sources: Power Division and BPDB (electricity); Water Resources Planning Organization (WARPO) (market centres); Department of Health (healthcare facilities); Local Government Engineering Department (LGED) (cyclone shelters); and Bangladesh Bureau of Statistics (educational facilities). We gathered and verified this data through a series of workshops, dialogues and stakeholder meetings held in 2022. These events were collaboratively organized by the Department of Environment (DoE) in Bangladesh, the Global Center on Adaptation (GCA), the United Nations Office for Project Services (UNOPS), and the Center for Environmental and Geographic Information Services (CEGIS). The close collaboration with CEGIS ensured that the most up-to-date information was being collected[30]. The geospatially located critical infrastructure assessed here included 113 electricity substations, 2,062 market centres, 3,086 healthcare facilities, 3,777 cyclone shelters and 73,814 educational institutions.

Each layer of infrastructure asset and network data was then intersected with all climate hazards to determine the exposure of infrastructure service provision under each scenario, including the estimated flood depth in metres.

Infrastructure service provision to coastal households

To assess the potential impacts of infrastructure service disruptions on households in the coastal region, three categories of data were combined: climate hazards, infrastructure asset data (as described above) and household characteristics. Household-level population data were obtained from the World Bank[38] as part of a spatially explicit synthetic household dataset for the coastal region of Bangladesh, which includes unique structural and socioeconomic attributes mapped to the local level and validated by independent household surveys. This includes household-level information on, among other things, access to electricity, tap water and sanitation, housing type, literacy, education levels and employment.

We conducted a nearest-neighbour analysis to link each household to its nearest service-providing asset for each subsector, thus estimating the household profiles (characteristics) dependent on each infrastructure asset. Service area estimation can be achieved through various methods, such as accessibility mapping using the road network[57] or conducting a sample of household surveys[36] to determine actual receipt of services. Here we used a simpler radius-based approach due to several factors including: (1) road network data for the coastal region of Bangladesh being not well-connected enough to allow for routing and unavailability of up-to-date information on the quality of roads; and (2) household positions in the synthetic dataset being represented in clusters which, while geographically accurate to the local district, do not represent exact positions, leading routing to be inherently inaccurate and less interesting. This simplified approach allowed the assignment of households to assets at the scale of the entire coastal region.

Only households reporting access to the corresponding service were included, and where these could not be determined from the survey, households were considered not to have access when they fell outside of a distance threshold (5 km for health centres, 1.6 km for cyclone shelters, see section 'Household infrastructure service accessibility and the SDGs'). Using the intersection of hazard and asset data as described above, the exposure of households was determined for each scenario on the basis of its supposed use of or connection to the nearest assigned asset. Based on in-country stakeholder feedback, the scenario chosen for this part of the analysis was a 1-in-50-year event for a time period of 2030 under RCP 4.5. This scenario was applied to the two flood hazards (coastal and fluvial flooding), while the hazards of erosion and cyclones were based on historical data with no simulations of future scenarios.

Household assignment to wealth quintiles

To estimate relative household wealth levels, we constructed a wealth index using several infrastructure access variables included in the available household dataset, in line with that created in ref. 45 for coastal Bangladesh. This approach provides a more objective proxy of household wealth than common variables such as income or consumption, which can be hard to measure accurately in low-income settings due to their variable or short-term nature, or the informal nature of much of the economy. The index was constructed separately for households identified as urban and rural due to differences in underlying variables between urban and rural dwellers (for example, electricity being more common in urban areas). Table 1 lists the variables that were used to construct the wealth index.

The data were first normalized, after which we ran a principal component analysis in line with the approach of creating a wealth index used by WFP-FAO[58]. The Kaiser–Meyer–Olkin measure of sampling adequacy showed values of 0.62 for rural dwellers and 0.71 for urban dwellers, which are above the minimum acceptable value of 0.6. The first principal component explained ~40% of the variance and was used to construct the wealth index. We separated the indexed households into quintiles, which ranged from the poorest (Q1) to the wealthiest (Q5) quintile.

Calculating statistically significant exposure bias

To explore and quantify whether there were poverty or wealth biases in the exposure of households to climate disruptions to infrastructure services, the risk ratio was calculated. This quantifies how much more likely a household in a given wealth group is to experience service disruption due to a hazard relative to the median wealth group. Such biases were then tested for statistical significance following typical hypothesis-testing procedures as outlined below. Only relative risks that were significantly different from those of the median group at the 95% confidence level were considered in this analysis.

Given two populations of size n and m with respective X_1 and X_0 households disrupted due to a climate hazard, the proportion of successes (number of households exposed to disruption in this case) is given by $p_1 = \frac{X_1}{n}$ and $p_0 = \frac{X_0}{m}$. We can understand these to be samples from two binomial distributions $\text{Bin}(p_1, n)$ and $\text{Bin}(p_0, m)$. If the underlying probability of disruption is the same for both populations, then $p_1 = p_0$. A. hypothesis test for this has the form,

$$H_0 : p_1 = p_0 \qquad (1)$$

$$H_1 : p_1 \neq p_0. \qquad (2)$$

The standard, normally distributed test statistic for this hypothesis test is given by,

$$z = \frac{p_1 - p_0}{\sqrt{\frac{p_e(1-p_e)}{n} + \frac{p_e(1-p_e)}{m}}} \qquad (3)$$

where

$$p_e = \frac{X_1 + X_2}{n + m}, \qquad (4)$$

and we used a critical z-score of ± 1.96. If our test statistic z fell outside of this range, we then rejected the null hypothesis of the distributions being the same at the 95% confidence level[59]. We applied this to compare both the poorest (Q1 and Q2) and the wealthiest (Q4 and Q5) population groups to the median wealth group (Q3). Given the large number of households in each upazila (in the order of 100,000 households per upazila), the confidence intervals became quite narrow, meaning that small deviations between the poor/wealthy and median proportion of households affected could produce a statistically significant result.

Household infrastructure service accessibility and the SDGs

This section focused on protecting or 'safeguarding' of existing progress towards several SDG indicators by identifying where achieved target levels might be most at risk from climate hazards. The Government of Bangladesh's SDG Working Committee has drafted prioritized national SDG targets ('NPTs') (https://sdg.gov.bd/). First, five targets closely linked to infrastructure service delivery in the sectors addressed in this study were identified; these fell under 5 relevant SDGs (3, 4, 7, 8, 13) and related to the share of the population having access. The targets linked to the water supply and roads subsectors (SDGs 6 and 9) were omitted due to a lack of data on water supply infrastructure and local road types in the synthetic household dataset.

Next, for each of the 150 upazilas in Bangladesh's 19 coastal districts, detailed survey data from the synthetic household dataset were aggregated to calculate current progress at the upazila level towards each target, on the basis of household responses to questions on access to education (SDG 4), electricity access (SDG 7) and employment (SDG 8). The calculated distance from each household to the nearest asset was further used to estimate access to health centres (SDG 3) and shelters (SDG 13). On the basis of previous studies, thresholds for reasonable access to health services were set at 5 km[60–62], while access to shelters was set at 1.6 km[63,64]. The households outside these thresholds were considered to have 'no access'.

All connected households in these upazilas were then assigned to the nearest asset within each subsector (substation, school, health centre, market centre and shelter). Households were considered exposed to hazards affecting their nearest asset if the flood exposure to the asset was >1 m (coastal and riverine flooding), if wind gusts were >30 m s^{-1} (cyclones) or if erosion occurred[43]. Under the following relevant climate scenarios for each of the four assessed hazards, the share of households (or population) in each upazila 'with current access to the service' and 'also facing disruption due to exposure' to a hazard, was calculated. The scenario in this analysis was based on:

- A 2030 timeframe, corresponding to the delivery date of the Sustainable Development Goals.
- A 50-year return period and RCP 4.5, based on consultations with local stakeholders.

This measure of 'progress at risk' was then calculated as a share of the total target, downscaled from the national scale to each upazila. An example is shown in Supplementary Fig. 3. The calculations and assumptions in Supplementary Table 2 were used to assess current (upazila-level) progress towards the government's stated SDG target for each relevant SDG.

Data availability

Data used in this study can be accessed at https://doi.org/10.5281/zenodo.10554713.

Code availability

Code relevant to the analysis can be accessed at https://www.dropbox.com/scl/fi/tpjcxtl4j9m9ht0tl0ocq/NCLIM-23071599-code_final.zip?rlkey=ux7du7k4rkru352moob6quwwu&dl=0.

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Author contributions

D.A., S.S.G. and A.P. contributed to the design of the study. S.S.G., D.A. and J.V. developed methods for the parts of the analysis. S.S.G., A.M.P. and D.A. performed most of the data analysis. D.A. and A.M.P. generated the figures and visualizations used in the manuscript. A.P. and M.S.G.A. contributed to the interpretation of the results. D.A. and A.P. wrote the manuscript. A.M.P., S.S.G., M.S.G.A., J.V. and J.W.H. provided written contributions and advisory feedback. A.P. coordinated the research and most of the stakeholder consultations. All authors reviewed and provided edits on the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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