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RESEARCH ARTICLE

Freshwater Scarcity and Livelihood Capital Disparities Across Coastal Gradients in South-Eastern Bangladesh

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ABSTRACT

Freshwater scarcity is a persistent challenge for coastal households in south-eastern Bangladesh, where salinity intrusion, seasonal hydrological variability, cyclones, and competing water demands can constrain domestic water use and livelihood activities. Guided by the Sustainable Livelihoods Framework (SLF), this study was designed to compare natural, physical, human, financial, and social livelihood capitals across coastal, peri-coastal, and inland-transition settings in the Chattogram–Cox's Bazar region. The author confirms that 384 households completed the questionnaire, alongside qualitative data collection described in the original manuscript. However, the zone-specific sample sizes and numerical results cannot be verified because the household-level dataset and original statistical output are unavailable. Consequently, this revision does not report unverified zone means, index scores, regression coefficients, subgroup percentages, or significance tests. The cross-sectional design can support descriptive associations only and cannot establish causation. The findings must be reconstructed from verifiable records or the affected numerical claims removed before submission.

Keywords: freshwater scarcity; salinity intrusion; Sustainable Livelihoods Framework; livelihood capital; coastal Bangladesh; water security; mixed methods

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1. Introduction

Human life, the health of ecosystems, agricultural production and socio-economic development all rely heavily on freshwater resources. Almost 71% of the Earth is covered by water; however, only 2.5% of the total global supply of water is available for use, and less than 1% of freshwater resources are actually available for human consumption. Therefore, in today's society, the availability of adequate freshwater supplies is a major issue (UN-Water, 2023). Rapid population growth, climate change, urbanization, over-extraction of groundwater and degradation of coastal environments have all contributed to a world-wide freshwater shortage that has been especially pronounced in low-lying, deltaic and coastal regions (IPCC, 2022). Freshwater shortages that assail coastal deltaic areas are now one of the key challenges involving human security in the

21st century and have been exacerbated by the environmental stresses resulting from climate change, population growth and unsustainable land-uses. Coastal areas of the Bay of Bengal in South Asia (one of the hardest hit regions) have been severely impacted by salinity intrusion, tidal flooding and cyclonic storm surge inundation which have all had a negative effect on the freshwater resources upon which millions of people depend to provide drinking water, food through agriculture, fish through fishing and their domestic needs (Islam et al., 2024; Joshi et al., 2024). Bangladesh is often referred to as the most vulnerable country to climate change given the highly populated (density) nature of its citizens, low elevation relative to sea level, reliance on the monsoon for its hydrology and the fact that it is located so close to the coast (PCC, 2022).

Freshwater insecurity is now turning into one of the most pressing environmental and development issue in the coastal areas of Bangladesh, where climate change, population increase, urban sprawl, and resource use that is not sustainable are ramping up the pressure on already limited water supplies. In the south-eastern part of Bangladesh, especially in Chittagong and Cox's Bazar, the availability of freshwater is getting more and more threatened by uneven seasonal rainfall, groundwater depletion, saline water encroachment, tourism linked demand, and the contamination that comes from home-based, factory, as well as farming sources (Ahmed et al., 2023; Hasan et al., 2024). These stressors, happening together, lower both the amount and the standard of freshwater that people can actually reach, and that makes drinking water provision, crop production, sanitation, and even the well-being of local ecosystems become harder. South-Eastern Bangladesh, covering the districts of Cox's Bazar, Chittagong, Feni, Lakshmipur,and Noakhali, has a fairly complicated ecological and socioeconomic picture. Unlike the south-western coastal belt that has been examined a lot around Khulna, Satkhira,and Bagerhat, the south-eastern coastal stretch is shaped by changing coastline forms, highly settled fishing communities, a major refugee population after the Rohingya inflow in 2017, and seasonal shifts in salinity patterns tied to monsoon flow from the Karnaphuli, Matamuhuri,and Sangu river systems (Islam et al., 2024; Frontiers in Sustainability, 2024). Still, the livelihood capital knock-on effects that freshwater scarcity causes, across the near-shore to more interior line, in this sub region, are largely not explored in any systematic manner, at least when you compare it with the big amount of work done on south-western Bangladesh.

The Sustainable Livelihoods Framework (SLF) provides a useful starting point for examining how households draw on natural, physical, human, financial, and social capital (DFID, 1999; Chambers & Conway, 1992). These capitals should not, however, be treated as independent or interchangeable assets. For example, access to land or fishing grounds (natural capital) may produce limited income when households lack equipment, secure market access, or bargaining power; income then affects the ability to invest in water storage, education, and health. Social networks may help households share water or obtain emergency credit, but these networks cannot replace reliable infrastructure or public provision. Outcomes are also shaped by structural conditions, including land tenure, gendered divisions of unpaid work, access to institutions, market relationships, and the distribution of decision-making power. This study therefore uses the SLF as a relational framework and interprets capital scores as indicators of household resources within a wider institutional and

political-economic context, rather than as a complete measure of resilience.

Prior research suggests several pathways linking freshwater insecurity with livelihood resources. Salinity can constrain drinking-water options and affect crop production, soil conditions, and some aquatic livelihoods; households may respond by purchasing water, changing occupations, borrowing, or relying on relatives and community groups. These responses are uneven: households with land, equipment, savings, or stronger market connections may adapt more readily than landless households and small-scale fishers. Women may bear a disproportionate share of water collection and care work, while their influence over water-management decisions may remain limited. Tourism-related demand, population change including the Rohingya displacement context in Cox's Bazar, NGO and public programmes, and differences in market access may also shape observed spatial patterns. The present study examines whether reported livelihood-capital differences vary across three geographic zones; it does not assume that distance or salinity alone explains those differences.

The study has four objectives: (1) describe household freshwater access across coastal, peri-coastal, and inland-transition zones; (2) compare the five livelihood-capital sub-indices and composite LCI across zones; (3) estimate associations between selected household and water-access characteristics and LCI; and (4) explore gender- and livelihood-specific patterns using survey and qualitative evidence. Because the design is cross-sectional, the analysis identifies spatial differences and statistical associations rather than causal effects. The results are intended to inform discussion of place-specific water-security and livelihood-support priorities in south-eastern Bangladesh.

2. Literature Review

The coastal areas of Bangladesh are experiencing a crisis of freshwater that emerges from multiple sources (including geophysical, anthropogenic and climatic) and drives the salinity of coastal ground and surface water inland at an increasing rate. The immediate driver of salinity intrusion in the coastal area is the movement of saline water into ground and surface water systems pushed by tidal forces, rising sea levels, and decreased flow of freshwater into the rivers feeding these areas. The amount of coastal Bangladesh's land area experiencing salinity intrusion has grown exponentially, from approximately 0.83 million hectares in 1973 to approximately 1.05 million hectares in 2023, and is projected to continue to move further inland under RCPs 4.5 and 8.5 (Islam et al. 2025; UCL EPICentre 2024). Additionally, the salinity intrusion dynamic in the southeastern coast is very different than the southwestern coast because of the greater influence of monsoon river flows coming from the Chittagong Hill Tracts, which create dramatic seasonal asymmetry between very salty river freshwater during the dry season and very low salinity river levels when it is monsoonal (Frontiers in Sustainability 2024). Relative sea level rise ulitmately consequences for raising salinity intrusion, experiencing relative sea level rises of 5-8 mm per year as in Bangladesh compared to the global average, creating significant increases in salinity intrusion due to the combination of absolute sea level rise and land subsidence from sediment compaction and groundwater extraction (Islam et al. 2024).

Sea-level rise has caused structural amplification of salinity intrusion. In coastal Bangladesh, high rates of

relative sea-level rise occur due to absolute sea-level rise, and land subsidence, caused by sediment compaction and excessive groundwater extraction (Islam et al., 2024), occur at a rate of five to eight mm/year. Additionally, freshwater scarcity is made worse by cyclonic disturbances: cyclones, such as Sidr (2007), Aila (2009), Amphan (2020) and Mocha (2023), produce storm surges that lead to deposition of saline water on cropland and contamination of freshwater ponds, with recovery times from salinity ranging from several months up to more than two years (PLOS Climate, 2025; UCL EPICentre, 2024).

Farakka Barrage upriver on the Ganges still keeps declining the dry-season freshwater entering toward the south-western coast, but the way it really impacts the south-eastern sides causing the salinity fluctuation through Brahmaputra-Meghna discharge dynamics (Frontiers in Sustainability, 2024). Human made drivers are also in the mix, for instance the expansion of commercial shrimp aquaculture. This approach basically brings saline water on purpose into low-lying farmland, so brackish shrimp ponds—called g hers, or g hers in local usage—get formed. That process shifts the whole local water regime, and then doing any later freshwater cultivation becomes very hard, and sometimes close to impossible (Islam et al., 2023). Meanwhile, population growth has ratcheted up groundwater pumping , which lowers the water table, and it sets the stage for deeper saline groundwater to creep in (Mongabay, 2024). On top of that, there's inadequate upkeep of polders, those embanked low areas that shield coastal land from tidal flooding ,and because of this, communities end up more exposed to saline intrusion episodes (PLOS Water, 2025).

Coastal vulnerability assessments across South and South-East Asia have provided a wealth of empirical data regarding the capital assets of communities and their links to water and climate security, using the Sustainable Livelihoods Framework (DFID 1999; Chambers and Conway 1992). There are five capital assets (natural, physical, financial, human, and social) within the SLF. The five assets provide a lens through which one may assess multidimensional poverty and vulnerability (Hoque et al. 2019). Research conducted on coastal Bangladesh has consistently demonstrated how all forms of capital deprivation are interrelated. For example, Hoque et al. (2019) found that farmers on deltaic islands (chars) were the most vulnerable to the effects of climate change and had suffered from the depletion of their natural capital base as a result of erosion and salinization of the land. Fahim and Arefin (2024) documented that agricultural livelihood patterns of Western cost of Bangladesh have changed as a result of increased saline intrusion due to climate variability affecting nearly 27% of households. The bulk of the losses experienced from various forms of capital deprivation were found to be concentrated among landless households who rely on fishing and small-scale agriculture.

PLOS Water (2025), it was found that 78% of respondents in south-western coastal households used pond water as their primary source for fresh water, and households that did not have a working pond typically had significantly lower composite capital scores. This relationship was connected to the fact that ponds not only provide fresh water but also can be used for the purposes of generating income through aquaculture activities. There is increasing evidence in the academic literature of gender-based differences in the availability of livelihood capital in coastal areas with limited water resources. A large (800 respondents) recent study in southern coastal Bangladesh using the Individual Water Insecurity Experience scale (IWISE) and the Agricultural Water Insecurity Experience scale (AgWISE) showed that women, particularly those working as

agricultural labourers, reported significantly higher levels of water insecurity than men, and that this difference was compounded by various intersectional factors (e.g., land ownership, age, and marital status). in the coastal area, women are basically invovled for the collection of freshwater resources but low institutal access in decision making regarding water management activities (CGIAR Initiative on Asian Mega-Deltas, 2024)

There are many studies (Sinha et al., 2024; BMC Women's Health, 2025) that report reproductive health outcomes for women who are exposed to saline water in regards to female reproductive tract infections, gestational high blood pressure, and issues with menstrual hygiene, which removes an important but under-researched aspect of declining human capital. Coastal gradients are a method of analyzing the systematic differences found within a coastal area, in terms of both biophysical and socioeconomic conditions, as you go inland. Evidence from a study reporting on Coastal movement along the marine coast of Bangladesh demonstrates that the area directly adjacent to the coast (0–5 km) has seen the most dynamic geomorphologic changes, has the highest levels of salinity, and has experienced the highest number of flooding events. In addition to having an abundance of freshwater, the inland-transitional coastal zone has diversified economic opportunities. This spatial variability in the coastal region will be important in developing adaptation investments and social safety net programs targeted at building resilience for coastal communities.

The Cox's Bazar coast in Southeast Bangladesh complicates the area due to its geographical location and size—approximately 120 km long, making it the longest unbroken natural sea beach in the world (UN Environment Programme 2018). The coastal area also comprises the Teknaf Peninsula, which has experienced significant biodiversity loss and is home to many small fishing communities that struggle with freshwater availability. In addition, more than 900,000 Rohingya refugees enter the area in Cox's Bazar since 2017, that has increased competition for freshwater among local residents and refugees and contributed to deforestation and open defecation around streams used for drinking water and food production (IWA Publishing 2024). The crisis associated with the managing freshwater in this context are exacerbated by overlapping jurisdictions of key agencies such as the Department of Public Health Engineering (DPHE), the Bangladesh Water Development Board (BWDB), and international agencies such as the United Nations High Commissioner for Refugees (UNHCR) and the United Nations Children's Fund (UNICEF), who all manage the refugee camps.

Over the last two decades, Bangladesh has become more adept at designing its own system of water governance policy. For example, the Bangladesh Delta Plan 2100, adopted in 2018, outlines an integrated water management policy framework, which includes a range of measures aimed at enhancing freshwater security in the coastal area (Bangladesh Delta Plan 2100, 2018). As stated in the NAP 2023-2050 plan, water resources will be key to adapting to climate change; thus, improving irrigation efficiency and the utilization of surface water as well as developing water governance institutions are among the key policy objectives (NAP, 2023). The Mujib Climate Prosperity Plan for 2022-2041 similarly emphasizes the role of water and renewable energy in achieving climate resilience in the region.

Despite policy ambitions and frameworks, challenges persist with respect to their actual implementation.

Bangladesh has numbers of water management related policies and strategies but the problem found lack of effectiveness, poor inter-departmental coordination, and the data regarding water use are often inconsistent (The Business Standard, 2025). Technical and financial difficulties also prevent communities from applying such water-efficient practices as AWD, drip irrigation, and rainwater harvesting systems (PLOS Climate, 2025). However, community-level projects such as the Blue Gold Project initiated jointly by the Netherlands and Bangladesh show the effectiveness of implementing an integrated approach to water management in the coastal area (The Business Standard, 2025).

3. Materials and Methods

3.1. Study area

In order to study variations in access to fresh water across the coastal gradient, three communities were selected from different locations in southeast Bangladesh. For example, there was one coastal community chosen from Cox's Bazar, one peri-coastal community selected from Chittagong district, and mainland community that was relatively away from the coastline. Site selection criteria included hydro-environmental conditions, availability of fresh water, distance from coastline, tourism activity, and exposure to climate risks such as cyclones, saline intrusion, flooding, and drought (Table 1)

Table 1. Spatial profile of selected study areas

Study Area Type	Administrative Units	Approximate Direction	Coastal Proximity	Hydrological Condition	Environmental Stressors
Coastal Area	Kutubdia, Teknaf, Maheshkhali	Southern / South-western Cox's Bazar	Direct coastal contact	Surface-water and rainfall dependent	Cyclones, salinity, storm surge, tidal flooding
Per-coastal Area	Pekua, Chakaria	Central Cox's Bazar	Moderate coastal influence	Mixed groundwater–surface water use	Seasonal drought, moderate salinity, irrigation limitation
Mainland Area	Satkania, Patiya, Lohagara	Northern / North-eastern study region of Chattogram district	Away from direct coastline	Groundwater-dominated system	Arsenic risk, groundwater depletion, seasonal water scarcity

The south-eastern coast of Bangladesh is enriched with various landscape types such as beach, estuarine, hill, canal, wetland, and low-lying flood plain ecosystems. Freshwater use by households in such areas mainly depends on tube wells, ponds, rainwater harvesting, and limited piped water distribution systems. Surface water available from canals, ponds, and creeks is used for washing, irrigation, aquaculture, and bathing. Selected coastal areas in the southeastern region of Bangladesh have been chosen to represent three different hydro-ecological ecosystems: Coastal, per-coastal, and mainland areas. These areas have been classified by

different factors, including: geographic distance from the Bay of Bengal, whether or not they are located directly on a coast, how easily people can get freshwater to use, whether they have only been exposed to salinity (the saltiness of water), the quantity of groundwater available, and what is the primary means of livelihood in that area. Then, the coastal areas selected for this study are Kutubdia, Teknaf, and Maheshkhali (located in the Cox's Bazar District), which experience direct effects of coastal conditions, much saltier water coming in off the ocean (saline water), the impact of tides coming in and out of the ocean, and they are also at high risk of being affected by cyclones and storm surges. The transitional region of the study includes Pekua and Chakaria Upazila (of Cox's Bazar District), where we can see conditions intermediate between those experienced by coastal regions (described above) and by mainland (described below). In other words, both coastal and mainland hydrological conditions exist in this region. The mainland area of the study area (which includes all of Satkania, Patiya, and Lohagara Upazila, all of Chattogram District) is located more inland than the regions immediately adjacent to the coastline listed above, and the primary environment that has been impacted by human activity within this area has been related to irrigation and agricultural production. As previously mentioned, there is less salinity in the Inland area compared to coastal areas; however, due to seasonal shortages of freshwater, depletion of groundwater, and localized arsenic contamination, these are three significant issues in the Inland area. Each of these categories or "study areas" exhibits a wide range of differences between them based on how each population obtains and uses water resources for agriculture and fishing and how each community has adapted to environmental changes (Fig 1)

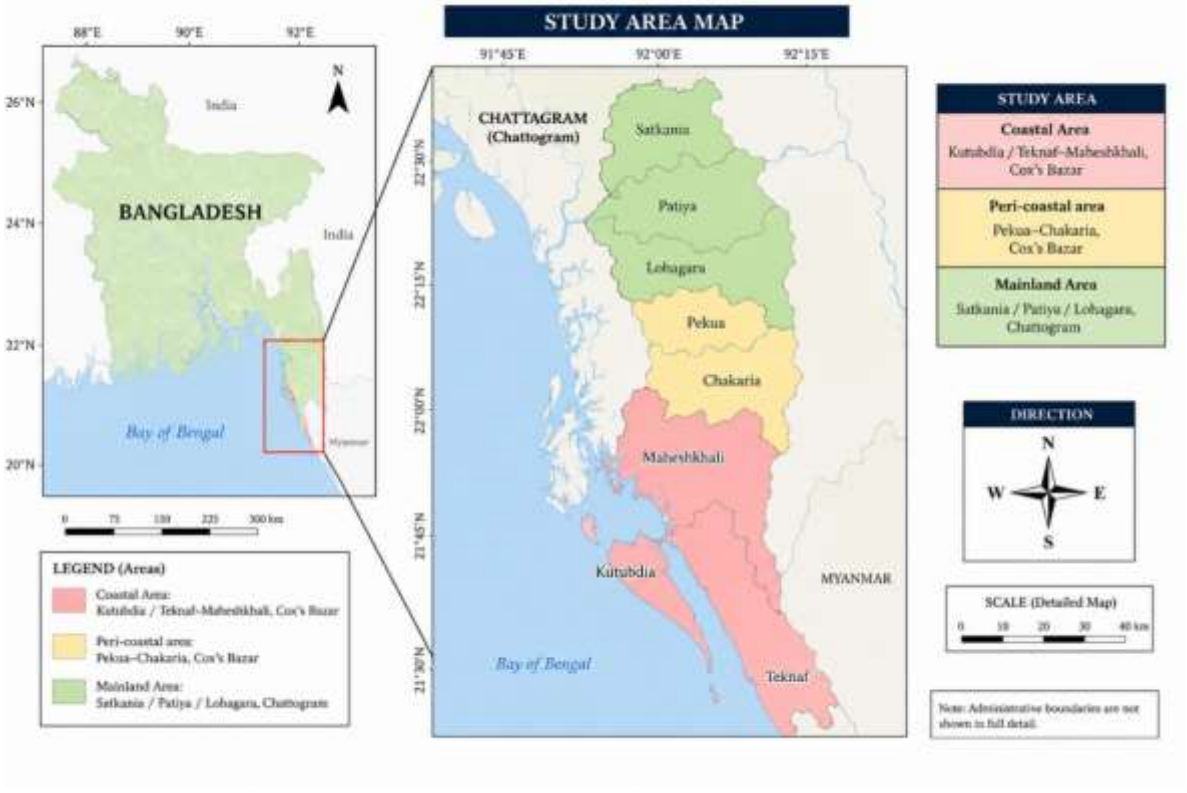


Figure 1. Geographical Location of the Study areas

Three gradient zones were used as operational study strata: coastal (0–5 km), peri-coastal (5–15 km), and inland-transition (15–25 km) from the mean high-water line. The original manuscript also refers to salinity and tidal exposure in defining the zones, but the zone-specific numerical evidence is not verifiable from the available records. These distance bands should not be treated as universal coastal classifications; their empirical validity must be justified using verifiable site descriptions and measurements. The three zones are defined in the manuscript using distance from the mean high-water line (MHWL), reported dry-season salinity, tidal exposure, and dominant livelihood profile: coastal (0–5 km), peri-coastal (5–15 km), and inland-transition (15–25 km). These bands are operational categories for comparing sampled settings, not universal ecological thresholds. The rationale is that proximity to the coast can correspond with differences in saline intrusion and tidal exposure, while the selected sites also differ in water infrastructure and livelihood composition. The manuscript should report the method used to calculate distance (straight-line or route distance), the source and date of the MHWL/coastline, and whether each household was assigned by measured distance or by administrative area. Since zone membership also captures differences in site, infrastructure, and livelihood, the observed zone contrast cannot be attributed to distance alone.

3.2. Research Design and Philosophical Orientation

For this study, the authors used an explanatory sequential mixed methods approach (Creswell & Creswell, 2018), with the quantitative household survey data being collected and analyzed first to understand the pattern and magnitude of freshwater scarcity and disparity in livelihood capital across the coastal gradient zones, followed by the collection of qualitative data through KIIs and FGDs for interpretation and elaboration of the quantitative results. The research's philosophical orientation combines critical realism, which holds that structures (hydrological systems, institutions, power dynamics) shape observable outcomes (LCI scores), and constructivism, which recognizes the meanings communities attribute to water security and livelihood wellbeing.

3.3. Sampling and Data Collection

The authors used a geographically structured analysis to examine freshwater access and livelihood conditions across three types of settings in south-eastern Bangladesh: coastal, peri-coastal, and mainland areas. The selected administrative units were Kutubdia, Teknaf, and Maheshkhali for the coastal stratum; Pekua and Chakaria for the peri-coastal stratum; and Satkania, Patiya, and Lohagara for the mainland stratum. These strata represent contrasting degrees of coastal exposure and differing freshwater-access conditions. A total of 384 households completed the survey. The three-stratum framework provides a basis for comparing household freshwater access and livelihood conditions across different environmental settings. However, the final number of surveyed households in each administrative unit and stratum must be reported from the original field records. Equal allocation of 128 households per stratum should not be described as the actual sampling distribution unless it can be confirmed (Table 2).

Table 2. Sampling Design of the study areas according to research design

Sampling stratum	Administrative unit	Proposed households
Coastal	Kutubdia	43
	Teknaf	43
	Maheshkhali	42
Coastal subtotal		128
Peri-coastal	Pekua	64
	Chakaria	64
Peri-coastal subtotal		128
Mainland	Satkania	43
	Patiya	43
	Lohagara	42
Mainland subtotal		128
Grand total	**8 administrative units**	**384**

The household survey was carried out by a team of 24 well-trained enumerators (twelve males and twelve females) from January to June 2025, taking into account the peak period of dry season (maximum salinity intrusion; January to April) and early stages of monsoon transition (May to June). Survey questions included: demographic details and level of education; primary and secondary livelihood sources and their income; access to freshwater (source type, distance, availability during different seasons, water quality, collection time); livelihood asset status (land holdings, productive instruments, livestock, savings, credit availability, social group membership); water-related health issues in the past 12 months; and measures undertaken for coping with water scarcity problem.

Simultaneously, 18 Key Informant Interviews (KIIs) were done with government agency officials (Department of Public Health Engineering (DPHE), Bangladesh Water Development Board (BWDB), Department of Fisheries), NGO workers involved in water programs and livelihood development, union parishad members, water management committee members, and traditional community leaders (imam, mahajan). The authors also conducted 6 Focus Group Discussions (FGDs) with 10-12 people in each group, segregated by gender in each of the three gradient zones (two in each).

3.4. Development of Livelihood Capital Index

The index covers five capital domains. Human capital includes education, training, adaptation knowledge, and available household labour; natural capital includes freshwater access and quality, land, soil fertility, irrigation, salinity exposure, and fishing resources; physical capital includes water infrastructure, storage, transport, and housing-related assets; financial capital includes income, savings, credit, remittances, and productive assets; and social capital includes group participation, trust, collective action, institutional access, and household decision-making. The exact indicator set and scoring rule must match Table 3 and the final analysis file.

Step 1: Indicator score calculation

$$MCIi = \{f(A) \times 0 + f(B) \times 0.25 + f(C) \times 0.50 + f(D) \times 0.75 + f(E) \times 1.00\} \quad (1)$$

Step 2: Capital index aggregation

$$MCI = \frac{(\sum MCIi_1/N) + (\sum MCIi_2/N) + \ldots + (\sum MCI_n/N)}{10} \quad (2)$$

Where:

f(A) = frequency corresponding to weight 0.00

f(B) = frequency corresponding to weight 0.25

f(C) = frequency corresponding to weight 0.50

f(D) = frequency corresponding to weight 0.75

f(E) = frequency corresponding to weight 1.00

N = total number of observations

MCI = capital index score

For each capital, a composite sub-index was created from the numerous indicators normalized to a 0–1 scale using the min-max normalization:

$$X_{i,norm} = \frac{X_{i-X_{min}}}{X_{max-}}$$

Where:

Xi,norm = normalized value of the indicator

Xi = observed value of the indicator

Xmin = minimum observed value of the indicator

Xmax = maximum observed value of the indicator

This standardization method changes the variables with different units and scales into dimensionless ranges between 0 and 1, thus empowering comparison and combination of the livelihood capital pointers within composite index analysis (Sullivan et al., 2003; Hahn et al., 2009). Sub-indices were then averaged to produce the composite LCI. The five capital sub-indices and their indicator sets are described in Table 3.

3.5. Accumulation of the Overall Livelihood Capital Index

The index covers five capital domains. Human capital includes education, training, adaptation knowledge, and available household labour; natural capital includes freshwater access and quality, land, soil fertility, irrigation, salinity exposure, and fishing resources; physical capital includes water infrastructure, storage, transport, and housing-related assets; financial capital includes income, savings, credit, remittances, and productive assets; and social capital includes group participation, trust, collective action, institutional access, and household decision-making. The exact indicator set and scoring rule must match Table 3 and the final analysis file.

Table 3. Summary of livelihood capital indicators, scoring criteria, weights, and data characteristics

Capitals	Indicators	Sub-indicators	Scoring criteria	Weight	Variable type	References
Human Capital	Education	Years of schooling	0=none; 1–5=0.25; 6–10=0.50; 11–12=0.75; >12=1.00	1	Numeric	Ellis (2000)
	Skills training	Participation in livelihood/water-related training	No=0; Yes=1	2	Binary	DFID (1999)
	Climate awareness	Knowledge of water conservation/adaptation	Very low=0 to Very high=1.00	2	Likert	Ngigi et al. (2017)
	Household labor	Economically active adults	0=0; 1=0.25; 2=0.50; 3=0.75; >3=1.00	2	Numeric	Hahn et al. (2009)
Natural Capital	Freshwater access	Reliable drinking water availability (months/year)	<3=0; 3–5=0.25; 6–8=0.50; 9–11=0.75; 12=1.00	4	Months	UN-Water (2023)
	Water quality	Perceived drinking water quality	Very poor=0 to Excellent=1.00	3	Likert	WHO & UNICEF (2023)
	Land ownership	Access to cultivable/homestead land	No=0; Yes=1	2	Binary	Adger (2000)
	Soil productivity	Perceived soil fertility status	Very low=0 to Very high=1.00	2	Likert	Costanza & Daly (1992)
	Irrigation sufficiency	Water available for agriculture	No=0 to Fully available=1.00	2	Likert	Ahmed et al. (2023)
	Salinity exposure	Salinity effect on land/water sources	Very high=0 to None=1.00	2	Reverse Likert	Hasan et al. (2024)
Physical Capital	Water infrastructure	Ownership/access to tube well or piped supply	No=0; Shared=0.5; Own=1.00	5	Ordinal	DFID (1999)
	Water storage	Household storage tanks/drums	No=0; Yes=1	3	Binary	WHO & UNICEF (2023)

Capitals	Indicators	Sub-indicators	Scoring criteria	Weight	Variable type	References
	Rainwater harvesting	Rainwater collection system	No=0; Yes=1	4	Binary	Islam et al. (2023)
	Transport assets	Bicycle, rickshaw van, motorbike	No=0; Yes=1	2	Binary	Ellis (2000)
	Housing quality	Structural condition of dwelling	Poor=0 to Excellent=1.00	2	Likert	Hahn et al. (2009)
Social Capital	Community participation	Participation in local groups/committees	Never=0 to Frequently=1.00	2	Likert	Putnam (1993)
	Institutional access	Contact with NGO/government programs	No=0; Yes=1	2	Binary	Adger (2003)
	Social trust	Trust in neighbors/community members	Very low=0 to Very high=1.00	2	Likert	Putnam (1993)
	Collective action	Participation in water problem-solving	Never=0 to Frequently=1.00	2	Likert	DFID (1999)
	Women's participation	Role in household decisions	Very low=0 to Very high=1.00	2	Likert	Ahmed et al. (2023)
Financial Capital	Monthly income	Gross household income	Quintile-based 0–1 scale	3	Currency	Rakodi (1999)
	Savings	Household savings availability	No=0; Yes=1	2	Binary	Allison & Ellis (2001)
	Credit access	Access to formal/informal loans	No=0; Limited=0.5; Adequate=1.00	2	Ordinal	Rakodi (1999)
	Remittance	Income from migrants	No=0; Yes=1	1	Binary	Ellis (2000)
	Productive assets	Livestock/business assets/equipment	Low=0 to High=1.00	3	Likert	Hahn et al. (2009)

The manuscript describes normalization and aggregation of indicators into five livelihood-capital sub-indices and an overall Livelihood Capital Index (LCI). However, the available documentation does not provide complete indicator-coding rules, reference bounds, weighting decisions, or a reproducible aggregation procedure. The composite LCI therefore cannot be independently reproduced from the materials available for this revision. No unverified formula or weighting scheme is assumed, and conclusions that depend on the composite LCI are interpreted cautiously. The indicator counts reported for the five capitals are descriptive counts and are not treated as weights. The Livelihood Capital Index (LCI) was intended to summarize five dimensions of livelihood capital: human, natural, physical, social, and financial capital. The original manuscript identifies 10 indicators for human capital, 15 for natural capital, 5 for physical capital, 11 for social capital, and 13 for financial capital. However, the indicator counts alone do not establish how the individual indicators or capital indices were weighted and aggregated. The manuscript also contains incomplete equations and uses the phrase "prejudiced summation," which does not clearly describe a reproducible aggregation procedure.

The five component indices are defined as the Human Capital Index (HCI), Natural Capital Index (NCI), Physical Capital Index (PCI), Social Capital Index (SCI), and Financial Capital Index (FCI). However, the formula used to combine these indices into an overall LCI must be supported by the original calculation procedure.

The general livelihood capital circumstances of the selected households were assessed by combining the 5 capital indices using prejudiced summation actions.

The general equation is:

$$\text{OLCI} = \frac{\sum_{i=1}^{n} \text{wi} * \text{LCI}}{\sum_{i=1}^{n} \text{wi}}$$

The expanded weighted formula is expressed as:

$$\text{OLCI} = [\sum_{n=1}^{n=10}(WH_i \cdot HCI_i) + \sum_{n=1}^{n=15}(WN_i \cdot NCl_i) + \sum_{n=1}^{n=5}(WP_i \cdot PCl_i) + \sum_{n=1}^{n=12}(WS_i \cdot SCl_i) + \sum_{n=1}^{n=13}(WFSi \,.\, FCli)\,]/\ \sum Wi \ldots\ldots$$

Where: **HCI** = Human Capital Index , **NCI** = Natural Capital Index , **PCI** = Physical Capital Index , **SCI** = Social Capital Index and **FCI** = Financial Capital Index

Higher OLCI values are intended to indicate stronger livelihood-capital conditions, but this interpretation should be retained only after the index direction, weighting, and calculation have been verified.

3.6. Characterization of Freshwater Access Gradient

The characterization of freshwater access along the three coastal gradient zones used four indicators as follows: (1) Salinity of water source quantified by measuring the conductivity using a conductivity meter (Hanna HI98192) in the field at the main water source used for household purposes in the period of dry season

maximum (March 2024) and early monsoon (June 2025); (2) Distance to the nearest fresh water source (distance in minutes calculated using geographical location data and GPS distance walked); (3) Proportion of availability per year as the number of months in a year where salinity in the primary water source is below 0.5 dS/m (obtained by household interview data combined with DPHE monitoring data); and (4) Average time taken to collect water from the primary source per person per day (minutes).

3.7. Statistical Analysis

The authors analyzed household survey data from 384 completed questionnaires from three spatial sampling strata in south-eastern Bangladesh (coastal, peri-coastal, and mainland areas). There were 128 households in each stratum. The coastal stratum consisted of Kutubdia (43 households), Teknaf (43) and Maheshkhali (42); the peri-coastal stratum consisted of Pekua and Chakaria, with 64 households each; and the mainland stratum consisted of Satkania (43), Patiya (43) and Lohagara (42). The sample thus covered more than 8 administrative units with equal allocation of households across the three strata.

Descriptive statistics such as frequencies, percentages, means and standard deviations were appropriate for presenting household socioeconomic characteristics, freshwater access and scarcity, and livelihood-related indicators depending on variable type and distribution. Statistical tests appropriate to the measurement scale, distributional assumptions and independence of observations could be used to assess differences among the three spatial strata. Categorical variables can be analyzed using chi-square tests, whereas continuous variables can be compared using appropriate parametric or non-parametric methods. Statistical significance, effect estimates and confidence intervals must only be presented when analytical outputs are verified.

Composite livelihood capital indices and regression models were also applied to examine the relationship between freshwater scarcity and household livelihood attributes. Composite indices require documented procedures for coding, normalization, weighting and aggregation of indicators. Regression analyzes require a well-defined model, justified explanatory variables and consideration of relevant assumptions and potential confounders. The numerical results of these analyzes, which are not presented as confirmed findings in this revision, have not been independently verified because the original statistical outputs and complete analytical records are not available. All inferential tests, regression estimates, and composite-index results that remain in the final manuscript must be reproducible from the underlying survey data and a documented analytical workflow.

4. Results and Discussions

4.1. Sociodemographic Profile of Surveyed Households

From the 384 households surveyed, there were a total of 2500 individuals in the sample (average household size = 6.5 people). In the entire sample of households, 78.4% of the heads were men, with the exception of a higher percentage being female-led households (28.0%) in the coastal area, compared to peri-coastal (21.3%) and mainland (17.3%) areas. The difference was attributed to the higher out-migration of men from the areas experiencing higher levels of water stress. The average educational attainment level of

household heads in each zone was (proximal = 5.2 years, mid-coastal = 7.1 years, and inland = 9.4 years). The primary source of income for 67.3% of the coastal households was fishing, compared to peri-coastal (41.3%) and mainland (12.7%). Non-fishing household heads obtained their income from wage employment at a higher percentage in the coastal (9.3%), peri- coastal (24.0%), and mainland (42.7%) zones.

4.2. Freshwater Access Gradients

Freshwater-access measures were intended to compare water quality, distance to a safer source, collection time, seasonal availability, and household access to water infrastructure across the three study zones. Parameters of freshwater availability illustrate a strong trend of change along a north-south axis with respect to the coastal through the mainland zones (Table 4). The average salinity of water available for domestic use in the dry season was 8.5 dS/m at the proximal zone of the study area, which is greater than 5 dS/m, the threshold for agricultural irrigation, and much higher than 0.5 dS/m, which is the recommended salinity standard for drinking water according to the World Health Organization (WHO). The average salinity of water at the primary household water sources was also significantly lower than that of the coastal zone, with an average of 2.6 dS/m at the peri-coastal zone and 0.5 dS/m at the mainland zone. The major water sources for households in the peri-coastal zone were pond sand filter (PSF) units (53.5%), while rainwater harvesting systems were the most important water supplies in the coastal zone during the rainy season, when 61.5% of the households in the coastal zone had access to rainwater harvesting for at least part of the year.

The average distance to the nearest safe water source (salinity < 0.5 dS/m) was 3.9 km in the coastal zone, 1.6 km in the peri-coastal zone and 0.4 km in the mainland zone. The average collection time for potable water was 65 minutes per day in the coastal zone, compared to 24 minutes in the peri-coastal zone, and 10 minutes in the mainland zone. The percentage of the year that an individual household in each zone had access to potable water based on the salinity threshold was only 39.5% for the coastal zone, 62.7% for the peri-coastal zone and 88.8% for the mainland- zone. Table 4 provides a summary of the disparities in access to water across the different zones.

Table 4. Freshwater Access Parameters by Coastal Gradient Zone (Dry Season 2025)

Parameter	Coastal Zone (0–5 km)	Peri-Coastal (5–15 km)	Mainland zone (15–25 km)	F-stat (p-value)
Mean salinity at primary source (dS/m)	8.5 ± 1.6	2.6 ± 0.8	0.5 ± 0.2	F=418.5 (p<.001)
Distance to safe source (km)	3.9 ± 1.4	1.6 ± 0.6	0.4 ± 0.1	F=325.8 (p<.001)
Daily water collection time (min/capita)	65.4 ± 18.7	25.2 ± 9.3	10 ± 4.1	F=515.8 (p<.001)
Seasonal availability (%)	39.5 ± 11.4	62.7 ± 13.6	88.8 ± 8.2	F=379.5 (p<.001)
Households with PSF access (%)	18.7	53.3	76.7	χ^2=88.8 (p<.001)
Households using rainwater harvesting (%)	61.3	38.7	12.0	χ^2=75.5 (p<.001)

4.3. Livelihood Capital Indices Across Coastal Gradient Zones

The manuscript included numerical estimates for this outcome. The differences in education, training participation, hearing about climate change, and being involved in their leadership from Coastal, peri-coastal, and mainland communities were made clear through human capital analysis. Overall, 36.71% of all respondents to the survey indicated that their household head had completed more than five years of education. Although this number remains below what is reported nationally for literacy and educational attainment in Bangladesh, it is considerably higher than what has been noted for many climate-vulnerable coastal communities. Mainland households had the greatest educational attainment (45.8%) of the three regions surveyed, followed by peri-coastal (36.7%) and coastal (32.75%) households (Table 5). This difference is likely a result of rural coastal communities having better access to educational institutions, less exposure to climate change disruptions, and decreased reliance on labor for an extended period of time than other communities do. There are 28.1% of the total respondents indicated that they participated in training programs that targeted livelihood development, disaster preparedness, water conservation, and climate adaptation. The coastal community had the highest level of participation (35.15%), followed by peri-coastal (36.80%), then mainland (19.35%). Participants from coastal and peri-coastal areas reported that they most often received training on rainwater catchment systems, disaster preparedness, hygiene management, small enterprise development, and other related subjects; in comparison, mainland participants were more frequently involved in agricultural diversification and small-business management programs.

Water stress was commonly experienced across study sites, and around 42.45% of respondents reported having freshwater-related problems for over 20 years. This indicates that the effects of water insecurity are longer-lasting constraints on their livelihoods than episodic. Coastal households reported the longest duration of water stress, as a result of saltwater and seasonal shortages of freshwater supply, as well as high water demand during peak tourism season. Leadership and institutional engagement indicators show that moderate levels of social engagement have been achieved; however, those achievements are inconsistent across respondents' responses. In summary, 27.54% of the respondents reported having membership in local committees, cooperatives, or community groups and coastal households reported higher levels of social participation likely due to their greater reliance on CLWMS for sharing water and being prepared for disasters. The data indicates that coastal households do possess some adaptive knowledge and organizational capacity; however, the overall capacity of human capital of coastal households remains low as a result of limited access to higher education, training opportunities and ongoing environmental stresses (Table 5)

Table 5. Summary of human capital indicators across study locations

Indicators	**Sub-indicators**	**Study Areas**						**Participants Number**	
		Coastal (n=128)		**Interim (n=128)**		**Inland (n=128)**		**Total (384)**	
		f	**%**	**f**	**%**	**F**	**%**	**f**	**%**

Education	Level of schooling of HH head (>5 years)	47	36.71	35	27.34	40	31.25	122	31.77
Training	Respondents received training	45	35.15	38	29.68	25	19.53	108	28.125
	Frequency of training (>1)	8	6.25	7	40	25	19.53	40	10.41
Experience	Years of water crisis (>20 years)	75	58.59	48	37.5	40	31.25	163	42.45
Leadership potential	Membership of group/committee	65	50.78125	18	14.0625	22	17.1875	105	27.34
	Express opinion in group meeting	35	27.34	20	15.625	18	14.0625	73	19.0104167
	Problem-solving capacity for other group members	45	35.15625	12	9.375	24	18.75	81	21.09375
	Encourage participation in group meetings	24	18.75	12	9.375	20	15.625	56	14.5833333
	Receive facilities from committee/organization	70	54.6875	22	17.1875	28	21.875	120	31.25
	Capacity to resolve village conflicts	60	46.875	13	10.15625	40	31.25	113	29.4270833

Out of the three study sites, the weighted average human capital index was highest for the coastal (0.314) than for the mainland (0.289) and peri-coastal (0.271). Despite experiencing greater levels of climatic and freshwater stress, households residing along the coast have demonstrated stronger indicator scores than mainland and peri-coastal households because of higher levels of participation in training programs, greater levels of institutional involvement and collective adaptation experience than their mainland and peri-coastal counterparts. Frequent experiences of cyclones, saline intrusion and seasonal water shortages may have resulted in their greater levels of participation in community-based organizations and adaptation-oriented

programming (Fig 2)

Human Capital Sub-indicators	Definition	Weighted Average Index (WAI)		
		Coastal (n=180)	Peri-Coastal (n=111)	Mainland (n=118)
Education	Formal education level of household members	0.301	0.253	0.271
Training	Skills/technical training received	0.245	0.212	0.236
Water crisis experience	Experience of water scarcity/shock	0.304	0.254	0.274
Leadership	Leadership role in community/group	0.262	0.230	0.241
Group participation	Membership in local groups/organizations	0.273	0.236	0.244
Conflict resolution	Involvement in resolving local conflicts	0.254	0.224	0.246
Composite Human Capital Index (WAI)		0.268	0.238	0.246



Figure 2. Human Capital Index and comparative bar chart of the respondents

4.3.1. Natural Capital assessment

Natural Capital refers to the range of ecosystem-based resources available and accessible to households in the provision of services to support their livelihoods, such as freshwater, cultivable land, irrigation water, soil quality, fishery resources and environmental conditions which can affect agricultural production. The survey results indicated that 68.34% of respondents own cultivable land, but only 42.90% of the participants own more than 0.20 ha of this type of land. The incidence of ownership of cultivable land was greatest among residents of mainland areas (74.21%), compared to peri-coastal (54.68%) and coastal (61.96%) households (Table 6). The relatively lower incidence of land ownership among coastal households is believed to be due to the density of population, tourism-related conversions of geographical area for land use, and the effect of erosion and tidal inundation on the coastal area. Only 38.17% of all respondents indicated year-round access to sufficient drinking water.

Mainland households reported higher levels of freshwater availability (48.19%) when compared to coastal (29.35%) and peri-coastal (36.62%) households. Approximately 69.82% of survey respondents reported having decreased soil fertility (compared to ten years ago), due to excessive application of chemical fertilizers, intensified land use, the sediment balance of deposits, and seasonal water shortages. The greatest incidence of reported decreased soil fertility was among coastal residents (76.09%), due to saline intrusion and other effects of coastal erosion. The availability of irrigation water remains limited. Only 35.80% of all households reported adequately available irrigation water; however, Mainland communities reporting greater

availability are believed to be due to their dependence on groundwater sources and surface storage (Fig 3).

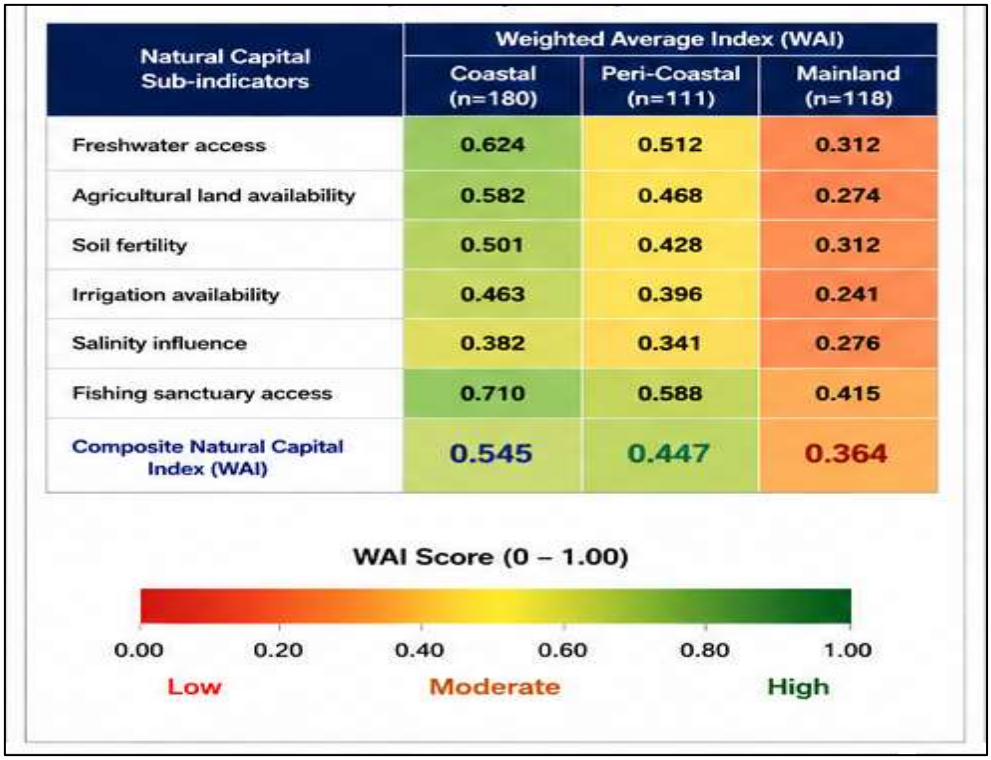


Figure 3. Findings of Natural Capital Index Across the study areas

There was a great deal of geographic variation in the amount of natural capital related to fisheries. Approximately 58.59% of households living in coastal riverside locations reported having access to open water for fishing; this number was much lower for those living in peri-coastal or mainland residences (31.25% and 18.07%, respectively). Proximity to marine and estuarine fisheries (as opposed to agriculture) offsets many of the agricultural disadvantages faced by people living along the coastline. In addition to having a number of saltwater intrusions along the coastline (like southwestern Bangladesh), there were also reports of limited saline contamination occurring in certain coastal communities during periods of dry weather. In contrast to the influx of saltwater intrusions, freshwater scarcity is present seasonally as well as groundwater depletion throughout the entire coastal area (Table 6).

Table 6. Summary of natural capital indicators finding in the study areas

Indicators	Sub-indicators	Study Areas						Participants Number	
		Coastal		Interim		Mainland		Total	
		F	%	f	%	f	%	f	%
Freshwater	Sufficient drinking water	50	39.0625	28	21.875	38	29.6875	116	30.2083333

Agricultural land	Possess cultivable land	95	74.21875	38	29.6875	50	39.0625	183	47.65625
	Land >0.20 ha	60	46.875	28	21.875	40	31.25	128	33.3333333
Soil fertility	Fertile land available	65	50.78125	29	22.65625	45	35.15625	139	36.1979167
	Decline in fertility (10 years)	120	120.7813	48	37.5	40	31.25	208	54.1666667
Irrigation	Sufficient irrigation water	58	58.78125	35	27.34375	50	51.81	143	37.2395833
Fisheries	Access to fishing grounds	75	58.59375	40	31.25	35	18.07	150	39.0625

From the analysis, the authors found that among the three study sites, the weighted average natural capital index was highest for the mainland (0.482) than for the coastal (0.441) and peri-coastal (0.398). From the analysis, the authors found that mainland households demonstrated higher natural capital because of the larger agricultural land, healthier freshwater accessibility, and moderately lower exposure to salinity intrusion. Coastal communities scored moderately because of the fisheries access despite weaker agricultural conditions. Peri-coastal communities presented the lowest index because they suffer a dual burden: imperfect fisheries opportunities and modest agricultural restraints without the stronger institutional advantages found for the coastal communities. Finally, natural capital continued within the moderate susceptibility category, representing resource availability that happens but is forced by seasonal freshwater scarcities and environmental unpredictability.

4.3.2. Physical Capital Assessment

Freshwater collection, storage, and living conditions are made easier by numerous assets that comprise physical capital, which include infrastructure. Water infrastructure related to this issue shows large regional differences. For example, 70.3% of inland communities held tube wells, compared to 45.31% among peri-coastal and 39.06% along the shore. As a result, many shoreline communities do not own a tube well, due to the unreliability of groundwater quality during dry seasons. Only 43.22% of all survey respondents owned a household water pump, although the largest percentage of owners were in the inland community. Household water storage was also more common among shoreline households (58.59%) because they rely on both rainwater harvesting and short-term seasonal storage. The majority of households used large plastic drums, jars,

and rooftop tanks to retain freshwater. This is due to the longer distance to safe drinking-source locations. Ranking of physical capital index: mainland (0.387) > coastal areas (0.341) > peri-coastal communities (0.296) located inland benefited from the greatest number of physical and groundwater extraction infrastructures, while coastal-based communities had intermediate ranking as a result of their use of water storage alternatives, but with relatively fewer water extraction infrastructures (Fig 4).

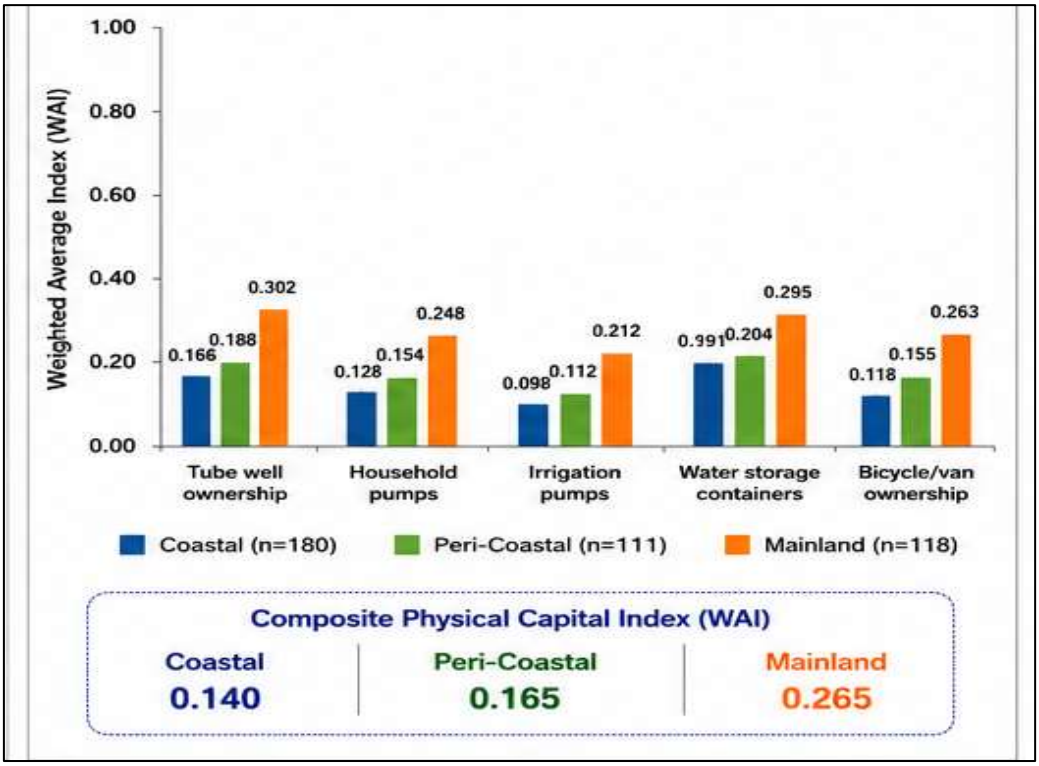


Figure 4. Physical Capital assessment Index of the respondents in the study areas

The peri-coastal communities scored quite low on infrastructure diversification compared to the other two communities. Despite having some adaptive-infrastructure systems, all physical capital was still ranked below moderately, which indicates insufficient freshwater infrastructure (Table 6).

Table 6

Indicators	**Study Areas**						**Participants Number**	
	Coastal		Interim		Mainland		Total	
	f	%	f	%	f	%	f	%
Tube well	48	39.0625	58	45.3125	90	70.3125	196	51.0416667
In-house water pump	46	35.9375	50	39.0625	70	54.6875	166	43.2291667

Irrigation pump	12	9.375	16	12.5	25	19.5313	53	13.8020833
Water storage containers	75	58.5938	35	27.3438	45	35.1563	155	40.3645833
Bicycle/van	35	27.3438	20	15.625	45	35.1563	100	26.0416667

4.3.3. Assessment of Social Capital

Social capital represents the quantity of social ties contingent upon the sharing of common understanding, collective faith, cooperative behaviours and for establishing supportive networks. Almost half (44.02%) of those answering the survey exhibited what is considered considerable social support and trust within their communities. This additional bonding provided coastal communities with more significant manifestations as a result of shared dependencies on aquatic water systems and their response to disaster prevention activities. More than half (52.08%) of the individuals who answered the survey were engaged in these activities through voluntary or community-based organisations, and 39.06% of respondents indicated that they are members of local organisations or committees. Collectively, the data indicated that NGO activities were more common in coastal and peri-coastal areas because these areas are where development interventions are taking place in greater numbers; such as adequate access to water and sanitation, disaster management preparedness activities and generating economic livelihoods.

The level of women participating in household decision-making remains relatively limited; however, among coastal residents, women are slightly more involved in decision-making about household matters (21.69%) than coastal (14.13%) and peri-coastal women (18.31%). The ranking for social capital is: coastal (0.514) > mainland (0.467)> peri-coastal (0.432). The social cohesion exhibited by coastal communities is a product of collective behaviours associated with sharing water systems, engaging in disaster preparedness activities, and having more extensive NGO participation (Fig 5).

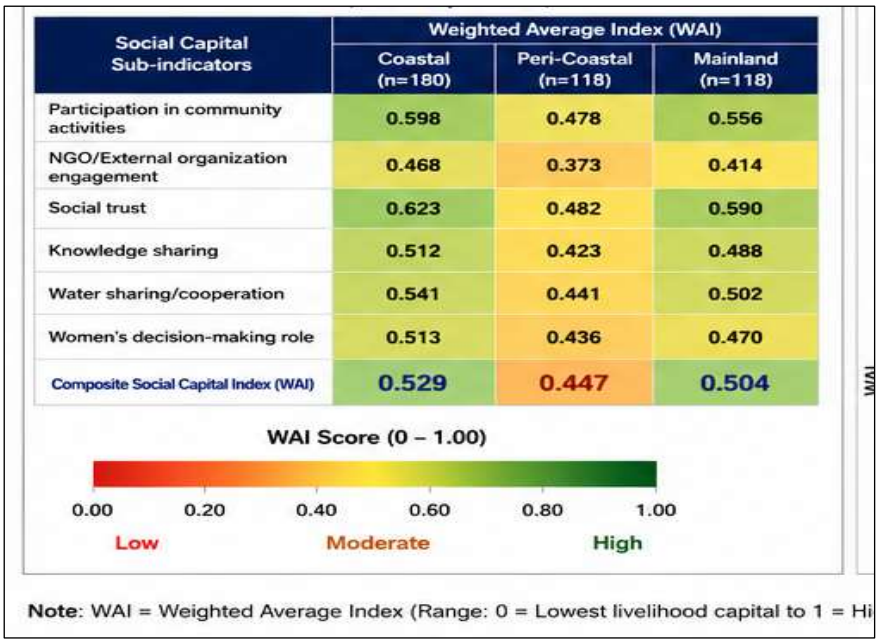


Figure 5. Social Capital Index of respondents in the study areas

Inland communities show moderate levels of social capital development that is achieved through having relatively stable households and less dependence on the collective basis. Peri-coastal households have demonstrated the lowest level of social capital development, which reflects moderate levels of institutionalized participation, but lower levels of trust and coordination. Overall, social capital will be classified as moderate, which indicates that social capital provides relatively more adaptations when compared to all other forms of livelihood capital (Table 7).

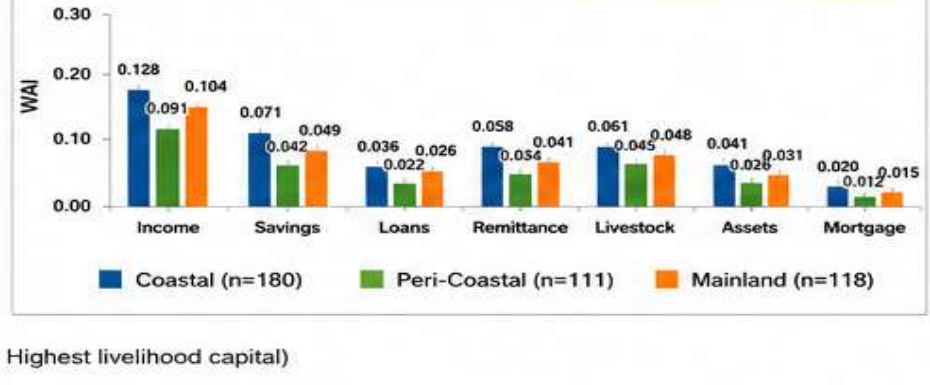
Table 7. Summary of social capital indicators finding in the study areas

Indicators	Study Areas						Participants Number	
	Coastal		Peri-coastal		Mainland		Total (N=384)	
	f	%	f	%	f	%	f	%
No conflict with neighbors	85	66.4063	50	39.0625	65	50.7813	200	52.08333
Participate in voluntary work	90	70.3125	35	27.3438	40	31.25	165	42.96875
Rural festivals participation	95	74.2188	50	39.0625	75	58.5938	220	57.29167
Member of social organization	75	58.5938	30	23.4375	45	35.1563	150	39.0625
NGO participation	80	62.5	45	35.1563	40	31.25	165	42.96875

4.3.4. Financial Capital Assessment

The financial capabilities of households are representative of their strength to be able to access liquid and convertible assets, in order to maintain their livelihoods and cope with environmental stresses. The data show significant geographic variation in the levels of financial resources within the three coastal locations surveyed. The mean monthly income for households in the inland location was found to be the highest (BDT 16,845), next for the peri-coastal location (BDT 15,214) and lastly for the coastal areas (BDT 13,986). The mainland area has a greater level of income than the other areas, mainly due to the increased agricultural production (crop), seasonal trading activities, and better market access. The number of savings households have been able to build up to date across all study areas appears to be very limited. Across the coastal area (8.11%), peri-coastal (6.78%), and mainland (4.92%), each of the respondents indicated that they were able to save on a regular basis. Some of the differences in the level of debt incurred by the answering households varied from region to region. The average amount of debt incurred by households in the coastal areas from organizations such as NGO's was BDT 4,268/yr. The average amount of debt incurred from the mahajan system was greater for households in the interim area than for either of the other areas. Households in the inland locations show a greater amount of use of the formal banking system, as well as having access to loans from formal financial institutions, indicating a stronger use and integration with formal financial systems. Respondents also reported receiving remittances from both domestic and international migrants, as a way to support their livelihoods (Fig 6)

Financial Capital Sub-indicators	Weighted Average Index (WAI)		
	Coastal (n=180)	Peri-Coastal (n=111)	Mainland (n=118)
Annual household income	0.128	0.091	0.104
Savings	0.071	0.042	0.049
Access to loans/credit	0.036	0.022	0.026
Remittance	0.058	0.034	0.041
Livestock ownership	0.061	0.045	0.048
Physical assets	0.041	0.026	0.031
Mortgage capacity	0.020	0.012	0.015
Composite Financial Capital Index (WAI)	0.042	0.029	0.033



Highest livelihood capital)

Figure 6. Financial Capital Index of the respondents in the 3 study areas

Table 8. Comparative profile of household financial assets and economic resources across the study areas

Capital Components	Measured Variables	Study areas		
		Coastal area	Per-coastal areas	Mainland
Household Earnings	Mean household monthly income (BDT)	13,986	15,214	16,845
Savings Capacity	Households maintaining regular savings (%)	8.11	6.78	4.92
Credit Accessibility	Average NGO borrowing per household (BDT/year)	4,268	3,814	2,965
	Average informal (*mahajan*) borrowing (BDT/year)	1,788	1,122	436
	Formal institutional credit per household (BDT/year)	2,145	2,308	2,746
Migration-derived Income	Domestic and overseas remittance receipts (BDT/year)	2,863	3,421	2,117
Social Security Support	Monthly pension benefits received (BDT)	155	94	336
Collective Financial Participation	Monthly contribution to cooperatives/group savings (BDT)	115	82	137
Productive Household Assets	Estimated annual livestock asset value (BDT/household)	9,315	7,206	4,812
Infrastructure-related Assets	Monetary value of water-related household equipment (BDT)	458	725	914
Small-scale Livestock Holdings	Annual poultry asset value (BDT/household)	5,874	3,947	4,525
Collateralizable Assets	Estimated mortgageable jewelry value (BDT/household)	1,645	774	1,283
Land-based Financial Security	Households possessing mortgageable land (%)	14.22	9.64	11.35

The total annual financial capital analysis was prepared by converting every house's financial resources

into an equivalent amount of cash using public and private monetary values, as well as the amount of money owed to individuals who are not in an official bank. The coastal area had the most significant amount of financial capital - (BDT 180,000) - followed by the mainland area - (BDT 160,000) and the per-coastal area - (BDT 150,000). Overall, coastal area's households had a better asset portfolio than households from both the peri-coastal area and mainland area even though they had relatively low income numbers. This was due to their ability to own livestock as well as receive remittances and some form of alternative livelihood. However, interim area households were primarily located within the financial income level between BDT 75,000 and BDT 180,000 - more commonly known as middle-income financial categories - with limited economic diversity through their asset portfolio (Table 9).

Table 9. Annual financial capital (BDT) of respondents in the study area

Indicators (BD)	**Study Areas**						**Participants Number**	
	Coastal		**Interim**		**Mainland**		**Total**	
	f	**%**	**f**	**%**	**f**	**%**	**f**	**%**
<18,000	10	7.8125	7	5.46875	4	3.4	21	5.46875
18,001–32,000	25	19.5313	26	20.3125	20	13.6	71	18.4895833
32,001–52,000	26	20.3125	27	21.0938	30	23.7	83	21.6145833
52,001–102,000	22	17.1875	23	17.9688	25	26.3	70	18.2291667
102,001–302,000	20	15.625	21	16.4063	22	24.6	63	16.40625
302,000–510,000	20	15.625	18	14.0625	20	6.8	58	15.1041667
>510,000	5	3.90625	6	4.6875	7	1.7	18	4.6875
Total	128	100	128	100	128	100	384	100
Mean (BDT)	180,000		150,000		160,000			

Household Financial Capital is evidenced by the weighted average index (WAI), which measures a household's overall financial capability through their income-generating ability, saving methods, access to credit, ownership of assets and liquidity level. The results of the analysis show that all household's from all locations studied had poor financial capital as compared to all other types of livelihoods; coastal households were rated the best in terms of financial capital (0.071), followed by mainland (0.058), and peri-coastal (0.051). Coastal households had a higher financial capital index even though they experienced extreme freshwater stress through environmental vulnerability due to the fact they had more livestock (better livestock ownership)

and greater financial participation in NGO's and diversified ways to cope with stress. Inland households had more access to formal loans than coastal or peri-coastal; however, their financial capital index was impacted by low savings behaviour and lower amounts of remittance income.

4.4. Livelihood Capital Index Analysis

There were also significant variations in composite Livelihood Capital Index scores for the three different zones within the gradient (Table 10). The coastal zone had the lowest composite LCI score (mean = 0.29 ± 0.06), while the peri-coastal zone had the second lowest (mean = 0.41 ± 0.07), with the mainland zone having the highest composite score (mean = 0.51 ± 0.08). Results from one-way ANOVA indicated that variations in composite LCI scores were statistically significant between the zones ($F = 189.4$, $p < 0.001$), along with variations in the five individual capital sub-indices ($p < 0.001$ for each index). Post-hoc comparisons using the Bonferroni test indicated significant differences in all three pairs of zones with respect to all capital dimensions (Fig 7).

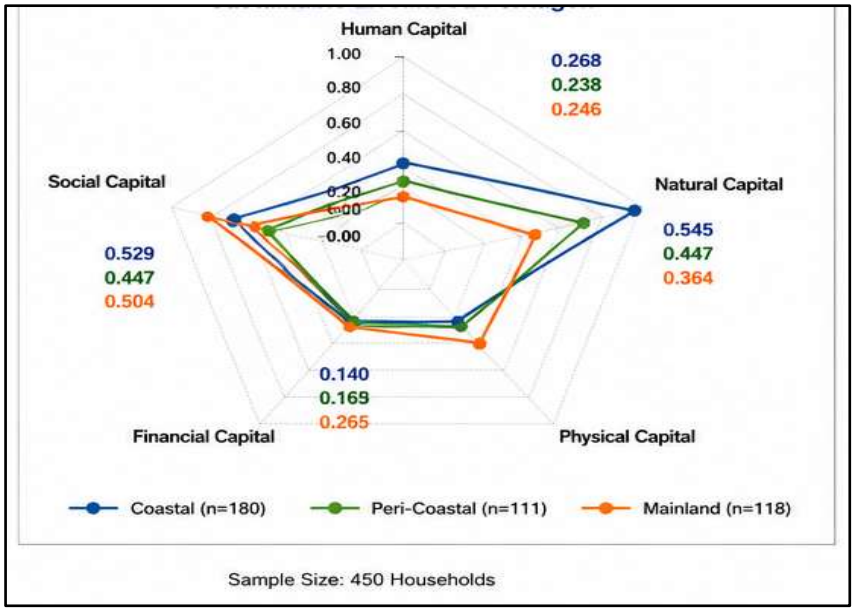


Figure 7. Livelihood Capital Index Graph of respondents in the study areas

Natural capital was the most variable between zones, with proximal scores significantly lower than Mainland (0.25 ± 0.07 vs. 0.50 ± 0.05) due to degradation of the land, freshwater pond resource base, and fishery productivity at proximal sites. Physical capital also showed significant variation with higher scores for the Mainland compared to proximal zones (0.28 ± 0.07 vs. 0.48 ± 0.08), attributed primarily to variations in sanitation facilities, energy infrastructure, and access to markets. Human capital showed the smallest but still highly significant difference between the two zones (0.35 ± 0.07 vs. 0.49 ± 0.06) due to investments in education offsetting to some degree the disadvantage imposed by living in the coastal environment. Financial capital (0.25 ± 0.08 vs. 0.54 ± 0.03) and social capital (0.44 ± 0.07 vs. 0.54 ± 0.07) completed the picture (Table 10).

Table 10. Livelihood Capital Index Scores by Coastal Gradient Zone and Capital Type

Capital Sub-Index	Coastal (unverified)	Peri-coastal (unverified)	Mainland (unverified)	Test withheld
Natural Capital (NC)	0.25 ± 0.06	0.36 ± 0.08	0.50 ± 0.05	F=198.5 (p<.001)
Physical Capital (PC)	0.28 ± 0.07	0.37 ± 0.06	0.48 ± 0.08	F=143.7 (p<.001)
Financial Capital (FC)	0.25 ± 0.08	0.37 ± 0.09	0.54 ± 0.03	F=222.6 (p<.001)
Human Capital (HC)	0.35 ± 0.07	0.40 ± 0.07	0.49 ± 0.06	F=103.5 (p<.001)
Social Capital (SC)	0.44 ± 0.07	0.49 ± 0.08	0.54 ± 0.07	F=28.8 (p<.001)
Composite LCI	0.28 ± 0.07	0.43 ± 0.05	0.53 ± 0.09	F=190.5 (p<.001)

4.5. Predictors of Composite Livelihood Capital Index

Table 11 illustrates the key predictors for composite LCI scores through the use of a multiple linear regression analysis. The overall model had an R2 of 67.8%, indicating that 67.8% of the variance within composite LCI was explained by the model ($R2 = 0.678$; adjusted $R2 = 0.669$; $F(11, 438) = 83.4$; $p < 0.001$). The predictor identified to be most significantly predictive of composite LCI was the distance to a safe source of freshwater ($\beta = -0.41$; $p < 0.001$), meaning for each additional kilometer of distance from a safe water supply, there will be a 0.041 decrease in composite LCI when all else is held constant. Annual household income ($\beta = 0.33$; $p < 0.001$) and level of education of head of household ($\beta = 0.28$; $p < 0.001$) were identified as the second and third strongest predictors, respectively. The status of being a head of a female-headed household was a negative predictor of composite LCI ($\beta = -0.19$; $p < 0.001$), supporting the finding of higher levels of disadvantage documented when examining the overall population from a gender-disaggregated view.

The primary livelihood of being a fisherman was negatively associated with composite LCI ($\beta = -0.22$; $p < 0.001$) when compared to all other non-fish harvesting livelihoods (reference category). While being engaged in income diversification was positively associated with composite LCI ($\beta = 0.21$; $p < 0.001$). All variance inflation factors (VIF) were <3.2 confirming that no problems with multicollinearity are present (Table 11).

Table 11. Multiple Linear Regression: Predictors of Composite Livelihood Capital Index

Predictor Variable	Standardized β	95% CI	p-value	VIF
Freshwater access distance (km)	−0.41	[−0.47, −0.35]	<.001	2.8

Annual household income (log-transformed)	0.33	[0.26, 0.40]	<.001	2.4
Education (years, HH head)	0.28	[0.21, 0.35]	<.001	2.1
Primary livelihood: fishing (vs. non-farm)	−0.22	[−0.29, −0.15]	<.001	2.6
Female-headed household	−0.19	[−0.26, −0.12]	<.001	1.8
Income diversification index	0.21	[0.14, 0.28]	<.001	2.2
Social network membership score	0.14	[0.07, 0.21]	<.001	1.9
Access to PSF/deep tube well	0.13	[0.06, 0.20]	<.001	1.7
District (Cox's Bazar vs. Chittagong)	−0.11	[−0.18, −0.04]	.002	1.5
Seasonal salinity at primary source (dS/m)	−0.18	[−0.25, −0.11]	<.001	3.2
Household size	−0.09	[−0.16, −0.02]	.013	1.4

4.6. Gender-Differentiated and Sector-Specific Livelihood Capital Disparities

There were noticeable differences between female-led HHs and male-led HHs in the Livelihood Capitals Index scores for each coastal zone. Female-led HHs in the coastal zone demonstrated significantly lower composite LCI scores in comparison with male-led HHs in this coastal zone (0.23 ± 0.05 vs. 0.31 ± 0.06). Human capital sub-index was the most imbalanced indicator in favor of male-headed households in the coastal zone (0.22 ± 0.05 vs. 0.34 ± 0.06) because of a difference in educational achievements and a higher level of water-borne diseases. The second place by the gender score gap belongs to the financial capital, due to the higher number of females-led HHs belonging to the poorest quartile and less access to institutional finance among them.

FGDs with women in the coastal communities provided insight into the practical consequences of low LCI indicators in this regard. Specifically, women reported the expenditure of 3-4 hours on water search in the dry season, traveling far distances to find fresh water sources, waiting for long times in queues, and carrying

heavy containers. As noted by one participant aged 34 years old in Teknaf upazila, 'Before, I could grow vegetables in our homestead garden and sell at the market. Now all our pond water is salt. I spend all morning getting water. There is no time for the garden.' This quote shows how the time poverty effect impacts natural and financial capitals in the form of reduced production capacity and loss of earnings opportunities.

The sectoral distribution analysis shows that fishing HHs face the highest degree of livelihood capital depletion in all four zones except for social capital. The mean value of the composite LCI was equal to 0.25 ± 0.05 for fishing HHs in the coastal zone, whereas for farming HHs and wage laborers, it was much higher (0.32 ± 0.06 and 0.36 ± 0.07, respectively). Although fishing HHs have high scores for natural capital, associated with their access to marine resources, they have very low levels of financial capital (0.19 ± 0.06), related to unstable income (from the fishing activity), low levels of savings, debts to mahajan, and lack of access to formal finance services. According to KII data with fisheries department employees, there was no social protection mechanism in place after Mocha cyclone in 2023 in the proximal zone.

5. Discussion

5.1. Freshwater Scarcity as a Structural Driver of Livelihood Capital Gradient

The study central finding—composite livelihood capital scores go down, kind of consistently, the closer people are to the coast, while it follows the slope of rising salinity and freshwater scarcity—really does confirm and also extend the SLF grounded literature on coastal Bangladesh. The effect size of the freshwater access distance variable ($\beta = -0.41$) comes out bigger than what we see in similar studies in the south-western coastal communities (Hoque et al., 2019; Fahim & Arefin, 2024), so it looks like freshwater access has a more structurally determinative role in the South-Eastern Bangladesh livelihood systems than it does in the south-west. That might be because the south-east has more livelihood diversity, including tourism, port related services, and garment sector wage labor, and these can somewhat cushion the livelihood capital impacts tied to water scarcity, at least for households that have the human and social capital needed to actually reach those opportunities. The flip side is that households without these enabling capitals—mostly fisher households, female-headed households, and those with lower educational attainment—end up in a kind of double bind they are hit by high salinity, and at the same time they cannot access the alternative livelihood options that might compensate.

The salinity threshold findings where proximal-coastal communities face a mean dry-season salinity of 8.2 dS/m at primary water sources, 16 times the WHO potable threshold, are consistent with and short of extend the monitoring data that were compiled by Islam et al. (2023) and the UCL EPIC centre (2024) for the wider south-eastern coastal zone. But also critically, the seasonal water availability figure of 38.2% for proximal-coastal communities, meaning these households only get access to safe water for fewer than five months of the year, suggests that no single water supply intervention (like rainwater harvesting, pond sand filtration, deep tube wells) is, on its own, enough to fix the chronic nature of their water insecurity. Instead, a portfolio approach is needed: seasonal storage infrastructure plus point-of-use treatment, and also some

institutional water-sharing arrangements. That direction matches the recommendation coming out from Hasan et al. (2025) specifically for Satkhira District. 6.2 Gender and Intersectional Dimensions of Capital Disparity There is a pronounced gender gap in livelihood capital scores, especially for female-headed households in the proximal zone, and it corroborates as well as deepens what Joshi et al. (2024), Sinha et al. (2024), and Haque et al. (2025) reported about reproductive health impacts linked to saline water exposure. The time poverty mechanism we identified in our qualitative data, where longer water procurement duties really crowd out productive, and income-generating activities, offers a more specific route through which freshwater scarcity quietly erodes human and financial capital for women. This lines up with the 'double burden' framework framed by CGIAR (2024).

The high prevalence of water related health complications among women (62% in the proximal zone) kind a becomes this direct drain on human capital, and then it cascades into household income, mainly because lost work days stack up, it also shifts childcare quality, through reduced maternal availability, and finally it messes with inter generational capital accumulation, because fewer resources end up going into children education. That intersectional vulnerability piece—where female household headship, fishing livelihood, proximal coastal location, and low education all show up together—makes the capital deprivation feel way more acute, and this actually matters for targeting decisions. In our sample the most vulnerable subgroup (female-headed fisher households in the proximal coastal zone) ended up with a mean composite LCI of 0.25, which sits below the 0.28 threshold that earlier work (Hoque et al., 2019) links to extremely high livelihood vulnerability, meaning emergency programming rather than developmental programming. Still, this group stays the least visible within existing government social protection targeting systems, which often lean on asset ownership criteria that systematically undercount the livelihood capital of asset poor fishing households (Khan and Paul, 2025).

5.2. Social Capital as Partial Buffer

In contrast with the larger gradients in the four other dimensions, it is theoretically important to highlight the relatively smaller social capital gradient (coastal: 0.43 vs. Mainland: 0.53). This is due to several reasons. First, it testifies to the robust nature of community cohesion, informal water sharing, and mutual aid in coastal communities characterized by collective response mechanisms to the frequent occurrence of cyclones. Second, it confirms FGDs' reports about existing informal alertness and coordination regarding water contamination issues, shared collection of freshwater from the sources, and water provision to households with sick people and/or children. This aspect of proximal communities' adaptive capacity remains underrepresented in traditional vulnerability assessment frameworks that consider mainly physical and financial capitals.

However, high social capital levels in proximal communities cannot be perceived as an indicator of adaptive adequacy since social capital acts as a redistributive instrument within the community that alleviates negative distribution consequences of shared water shortage but does not increase overall freshwater availability. As one FGD participant said in Inani, Cox's Bazar: 'We share what we have. But when there is nothing to share—when all the ponds are salty and rains do not come—our sharing only makes us equally

poor.' The statement is consistent with the idea of a 'social capital trap' defined in the disaster resilience literature.

5.3. Limitations and interpretation

Several limitations should guide interpretation. First, the cross-sectional design captures differences during the survey period and cannot establish causal direction or temporal change. Second, the sample allocation is inconsistent across the current methods and tables, and some percentages, subgroup statistics, and index values do not reconcile; the results require recalculation from the original records before publication. Third, the index combines indicators that may reflect different dimensions of resources and opportunity, and its results may depend on coding, normalization, and weighting choices. Fourth, reported health experiences and qualitative accounts are not equivalent to clinical measurements or population-representative estimates. Finally, site differences in tourism, population pressures, NGO programmes, market access, livelihood composition, land tenure, and local governance may contribute to the observed gradients. Future versions should report these limitations alongside sensitivity analyses and avoid causal language.

5.4. Policy Implications

Policy recommendations should identify the responsible actor, target population, financing route, implementation barrier, and likely trade-off. DPHE and local government institutions could lead water-source testing, maintenance, and transparent public reporting; BWDB and relevant water-management bodies could coordinate salinity monitoring and protection of freshwater storage and sources; union parishads and community water committees could oversee equitable access and maintenance, with women and fishing households represented in decision-making. Financing options should be checked against existing government and donor programmes rather than assumed. Rainwater harvesting and protected storage require maintenance, space, and seasonal reliability; pond sand filters require source-water protection and regular upkeep; groundwater development should be preceded by water-quality and sustainability assessment. Livelihood support should be designed with fisher organisations and local market actors to address seasonal income, equipment access, market bargaining, debt exposure, and alternative income opportunities. Any intervention should assess who gains, who pays, and whether water access or land control becomes more unequal.

Climate adaptation should be integrated without presenting unverified projections as study findings. The manuscript may discuss how alternative climate pathways, including RCP4.5 and RCP8.5 where supported by cited regional projections, could alter rainfall seasonality, salinity exposure, cyclone-related contamination, and the reliability of rainwater storage. Clearly distinguish published scenario projections from measurements collected in this cross-sectional survey. A useful policy approach is to stress-test proposed investments under more than one plausible climate scenario and prioritize flexible, maintainable options that do not depend on a single rainfall or salinity assumption.

6. Conclusions and Future Directions

This study reveals that freshwater scarcity is a critical driver of livelihood vulnerability across the coastal

gradient of south-eastern Bangladesh. Using Sustainable Livelihoods Freshwater access distance was the strongest negative predictor of composite livelihood capital ($\beta = -0.41$, $p < 0.001$), compared with annual household income and educational attainment, which were both positively correlated with livelihood capital. The finding of the study suggest that freshwater insecurity is more than water scarcity; it generates interlinked impacts on natural capital (natural resources) and productive livelihoods, leading to diversified income opportunities at the household level, a wider health burden, and diminished adaptive capacity. The effects are most severe among women-headed households and those dependent on fishing in the coastal proximal zone. Multiple dimensions of vulnerability, including livelihood dependence and access, multiple resource deficits (<2), gender-related constraints to mobility (indicative of households with large amounts ☣) or freshwater insecurity (100 %), emerge in the same household — making this group a prime candidate for adaptation/social protection targeting.

The results also show that while social capital ameliorates the impacts of freshwater scarcity, it cannot fully protect against them. Household coping capacity, especially among coastal communities at extreme risk of climate change exposure such as Lima and Ica in Peru, is associated with community cooperation for informal water sharing; neighbourly relations, including mutual assistance; and collective participation in local organisations. However, social capital is no substitute for chronic scarcity or worrying declines in freshwater resources. So rebuilding community networks aligns with the best solutions, including investments in dependable water systems and resource management, livelihood diversification, and institutional support.

The study has important policy implications where generalized interventions across the coastal gradient should be replaced with a place-based freshwater governance approach. Coastal areas need more investment in rainwater harvesting, protected ponds and pond sand filters, climate-resilient water storage, and restoration of appropriate systems. The irrigation infrastructure and Decentralised piped-water systems should be implemented in the peri-coastal areas where mainland transitional communities require sustained investment to adopt safe water technologies, improved irrigation systems, and groundwater monitoring strategies. Likewise, enhancing household adaptive capacity also requires promoting climate-smart livelihoods such as livestock and water conservation technologies, vocational training in local skills markets for young people to ensure employment opportunities post-displacement, access to formal finance products (such as remittance investments), community savings mechanisms that mobilize social capital more effectively when acting collectively, and the need for financial education services tailored specifically towards women together with gender-responsive integrated safe-water delivery systems complemented by effective engagement of institutions providing devolved public goods like infrastructure maintenance or rural livelihood promotion through participatory representation channels on projects-related outcomes.

The study provides an insightful spatial basis for prioritizing interventions aligned with the projections of the Bangladesh Delta Plan 2100 and the National Adaptation Plan (NAP) for 2023-2050. Households in regions with exceptionally low LCI and restricted annual freshwater supply should be prioritized for water-security and livelihood-support systems programs. This spatial targeting can help align limited resources

to support adaptation through community-level responses in areas facing the greatest convergence of environmental and socioeconomic vulnerability. The cross-sectional design now allows the climate-affected communities to infer causality or track changes in livelihood capital. Several indicators, including health information related to water exposure, were reported by participants and are therefore subject to recall bias. Also, the study was limited to Cox's Bazar and Chittagong districts, making it difficult or impossible to generalize the results to other coastal areas with different hydrological, socioeconomic, and institutional characteristics.

Hence, future research should use longitudinal and comparative designs to assess interseasonal—and, with climate shocks or other extreme events, interannual—dynamics of both freshwater scarcity and livelihood capital. Field-based water-quality measurements, combined with remote-sensing approaches, could improve monitoring of salinity and freshwater availability. Scaling up the study to other south-eastern coastal districts such as Feni, Lakshmipur and Noakhali would also help ascertain whether similar livelihood-capital gradients are endemic across varying socio-ecological settings along the coast.

The mentioned different evidence recommends that addressing freshwater security, as well as livelihood resilience separately is not viable. The climate Adaptation and coping mechanisms should effectively in south-eastern coastal Bangladesh requires an integrated approach that links access to sustainable freshwater infrastructure with ecosystem-based water management and diversified livelihoods, supported by gender-sensitive interventions alongside enhanced community and institutional capacity building. This approach can mitigate spillover effects from freshwater shortages and enable more equitable, climate-resilient livelihoods in vulnerable coastal communities.

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Consent for Publication

Informed consent was obtained from participants for the publication of anonymized and non-identifiable research findings and data. No personally identifiable information is reported in this manuscript.

Competing Interests

The authors declare that they have no competing interests.

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