Manufactured vulnerability in the Ganges–Brahmaputra–Meghna delta: engineered drivers and coastal displacement in south-west Bangladesh

A critical review

Arghya Protik Chowdhury
Department of Environmental Science, Bangladesh University of Professionals, Mirpur Cantonment, Dhaka 1216, Bangladesh
Correspondence: arghyaprotik1183@gmail.com
ORCID: **[0009-0005-8387-7549]**

Preprint statement. This manuscript is a non-peer-reviewed preprint submitted to EarthArXiv. It has not been submitted to a peer-reviewed journal at the time of posting. Should it subsequently be submitted to, or accepted by, a journal, that information and the resulting DOI will be recorded in a revised version of this preprint. Readers are welcome to contact the author with feedback; comments received before journal submission are particularly welcome and will be acknowledged.

Contents of this file. This single PDF contains the full manuscript (Sections 1 to 9, Tables 3 to 6, Figures 1 to 7 and the reference list) followed by the Supplementary Material as an appendix beginning on a new page. EarthArXiv hosts one file per submission, so no separate supplementary document accompanies this posting.

Scope and design. This is a critical review of a defined region, not a systematic review or a meta-analysis, and it does not report primary data. Section 3.1 sets out why a conventional systematic synthesis is inappropriate to the question, which items of PRISMA 2020 are adopted and which are deliberately not, and Section 8.3 states the limitations of the approach. The search protocol is documented in full in the appendix so that readers can judge what the review is likely to have seen and missed.

Data and reproducibility. No new data were generated. Every value reported is taken from, or arithmetically derived from, a cited source, and each derivation is documented in Supplementary Table S2.2. Figures 2 and 4 were generated from scripts that read no external data; the values in them are hardcoded from the cited sources and are listed in that same table.

Use of generative AI. Generative AI tools were used for language editing and for checking internal consistency of numerical values and citations against their sources. No text, data, analysis, citation or conclusion was generated by such tools without author verification against the primary source. The author reviewed and approved all content and takes full responsibility for the integrity and accuracy of the manuscript.

Suggested citation. Chowdhury, A. P. (2026). Manufactured vulnerability in the Ganges–Brahmaputra–Meghna delta: engineered drivers and coastal displacement in south-west Bangladesh. A critical review. EarthArXiv preprint. https://doi.org/[DOI ASSIGNED AT POSTING]

Funding. This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.
Competing interests. The author declares no competing interests.

Manufactured vulnerability in the Ganges–Brahmaputra–Meghna delta: engineered drivers and coastal displacement in south-west Bangladesh

A critical review

Arghya Protik Chowdhury

Department of Environmental Science, Bangladesh University of Professionals, Mirpur Cantonment, Dhaka 1216, Bangladesh
arghyaprotik1183@gmail.com

Abstract

Displacement from the Ganges–Brahmaputra–Meghna delta in south-west Bangladesh is usually attributed to sea-level rise, cyclones and salinity. The evidence assembled here points to a jointly produced process, in which hazards act together with engineered landscape change, governance arrangements and the interval households spend unable to return. Peer-reviewed and grey literature for Khulna, Satkhira and Bagerhat is sorted into four categories: physical transformation, ecological degradation, human impact and governance process. The strongest evidence concerns polder-related elevation loss: land inside embankments has lost 1.0–1.5 m of relative elevation against the adjacent Sundarbans and natural riverbank terraces, a differential of roughly 20–30 mm yr^{-1} over five decades and some seven to ten times the regional water-level trend of about 3 mm yr^{-1}. Chronic waterlogging affects approximately 128,000 ha for six to nine months annually. Modelled dry-season sodium intake from drinking water in one Khulna upazila reaches 2.5 to 8 times the WHO recommended maximum for adults, although the measured urinary biomarker in the same study is roughly a third of the modelled upper bound. Attribution is far weaker: the contributions of aquaculture, upstream freshwater reduction, subsidence and climate forcing to salinisation remain unresolved. A second finding is methodological. Vertical land motion estimates for this delta diverge by up to an order of magnitude, and the divergence is a category error rather than an empirical dispute, because gauge, InSAR and stratigraphic methods sample different depth intervals and timescales. Across three cyclones spanning thirteen years, national mortality fell 131-fold while embankment breaches and livelihood disruption persisted for months to years afterwards. Recovery latency, the interval between hazard-related loss of return conditions and their restoration, is therefore proposed as a complementary measure for climate-displacement research. Restoration intervals are reported only anecdotally and at landscape scale in the reviewed literature, never at household level against a defined restoration criterion, so the quantity is right-censored and needs survival-analytic estimation from panel data that do not yet exist.

Keywords: climate displacement; maladaptation; coastal polders; salinisation; Ganges–Brahmaputra–Meghna delta; recovery latency; recognitional justice

1. Introduction

Coastal deltas carry a disproportionate share of global environmental risk, hosting roughly half a billion people on land subsiding faster, on average, than global mean sea level is rising. An assessment of major deltas found 85 per cent had experienced severe flooding in the previous decade, temporarily submerging some 260,000 km² (Syvitski et al., 2009); where exposure is calculated from locally measured subsidence rather than sea-level rise alone, it comes out up to four times greater (Nicholls et al., 2021). The Ganges–Brahmaputra–Meghna (GBM) delta is the largest of these systems and home to nearly 200 million people (Becker et al., 2020). Its western fringe has been altered at landscape scale by embankments built from the 1960s, brackish aquaculture that has replaced much former paddy since 1990, and retreat of the Sundarbans mangrove belt (Jaman et al., 2023). These changes coincide with the country's most cited vulnerability metric, displacement of the order of one million people annually, a figure drawn from policy syntheses and not from any primary enumeration (Kisinger and Matsui, 2021).

Coastal displacement is commonly read as a direct consequence of sea-level rise and intensifying storms. That reading is not wrong, but it is incomplete, and the incompleteness has a policy cost: where hazard is treated as the operative variable, response concentrates on forecasting, early warning and evacuation (Rigaud et al., 2018; Clement et al., 2021). A second reading asks what the coast has been made into. Embankment construction, the conversion of paddy to brackish ponds, upstream flow regulation and the institutional arrangements governing post-event repair all alter the conditions under which households can remain in place or return to it. That reading brings two things into view that the hazard-only account cannot accommodate: the possibility that interventions undertaken as adaptation increase vulnerability, and the duration for which people remain displaced after an event has passed (Barnett and O'Neill, 2010; Schipper, 2020; Eriksen et al., 2021).

Evidence for the second reading has strengthened since 2015. Sediment-core, geodetic and satellite methods converge on a substantial relative elevation deficit inside the polders: land enclosed by embankments in the 1960s has lost of the order of a metre against adjacent unembanked terrain, which has continued to accrete at rates close to relative sea-level rise (Auerbach et al., 2015). Salinity has both spread and intensified, with consequences for cultivation, drinking water and health (Lam et al., 2022; Khan et al., 2011; Rahman et al., 2026), and higher soil salinity is associated with a greater probability of household migration (Chen and Mueller, 2018). Mangrove loss has weakened a protective function valued globally at more than USD 65 billion of flood damages avoided each year (Menéndez et al., 2020).

Theory has developed alongside. Maladaptation began as a taxonomy of failure modes (Barnett and O'Neill, 2010; Magnan et al., 2016) and is now supported by evidence that a substantial fraction of interventions labelled adaptation measurably increase vulnerability (Schipper, 2020; Eriksen et al., 2021). Frameworks separating exposure, sensitivity and adaptive capacity locate the binding constraint (Turner et al., 2003; Adger, 2006). Climate-justice scholarship has foregrounded the standing accorded to marginalised groups as knowledge-holders (Fraser, 2000; Schlosberg, 2004; Sultana, 2010). Brammer (2014) had already cautioned that Bangladesh's coastal geography is more diverse than uniform sea-level narratives allow.

So the settled ground is this. Relative elevation inside polders has fallen, salinity has spread and intensified, mangrove extent has declined, and cyclone mortality has fallen sharply. What remains open is the relative contribution of engineering, aquaculture, upstream flow reduction and climate forcing to salinisation, and the determinants of displacement duration as distinct from incidence. The second question is unanswered for a structural reason: the biophysical literature measures landscape change without tracking households, while the mobility literature tracks households but concentrates its major panels outside this coast, principally at Matlab (Call et al., 2017).

This review reads those two literatures against each other for Khulna, Satkhira and Bagerhat (Figure 1), separating engineered and governance components from strictly climatic ones and engaging recent Bangladesh mobility scholarship (Black et al., 2011; Call et al., 2017; Ayeb-Karlsson et al., 2016; Chen and Mueller, 2018; Ahsan et al., 2024). It addresses three questions.

(i) What does the reviewed evidence establish about the relative contributions of engineered landscape modification and climatic forcing to elevation loss, salinisation and loss of protective function on this coast, and at what point does attribution fail?

(ii) Where estimates of the same nominal quantity disagree, is the disagreement empirical, or an artefact of non-standardised measurement?

(iii) Can the duration of post-event displacement be estimated from the existing evidence base, and if it cannot, what would a study design that estimates it require?

The contribution is an operational definition of recovery latency, a demonstration that the quantity is currently unmeasurable because restoration is not recorded at the household level against any defined criterion, and a design that would measure it.

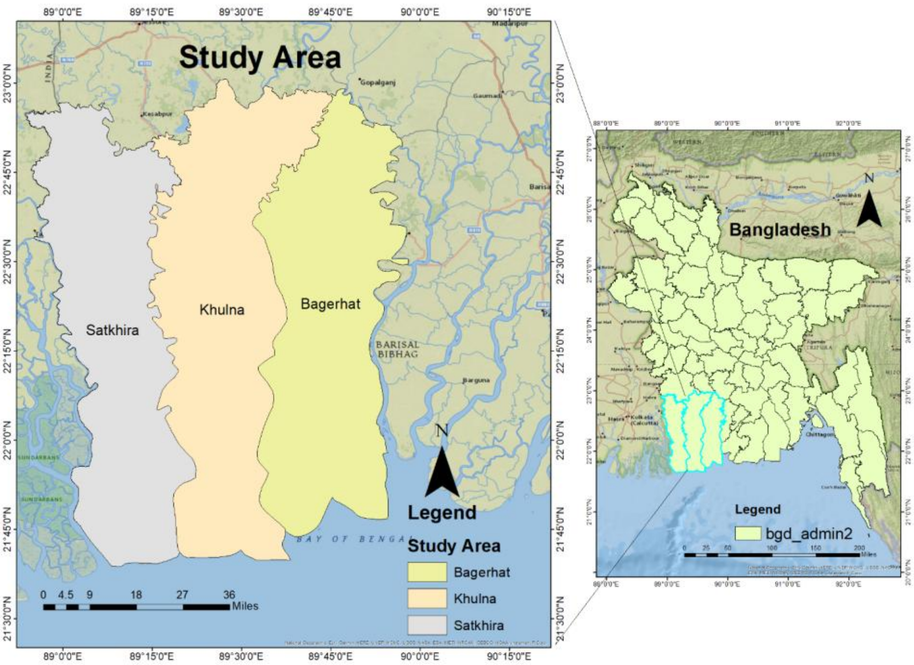

Figure 1. Study area. Khulna, Satkhira and Bagerhat districts, south-west Bangladesh, within the Ganges–Brahmaputra–Meghna delta. Administrative extent only.

2. Conceptual framework

The analysis rests on four positions, each tested against the evidence rather than assumed. Vulnerability is treated as jointly produced, a composite of exposure, sensitivity and adaptive capacity rather than a function of hazard alone (Turner et al., 2003; Adger, 2006); across coastal upazilas, where exposure is broadly high, differences in adaptive capacity help explain differences in livelihood disruption and displacement duration, though the evidence is heterogeneous.

Maladaptation is defined as intervention undertaken in the name of adaptation that increases vulnerability, including through unequal distribution of costs and benefits (Barnett and O'Neill, 2010; Magnan et al., 2016; Schipper, 2020). Polders and selected forms of brackish aquaculture are treated as candidate maladaptive pathways, since both have generated real benefits alongside context-specific costs; the operative question is whether vulnerability-enhancing effects are externalised onto groups receiving disproportionately fewer benefits.

Recognitional justice concerns the standing accorded to marginalised groups as knowledge-holders and participants (Fraser, 2000; Schlosberg, 2004; Sultana, 2010). The review uses the frame for one narrow question: was local ecological knowledge incorporated into technical decision-making? Recognition failure is treated as a contributing mechanism, not an established cause.

Finally, drawing on mobility scholarship (Black et al., 2011; Ayeb-Karlsson et al., 2016; Call et al., 2017), some climate-related displacement is better represented as a duration of disrupted access to land, housing and infrastructure than as a single relocation event. Recovery latency, defined in Section 3.4, is therefore a testable explanatory dimension.

Figure 2 assembles these positions. Climatic hazards interact with polders, aquaculture and mangrove alteration to generate four cascades: elevation loss, waterlogging, salinisation and loss of protective function. These reach exposed populations through sensitivity and adaptive capacity, with governance modifying the whole structure through planning, accountability, recognition, benefit distribution and post-event repair.

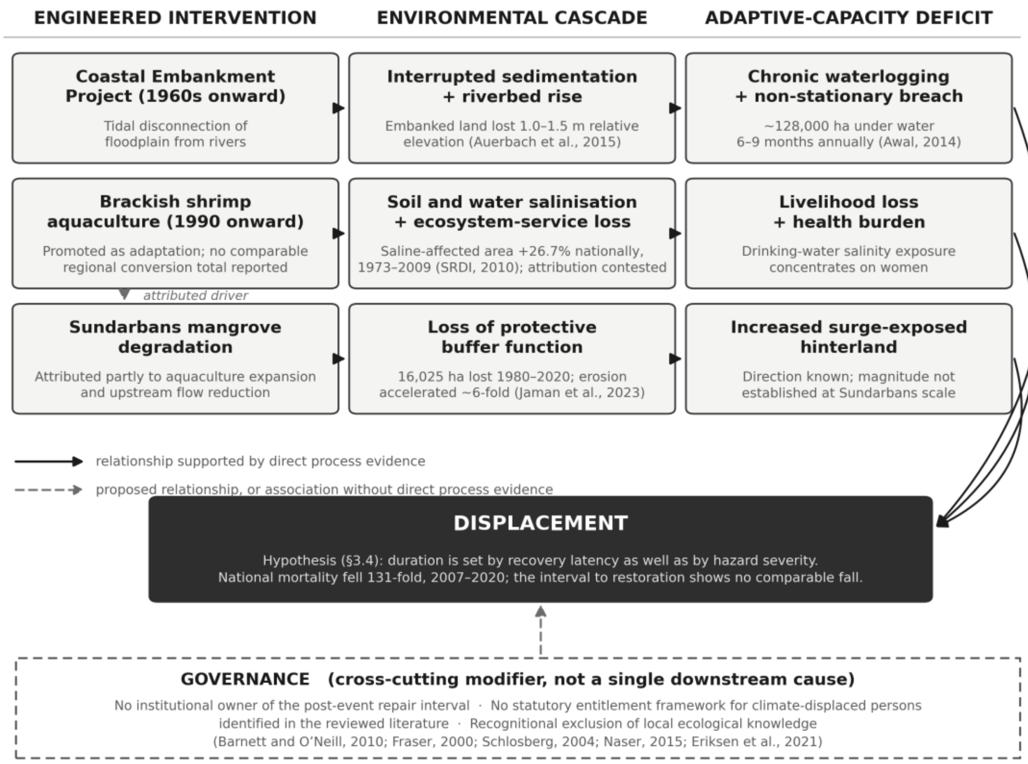

Figure 2. Conceptual framework linking climatic hazards, engineered pathways, environmental cascades, adaptive capacity, recovery latency and displacement. Governance is a cross-cutting modifier, not a single downstream cause. Solid arrows denote relationships supported by direct process evidence; dashed arrows denote proposed relationships, or associations for which direct process evidence is absent. Arrow direction indicates the structure of the proposed pathway, not an estimated effect size; the strength of the evidence behind each stream is graded separately in Table 3 and summarised in Section 7.

3. Review methodology

3.1 Review design and search strategy

This is a critical review of a defined region, not a systematic review or a meta-analysis. The question cuts across four disciplines, geomorphology, hydrology, epidemiology and demography, and governance, whose constructs are not commensurable. A conventional systematic synthesis would have to either exclude the evidence that makes the question interesting, or force incompatible outcome measures onto a shared scale that none of the contributing fields recognises. Reporting follows SANRA (Baethge et al., 2019).

Five PRISMA 2020 items are adopted where they improve transparency without implying a synthesis that was not performed: eligibility criteria, information sources, full search strategy, selection process, and data items. Four are deliberately not adopted, and the reasons are substantive rather than practical. No protocol was registered, because the review question was refined iteratively as the incommensurability of the four literatures became apparent. No validated risk-of-bias instrument is applied, for the reason given in Section 3.3. No synthesis of results is performed, because there is no common effect measure. No certainty-of-evidence assessment in the GRADE sense is reported, because GRADE is calibrated to intervention effects and does not transfer to sediment cores and political ethnography. PRISMA is used here as a reporting aid for specific items, not as a design label.

A three-block Boolean string combining place, mechanism and outcome terms was run against the Web of Science Core Collection, Scopus and Google Scholar for the period 2010 to 2026. Earlier work entered the reference list through citation chasing where it establishes a mechanism or a baseline; the database window therefore constrains the search, not the reference list. Grey literature was searched by named institution and retained only where it reported primary data or an official assessment unavailable in the peer-reviewed literature. The named-institution list does not include a systematic search of primary legislation or the Bangladesh Code, which bounds the legal claims in Section 6.3.

Eligibility required a south-west or GBM setting bearing on this coast; a phenomenon among polder effects, salinisation, aquaculture conversion, mangrove change, subsidence or accretion, mobility, and adaptation governance; a measured or clearly interpretable outcome, or a documented governance process with an identifiable mechanism; and a method reported in enough detail to judge scale, coverage and measurement basis. Restricting to English is a substantive exclusion: it removes Bengali-language technical reporting holding primary data with no English equivalent. Verbatim search strings and the full eligibility criteria are given in Supplementary Material S1.

3.2 Screening, extraction and evidence classification

Records were screened by title, then abstract, then full text, by the single author. No second screener was available, so no inter-rater statistic can be reported, and that is a genuine limitation rather than one this review can offset. One safeguard was applied and is worth stating because it shapes the direction of any residual error: records of uncertain eligibility were carried forward rather than excluded, so every exclusion under doubt was made against full text rather than against a title or abstract. The resulting error is therefore more likely to be over-inclusion than silent omission.

Stage-by-stage record counts are not reported, and the reason is a property of the design rather than an omission. Because the review is deliberately non-exhaustive, a count of records screened would describe the volume of material inspected without bounding the material that exists, and reporting it in the format of a systematic review would imply a completeness the search was not built to deliver. What can be audited instead is the selection rule: the verbatim strings, field tags, database limits and full eligibility criteria are given in Supplementary S1, so any reader can re-run the searches and judge what this review is likely to have seen and missed. Section 8.3 states the consequence.

Extraction used a structured template recording design, spatial scale and named sites, temporal coverage, sample size, the measured variable and its unit, the reported value or range, the measurement method, stated limitations and the evidence category. Holding unit and method as separate fields is what makes the divergence analysis in Section 4.1 and Figure 3 possible, because it reveals when two estimates of nominally the same quantity describe different physical measurements. A dedicated field recorded what each reported range represents, so unspecified ranges appear as such in Table 3 rather than as uncertainty bounds.

Evidence was classified into four categories, each anchored to an indicator type: physical transformation (elevation loss and deficit rate, subsidence, land-use conversion), ecological degradation (mangrove loss, shoreline erosion, protection-value loss), human impact (displacement counts, migration probability, exceedance ratios, dose-response) and governance failure (recovery latency, institutional delay, inclusion in planning). Applying it surfaces a recurring asymmetry: physical-transformation evidence is strong and convergent, human-impact evidence strong in direction but variable in magnitude, and governance evidence the least quantified of the four.

3.3 Critical appraisal and synthesis

No validated risk-of-bias instrument covers an evidence base spanning sediment cores, InSAR interferometry, demographic panels, cohort epidemiology and political ethnography. Each study was appraised against five domains: clarity of aim and outcome definition; transparency of method; appropriateness of study scale to the claim drawn from it; proximity of the measurement to the causal pathway; and independence from other included studies. These judgements inform the evidence grades reported in Table 3. No numerical total is computed, because summing ordinal ratings across incommensurable domains would imply a precision the judgements do not support.

Independence deserves note: several studies draw on the same underlying data, notably the SRDI salinity inventory, the Matlab demographic surveillance system and overlapping Landsat archives, and convergence among such studies is weaker evidence than convergence among independent ones. High evidence denotes multiple relatively independent studies with convergent findings; moderate, consistent findings with important scale, attribution or measurement limitations; low, sparse or strongly context-dependent evidence. Causal verbs are reserved for relationships supported by direct process evidence.

Formal meta-analysis is not defensible here. There is no common effect measure, since outcomes span metres of elevation, hectares, counts of displaced persons, migration probabilities and dimensionless indices. Most studies report estimates without standard errors. Several share underlying datasets, and the LVI-IPCC studies use different normalisations. The alternative is a structured evidence matrix (Table 3). Where estimates are comparable in unit, they are shown on a common axis without a pooled summary (Figure 3), because the methods are not estimating a common quantity.

3.4 Recovery latency: definition and estimator

Recovery latency is the interval between hazard-related loss of return conditions and their restoration. For household or settlement i,

$$L_i = t\_restore_{,i} - t\_event_{,i} \quad (1)$$

where L_i is recovery latency in months, t_event is the date at which hazard-related damage removes minimum return conditions, and t_restore is the date at which those conditions are restored. Aggregated across affected units, the displacement burden is

$$D = \Sigma_{i=1}^{n} N_i \cdot L_i \quad (2)$$

where N_i is the displaced population of unit i, D is expressed in person-months and n is the number of affected units. N_i counts only those members of the unit who lost return conditions, not its total population. Minimum return conditions must be specified operationally for any given study; candidate criteria include restoration of embankment integrity at the relevant reach, drainage of the settlement below a defined inundation depth, and restoration of habitable dwelling and potable water access.

Three distinctions keep the construct from collapsing into adjacent ones. Recovery latency is not displacement duration: a household may return before conditions are restored, or remain away after they are, so the two quantities coincide only where return tracks restoration exactly. It is not migration: migration is a movement, latency is a property of the place, measured by the state of the land, the embankment and the water supply rather than by where anyone is living. And it is not recovery in the broader sense used in the disaster literature, which encompasses livelihood, income, health and psychosocial trajectories that may continue for years after the physical threshold is crossed. Latency measures one narrow thing, the restoration of a stated minimum condition for return, and its value lies in that narrowness: it is the component of recovery that is governed by identifiable institutions with identifiable mandates.

The measurement problem is central, so it is stated here. Restoration intervals are reported in the reviewed literature only anecdotally and at landscape scale. Auerbach et al. (2015) note that following Cyclone Aila the embankments of several large islands failed, leaving substantial areas tidally inundated for up to two years until repair, which is the single closed interval available anywhere in this evidence base. No reviewed source records restoration at the household or settlement level, against a defined restoration criterion, with the systematic follow-up that estimation requires. Recovery latency is therefore right-censored in effectively every observation, and the appropriate estimator is a survival function rather than a mean. Under the Kaplan–Meier estimator,

$$\hat{S}(t) = \Pi\ [\ 1 - (d_j / n_j)\ ]\ \text{for all}\ t_j \leq t \quad (3)$$

where d_j is the number of units achieving restoration at time t_j and n_j the number still displaced and under observation immediately before t_j. Because the event of interest is restoration rather than failure, $\hat{S}(t)$ is the estimated probability that a unit remains displaced beyond time t. Permanent out-migration is a competing event and should be modelled as such rather than treated as censoring, since a household that leaves permanently does not later become restored and treating it as censored would bias the survival function downward.

No value of L or D is calculated here, because the data required do not exist. The contribution claimed is not the observation that recovery takes time, which is well established in the post-disaster literature, nor the observation that displacement can be protracted, which is the subject of an established body of work on protracted and secondary displacement. It is narrower and, correspondingly, testable: a definition tied to a stated restoration threshold, an aggregation to person-months, an estimator appropriate to the censoring structure the data actually have, and a specification of the competing risk. Stating the quantity formally converts a general call for longitudinal data into a designable study with defined restoration criteria, observation intervals and explicit handling of censoring and competing risks.

Section 4.2 uses one further quantity. The exceedance ratio for drinking-water sodium is

$$ER = I\_Na \,/\, WHO\_Na \qquad (4)$$

where I_Na is estimated daily sodium intake from drinking water (g d^{-1}) and WHO_Na is the WHO recommended maximum dietary sodium intake for adults, approximately 2 g d^{-1}. Both quantities are per person per day, so ER is dimensionless. No separate estimated daily intake term normalised by body weight is introduced, because the reference value is a per-person dietary recommendation rather than a per-kilogram toxicological reference dose, and dividing intake by body weight would make numerator and denominator non-comparable. For the same reason ER is an exceedance against a dietary recommendation and not a toxicological hazard quotient.

4. Engineered drivers of displacement

Three engineered pathways recur across the reviewed evidence, and they interact. The evidence does not permit a quantitative decomposition of their separate contributions to displacement.

4.1 Coastal polders and engineered subsidence

Embankment construction on the south-west coast from the 1960s enclosed low-lying islands behind earthen dikes, converting a tidally connected floodplain into a network of drained compartments. The intended effect was protection from saline inundation and the stabilisation of a cropping calendar, and for the first decades it broadly delivered that. The unintended effect followed from the same mechanism: an embankment that keeps tidal water out also keeps tidal sediment out. Unembanked terrain in this delta gains elevation each monsoon from suspended sediment delivered on the flood tide, at rates that have kept pace with relative sea-level rise. Inside the polders that supply was cut, while drainage accelerated compaction of the organic-rich upper soil column and the removal of forest biomass reduced surface accretion further. The interior surface therefore fell relative to the surrounding platform, and regional tidal range increased as the tidal prism was redistributed into a smaller channel network (Auerbach et al., 2015; Higgins et al., 2014; Wilson and Goodbred, 2015).

The magnitude is substantial. Auerbach et al. (2015) report that embanked islands in south-west Bangladesh have lost 1.0–1.5 m of elevation relative to the adjacent Sundarbans and natural riverbank terraces, which remained comparatively stable over the same period. Dividing that deficit by the interval since embankment closure, approximately 50 years, gives a differential rate of about 20–30 mm yr^{-1}. Three qualifications attach to that derived rate. Construction was phased through the 1960s and 1970s, so the denominator is approximate rather than exact. The rate is a differential between embanked and unembanked surfaces, not an absolute subsidence rate, and it therefore combines interior lowering with exterior accretion in unknown proportion. And the sampled sites are not a random sample of the polder network, so the figure describes the locations measured rather than the system as a whole. With those qualifications the comparison still holds: the anthropogenic elevation differential of roughly 20–30 mm yr^{-1} exceeds the regional water-level trend of about 3 mm yr^{-1} over the same period (Becker et al., 2020) by some seven to ten times (Figure 3).

The point is not that sea-level rise is unimportant. It is that on this coast, over this period, the dominant contribution to the loss of relative elevation traces to a dated engineering decision rather than to a diffuse global forcing, and that the two have been conflated in most policy framings of coastal risk here (Auerbach et al., 2015; Higgins et al., 2014; Wilson and Goodbred, 2015; Becker et al., 2020).

The material consequence is chronic waterlogging that affects livelihoods without a cyclone. Since the early 1980s, approximately 128,000 ha across Jessore, Satkhira and Khulna have gone semi-permanently under water for six to nine months annually, affecting the livelihoods of roughly one million people (Awal, 2014). No displacement count is attached to that figure, so it measures exposure rather than movement. Ishtiaque et al. (2017) characterised the resulting system as robust yet fragile: stable under design conditions, but with breach probability rising non-stationarily as the polder loses elevation and the adjacent riverbed rises. Post-cyclone assessments consistently identify embankment breach as a primary determinant of flood extent (GFDRR and Government of Bangladesh, 2008).

Cyclone Amphan illustrates both the scale of breaching and the state of the reporting. National figures relayed through UNDP record approximately 150 km of protection embankment washed away at 84 points across thirteen districts, while the joint needs assessment issued eleven days after landfall records 76 km damaged (NAWG, 2020). Preliminary district compilations attribute 24.6 km of collapse at 65 points to Satkhira and 29.2 km at 28 points to Khulna, the two worst-affected districts. These figures come from different reporting instruments at different dates and are not additive: the two district point counts alone exceed the stated national total. The divergence is itself informative about the evidence base. What no source records is when any of those breaches was closed. That is the measurement problem formalised in Section 3.4, and Eriksen et al. (2021) treat it as a canonical failure mode of engineered adaptation.

The subsidence literature sharpens the picture without resolving it. A reconstruction from 101 gauges found regional water levels rising at approximately 3 mm yr^{-1} against a global mean near 2 mm yr^{-1} during 1968 to 2012, with maximum subsidence of 1–7 mm yr^{-1}; under RCP4.5, subsidence could roughly double projected sea-level rise by 2100 (Becker et al., 2020). Engineered deltas behave this way generally (Syvitski et al., 2009; Tessler et al., 2015), and coastal inhabitants worldwide experience population-weighted relative sea-level rise of 7.8–9.9 mm yr^{-1} (Nicholls et al., 2021).

Estimates from gauges, InSAR and geomorphology nonetheless diverge by up to an order of magnitude for individual GBM locations (Figure 3), and the disagreement reflects method-dependence, not measurement error. Gauge reconstructions integrate over the full sediment column and multi-decadal timescales; InSAR resolves shallow compaction over years; stratigraphic reconstructions capture Holocene-scale accommodation. Reporting these as competing estimates of one parameter is a category error, and it has a practical cost: a polder rehabilitation design keyed to a regional average is keyed to a quantity that does not describe the site it is meant to protect. Polder-level design should rest on locally standardised measurement stating explicitly the depth interval, timescale and footprint it represents.

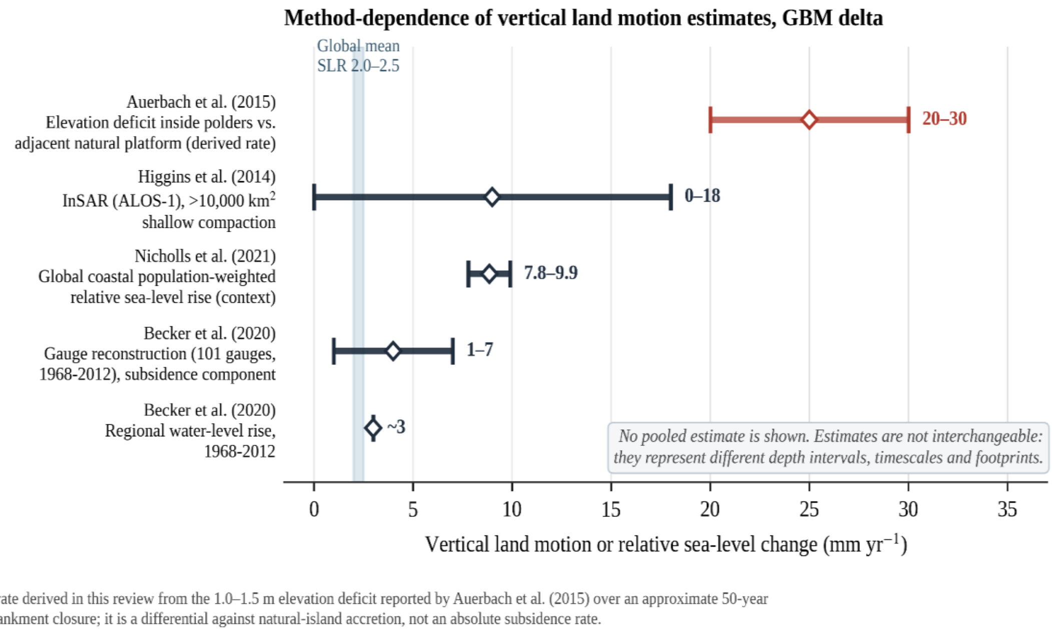

Figure 3. Method-dependence of vertical land motion and relative sea-level change estimates in the GBM delta, on a common axis (mm yr^{-1}) with no pooled estimate because the methods sample different depth intervals, timescales and footprints. The polder elevation deficit is derived here from Auerbach et al. (2015), a differential against natural-island accretion rather than an absolute subsidence rate.

4.2 Aquaculture, salinisation and displaced health burdens

Salinity has both spread and intensified, but the change that matters more for cultivability is the severity shift within already-affected land. Nationally, saline-affected land rose from about 833,450 ha in 1973 to 1,056,190 ha in 2009, an expansion of 26.7 per cent (SRDI, 2010), or an average net rate of approximately 6,190 ha yr^{-1}. That is a net change in classified area, not gross annual incursion. Monthly monitoring at 24 stations in Bagerhat, Khulna and Satkhira between 2004 and 2022 shows that seasonality dominates the signal, accounting for around 60 per cent of the variance in soil salinity and 78 per cent in river-water salinity, with no significant monotonic trend across the record as a whole: a decline to about 2014 is offset by a rise thereafter, and dry-season soil salinity has been increasing since the mid-2010s (Rahman et al., 2026). Salinity on this coast is therefore better characterised as a seasonally varying state with a shifting dry-season maximum than as a monotonically expanding classification, and the SRDI inventory above, which compares two survey years, cannot distinguish the two.

Brackish shrimp gher has expanded substantially along the shoreline over recent decades, replacing paddy (Akber et al., 2017). No regional conversion area is reported here, because classification schemes and baseline years differ across the available assessments. Aquaculture has generated income and export value and functions in places as a livelihood response to rising salinity. The literature also documents salinity feedbacks, land-use conflict and barriers to returning converted land to paddy (Shameem et al., 2014; Paprocki, 2021). The relationship is endogenous: where brackish ponds sit behind an existing salinity front, conversion is plausibly a response; where they sit ahead of it and require deliberate saline-water intake, it is plausibly a driver. Telling the two apart needs spatially explicit data on the sequence of front movement and conversion, unavailable at regional scale. Studies accordingly differ in whether they attribute intensification to aquaculture, to reduced upstream freshwater flow following Farakka barrage operation, to loss of sedimentation-driven elevation, or to some combination (Rahman et al., 2026).

Chen and Mueller (2018) found higher soil salinity associated with a greater probability of household migration across the observed gradient, and the direction and graduated shape of that response are the findings carried forward here. The associated national projection of additional annual movers is a model-derived quantity rather than an observed displacement count, and it is not used, because its transportability to Khulna, Satkhira and Bagerhat specifically was not assessed in the source. Recent work reinforces the need to distinguish temporary, circular and permanent mobility (Ahsan et al., 2024).

The health burden was largely absent from the policy framing when shrimp expansion was promoted, and the evidence on it needs stating precisely because it is frequently over-read. Khan et al. (2011) estimated dry-season sodium intake from drinking water in Dacope, Khulna, at 5–16 g per day, against 0.6–1.2 g per day in the rainy season. That range is modelled, not measured: it applies an assumed consumption of 2 L per day to water-salinity records for 1998 to 2000, and the estimate varies by source, from rainwater at the low end to shallow tubewell and pond water at the high end. Against the WHO recommended maximum dietary sodium intake for adults of approximately 2 g per day, the modelled range corresponds to an exceedance ratio of 2.5 to 8 (Equation 4; Figure 4a). Two caveats belong with that number. The measured biomarker in the same study, 24-hour urinary sodium excretion in 343 pregnant women, averaged 3.4 g per day with a range of 0.4 to 7.7, which is roughly a third of the modelled upper bound and reflects total dietary sodium rather than drinking water alone. And the salinity records predate the cohort by about a decade. The health outcome reported is a seasonal contrast in hospital-based prevalence of hypertension in pregnancy, 12.2 per cent (95 per cent CI 9.5 to 14.8) in the dry season against 5.1 per cent (2.91 to 7.26) in the rainy season, which is an ecological association at hospital level rather than an individual-level exposure-response relationship. Water-collection labour and the exposure it produces fall disproportionately on women (Sultana, 2010). A health burden falling on the population least represented in adaptation decisions is among the stronger arguments for reading this case as maladaptation (Eriksen et al., 2021), and it holds on the measured biomarker as well as on the modelled range.

4.3 Mangrove degradation as protective infrastructure

The Sundarbans belt attenuates cyclone surge through several independent mechanisms, reducing surge run-up, dissipating wind energy and stabilising shoreline sediments. Menéndez et al. (2020) calculated at 20 km resolution that mangroves provide flood-protection benefits to more than 15 million people, prevent property damages exceeding USD 65 billion annually, and place Bangladesh among the top three national beneficiaries by people protected; some stretches near cities receive more than USD 250 million annually per 20 km. Event-specific attribution of surge attenuation during recent cyclones is not established in the sources reviewed here.

The buffer is degrading measurably. Sundarbans mangrove area across the Bangladesh and Indian portions declined by 16,025 ha between 1980 and 2020, with a further 22,286 ha projected by 2050, while shoreline erosion by end-point rate accelerated from approximately −0.90 m yr^{-1} in 1980–2000 to −5.81 m yr^{-1} in 2000–2020 (Jaman et al., 2023). That assessment covers the transboundary system, so the figures are not Bangladesh-specific. Drivers include the aquaculture expansion documented above, upstream freshwater diversion, cyclone damage that no longer recovers between events, and industrial pressure along the inland boundary.

Loss of mangrove area increases the surge-exposed hinterland, and the increase is expected to be non-linear, because protection depends on continuous canopy connectivity and root-network integrity rather than on area alone (Menéndez et al., 2020). This is an inference from the mechanism rather than a measured relationship for the Sundarbans. If it holds, fragmented mangroves protect less than their area implies, and area-based accounting overstates residual protection wherever the canopy has become discontinuous.

Across the three pathways, vulnerability amplification differs in magnitude and in mechanism: elevation loss works through physical landscape modification, aquaculture through livelihood and land-use transformation, and mangrove degradation through reduced protective ecosystem services (Figure 4). The evidence does not permit a quantitative decomposition of their contributions.

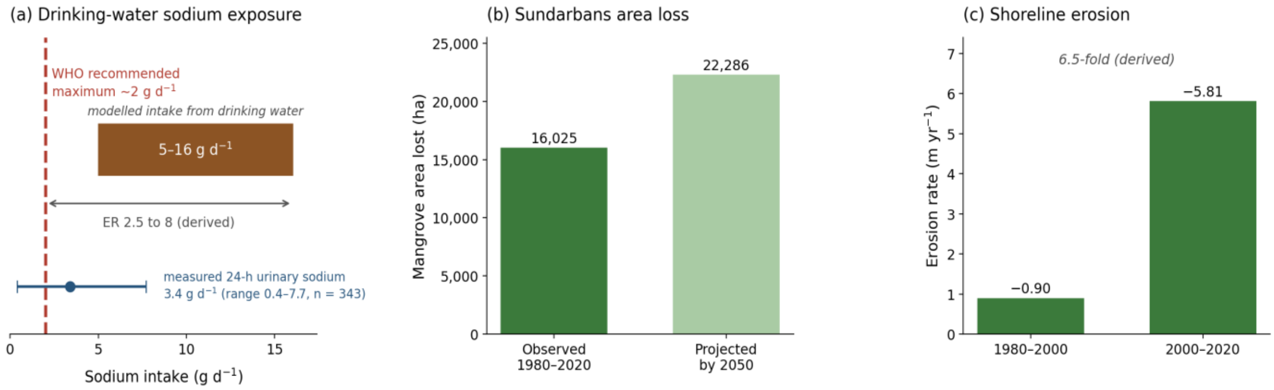

Figure 4. Magnitude of the ecological and health signals. (a) Modelled dry-season sodium intake from drinking water in Dacope, Khulna (Khan et al., 2011) against the WHO recommended maximum dietary intake for adults, with the measured 24-hour urinary sodium concentration from the same study shown for comparison. The modelled range lies wholly above the recommendation, so its lower bound and not only its central tendency exceeds the guidance value; the measured biomarker, which reflects total dietary sodium rather than drinking water alone, is substantially lower. (b) Sundarbans mangrove area lost, observed and projected on current trends, and (c) end-point shoreline erosion rate by epoch, plotted as magnitude (Jaman et al., 2023). Panels (b) and (c) cover the transboundary system and are not Bangladesh-specific.

Table 3. Structured evidence matrix for the principal evidence streams on engineered drivers. Grades follow Section 3.3; per-study appraisal against the five domains is given in Supplementary Table S1.6.

Evidence stream	Indicator and unit	Range across studies	What the range represents	Evidence grade	Studies (n)	Principal attribution limit and key sources
Polder elevation loss	Relative elevation deficit (m); derived rate (mm yr^{-1})	1.0–1.5 m; 20–30 mm yr^{-1} (derived)	Contrast between embanked and adjacent natural platforms at sampled sites	High	3–4	Sites not a random sample of the polder network; embankment closure phased, so the derived rate carries an approximate denominator. The 1.0–1.5 m figure is from Auerbach et al. (2015) alone; Higgins et al. (2014) and Wilson and Goodbred (2015) support the mechanism, not the value.
Vertical land motion and regional water-level rise	Subsidence rate; water-level trend (mm yr^{-1})	Gauge 1–7; InSAR 0 to >18; water level ~3 (1968–2012) vs global mean ~2	Inter-method range, not a confidence interval; methods sample different depths and timescales. Water level from a single 101-gauge reconstruction	Moderate (subsidence); High (water level)	3–4	Estimates are not interchangeable and should not be pooled (Figure 4); regional aggregate masks sub-delta variation. Becker et al. (2020); Higgins et al. (2014); Brown and Nicholls (2015)
Waterlogging extent (SW Bangladesh)	Area under water (ha); duration (months yr^{-1})	~128,000 ha; 6–9 months	Reported extent; not disaggregated by causal contribution	Moderate	1–2	Not disaggregated by cause: drainage congestion, SLR and subsidence not separated. No displacement count attached. Awal (2014); Ishtiaque et al. (2017)
Salinisation (extent and attribution)	Saline-affected area (ha); net rate (ha yr^{-1}); attributed mechanism	833,450 (1973) to 1,056,190 (2009); +26.7%; ~6,190 ha yr^{-1} net (derived); attribution contested	National inventory at two time points, derived average net rate; divergent attributions across studies, from both spatial heterogeneity and methodological non-standardisation	Moderate (extent); Low (attribution)	4–5	National scale; severity thresholds and survey methods not harmonised over time. Aquaculture, Farakka flow reduction, sedimentation loss and climate forcing not separated at regional scale. SRDI (2010); Rahman et al. (2026); Lam et al. (2022); Akber et al. (2017)
Aquaculture expansion	Area converted (km^2); political-economy findings	Substantial expansion; no comparable regional total	Remote-sensing time series plus qualitative fieldwork	Moderate	3–4	Ecosystem-service loss unquantified at watershed scale; political-economy coverage regionally uneven. Akber et al. (2017); Shameem et al. (2014); Paprocki (2021)
Sundarbans extent and mangrove protection function	Mangrove loss (ha); shoreline change (m yr^{-1}); damages avoided	16,025 ha (1980–2020); −0.90 to −5.81 m yr^{-1}; >USD 65 bn yr^{-1}; >15 M people	Transboundary system total, not Bangladesh portion; end-point rate across two epochs. Protection value from	Moderate (extent); High (global valuation,	1–2	Bangladesh partition not reported; protection not adjusted for canopy fragmentation at Sundarbans scale and event-specific

Evidence stream	Indicator and unit	Range across studies	What the range represents	Evidence grade	Studies (n)	Principal attribution limit and key sources
	(USD yr^{-1}); people protected		a global 20 km-resolution valuation	not locally validated)		attenuation not established. Jaman et al. (2023); Menéndez et al. (2020)
Drinking-water salinity and health	Modelled sodium intake (g d^{-1}); measured urinary sodium (g d^{-1}); exceedance ratio	Modelled 5–16 g d^{-1}; measured urinary mean 3.4 (range 0.4–7.7); ER 2.5–8 (derived from the modelled range)	Modelled dry-season intake from 1998–2000 salinity records at an assumed 2 L d^{-1}; measured 24-hour urinary excretion in a cohort of 343 pregnant women, one upazila	Moderate	1–2	Single-site cohort; intake modelled rather than measured, and salinity records predate the cohort by about a decade; measured biomarker is roughly a third of the modelled upper bound and reflects total dietary sodium. Health outcome is a seasonal hospital-prevalence contrast. Population-scale dose-response not established. Khan et al. (2011); Sultana (2010)
Mobility response to environmental stress	Migration probability; direction of effect	Flooding: no long-term effect; salinity: positive, graduated	Panel and survey estimates from differing populations	Moderate	4	Major panel sits outside the SW coast (Matlab); SW-specific longitudinal cohorts scarce. Call et al. (2017); Chen and Mueller (2018); Ayeb-Karlsson et al. (2016); Ahsan et al. (2024)
Adaptive capacity (LVI-IPCC)	Composite index (dimensionless)	Composite LVI-IPCC 0.13–0.52; exposure ~0.75 vs adaptive capacity ~0.34 in one study	Across-study range of incommensurable indices, not a gradient	Low	3	Threefold divergence for the same construct in adjacent upazilas indicates incompatible operationalisation. Khan et al. (2022)

Study counts are as plotted in Figure 7(b); ranges arise where a source contributes to a stream only in part. The "key sources" column names the studies carrying the reported values and is not an exhaustive list of contributing studies.

5. Displacement production: adaptive capacity and the mobility question

Exposure is high across many coastal upazilas while adaptive capacity varies, but the measurement of that variation is unreliable. Three unions of Koyra upazila record composite livelihood vulnerability values between 0.48 and 0.52, against a range of roughly 0.13 to 0.52 across the wider set of LVI-IPCC assessments for this coast, with exposure sub-indices running far above adaptive-capacity sub-indices in the same locations (Khan et al., 2022). Those values do not sit on a shared scale. A near-fourfold spread in what is nominally the same construct, across upazilas that share a coastline, a hazard regime and an administrative system, is more plausibly a sign of incompatible operationalisation than of a real gradient, and composite indices of this family should not be compared across studies without harmonisation. The practical consequence is that adaptive capacity, the term that carries most of the explanatory weight in the vulnerability framework, is the least reliably measured quantity in this literature.

The cyclone record speaks more clearly. Cyclone Sidr (2007) killed 3,406 people and affected 1.1 million; Cyclone Aila (2009) killed 190 and affected 3.9 million; Cyclone Amphan (2020) killed 26, with more than 2.4 million people evacuated to shelters before landfall (Table 4; Figure 5). National mortality fell 131-fold between Sidr and Amphan, a reduction of 99.2 per cent. Normalising by the population evacuated gives roughly 113.5 deaths per 100,000 evacuees at Sidr against roughly 1.1 at Amphan (Figure 6). Two cautions apply. Affected populations differ by nearly an order of magnitude across the three events, so mortality counts are not directly comparable, and the three storms differed in track, surge height and landfall timing relative to the tidal cycle. What the series supports is not a controlled comparison but a directional inference that warning and evacuation capability improved substantially over thirteen years, which is consistent with the deliberate build-out of the cyclone preparedness system over that period.

Displacement shows no comparable trajectory, and it is also reported far less consistently. No harmonised south-west-coast displacement figure exists for Sidr, and the Amphan estimates sit on footprints not comparable with those used for Aila. Saha (2017) reports 375,000 people displaced in Khulna and Satkhira following Aila and more than half of them, roughly 200,000, still in temporary accommodation or shelters five months later, both figures taken from a contemporaneous humanitarian assessment rather than from the author's own survey. Saha's own fieldwork records families still living on embankments at Bhitabhanga village, Kamarkhola Union, Dacope, more than four and a half years after landfall, that is, into late 2013. Sadik et al. (2018) assessed the Koyra recovery against 23 indicators of pre-disaster vulnerability reduction and found one fully incorporated, ten completely absent and the remaining twelve only partially included. Those observations are lower bounds on the interval to restoration, not measured durations, because none of them records the point at which return conditions were restored.

The contrast between the two series is the substantive finding of this section. Warning and evacuation improved measurably; the interval between an event and the restoration of conditions permitting return did not, so far as the evidence allows anyone to say. That supports a hypothesis rather than a conclusion: if the interval to restoration is the binding constraint, then variance in displacement burden D is driven more by variance in L than by variance in event severity. The hypothesis needs to be read against the Bangladesh mobility literature, which complicates any simple reading of displacement as movement. The migration-as-adaptation framing treats environmental mobility as a household response to stress (Black et al., 2011), and work in that tradition finds most environmental migration to be temporary, circular or short-distance. Call et al. (2017), using 18 years of demographic surveillance at Matlab, found no long-term effect of riverine flooding on temporary migration. Ayeb-Karlsson et al. (2016) document widespread immobility, and Chen and Mueller (2018) find a graduated, mediated response to salinity rather than a threshold effect. Displacement in the biophysical and policy literatures therefore does not imply a chosen move. Prolonged separation from productive land and functioning infrastructure ends either in return to a degraded environment or in involuntary immobility on marginal ground, and policy attention has concentrated on facilitating movement rather than on shortening the recovery interval or protecting adaptive capacity before an event.

Table 4. Comparative summary of the three cyclone events used as the primary temporal comparison. Infrastructural and recovery findings are given in Sections 4.1 and 5. Affected populations differ by nearly an order of magnitude across the three events, so mortality counts are not directly comparable.

Cyclone	Year	National mortality	Evacuation	Displacement, SW coast	Source
Sidr	2007	3,406	~3.0 million	No harmonised figure reported	GFDRR and Government of Bangladesh (2008)
Aila	2009	190 (3.9 M affected)	Not reported as a single figure	~375,000 in Khulna and Satkhira; >50% still in temporary accommodation at survey	UNDP (2010); Saha (2017); Sadik et al. (2018)
Amphan	2020	26 (10 M affected)	>2.4 M to 14,636 shelters	No harmonised SW-coast figure	NAWG (2020)

Note. Mortality and evacuation figures are national; displacement is reported only for Aila, where a south-west-coast estimate on a defined footprint exists.

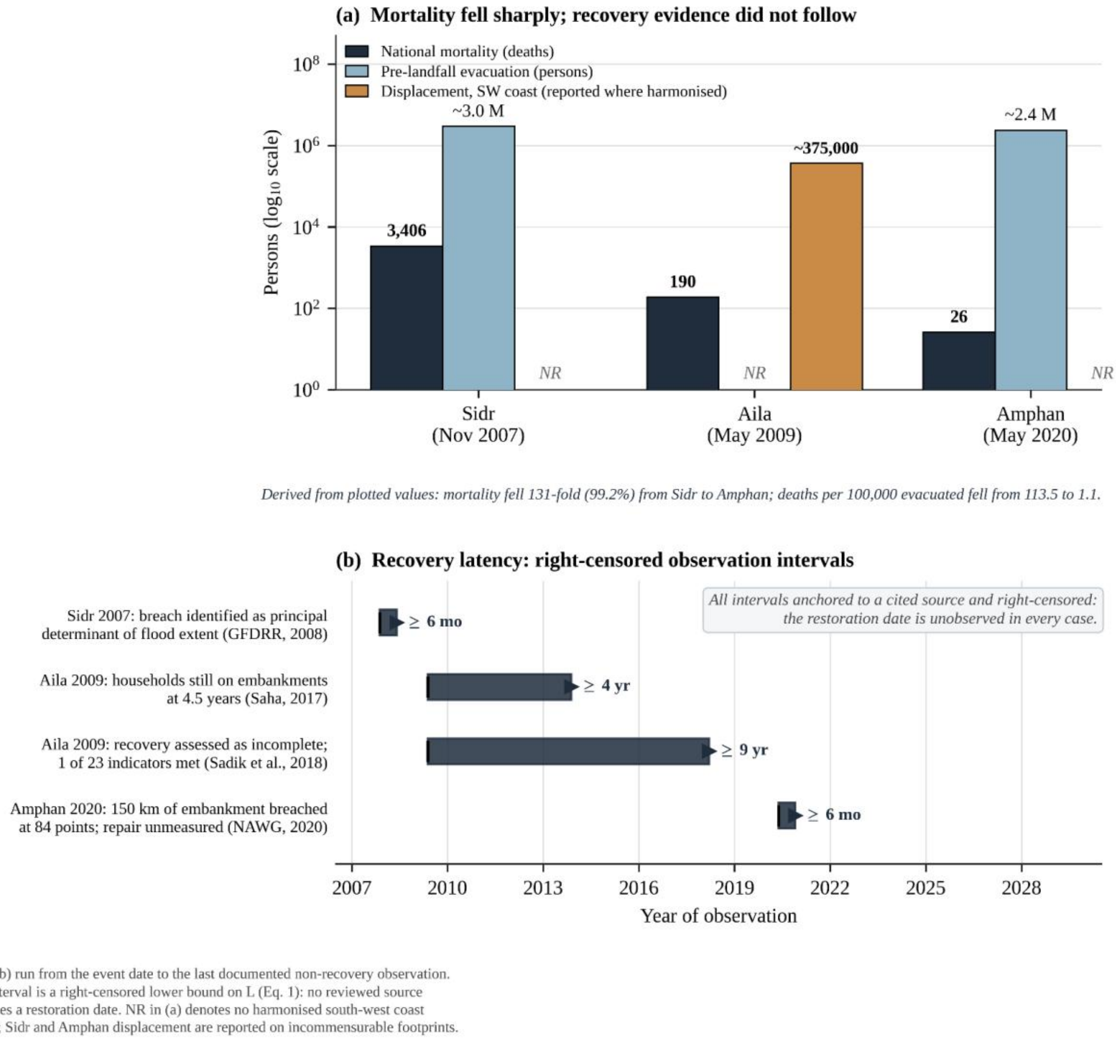

Figure 5. Divergence between cyclone mortality and recovery persistence in south-west Bangladesh, 2007–2020. (a) National mortality and pre-landfall evacuation on a $\log_{10}$ scale; displacement is marked NR for Sidr and Amphan because the available figures sit on non-comparable footprints. (b) Recovery-latency observation intervals, running from the event date to the last documented observation of non-recovery. These are right-censored lower bounds on L (Equation 1), not measured durations; none is closed, because no reviewed source records a restoration date at settlement level.

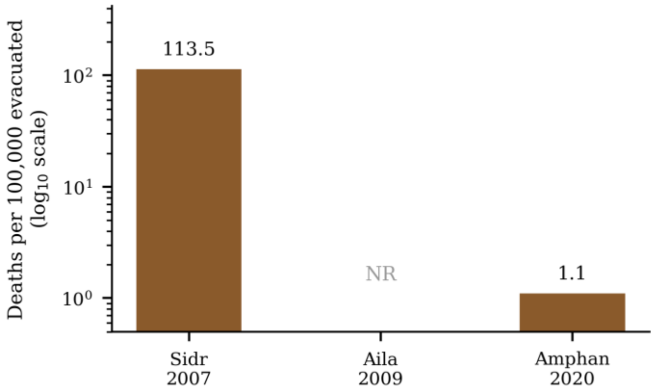

Figure 6. National cyclone mortality normalised by the population evacuated before landfall, derived from Table 4. Normalisation isolates the performance of the warning and evacuation system from the size of the event. Aila is marked NR because evacuation was not reported as a single figure and is not imputed. The fall should be read against Figure 5(b), which shows no corresponding shortening of the interval to restoration.

6. Governance and recognitional injustice

6.1 The Tidal River Management case

The most useful recognitional finding here concerns the timing of technical insight. Donor-supported drainage projects designed in the late 1980s and 1990s were implemented with limited local consultation, did not resolve waterlogging, and prompted sustained protest (Gain et al., 2017). In September 1990 residents made four breaches in the Beel Dakatia polder, reasoning that restored tidal flow would deposit silt inside the beel and raise land elevation. When the crisis intensified after the 1997 monsoon, local people at Beel Bhaina cut the polder embankment along the Hari River in October 1997, acting without effective government support (Gain et al., 2017; Mutahara et al., 2018). Over the following three years the Hari deepened by 10 to 12 m and widened two to threefold, while land inside Beel Bhaina rose by 1.5 to 2 m near the cut point, tapering to roughly 0.2 to 0.5 m at the far end (Gain et al., 2017). The practice was formalised as Tidal River Management (TRM), still evaluated as a sustainability-oriented approach on this coast (Al Masud et al., 2018, 2025).

Residents identified and acted on a hydro-geomorphic mechanism seven years before it entered formal practice, and the measured gain of 1.5 to 2 m near the cut point is of the same order as the deficit poldering produced in the first place. Recognition failure here carried a quantifiable technical opportunity cost, not merely a procedural one. Formalisation has introduced problems of its own: uneven sedimentation, no compensation for landowners inside an operating beel, and difficulty sustaining basin-to-basin rotation (Gain et al., 2017; Mutahara et al., 2018).

6.2 Distributive and epistemic exclusion

The distributive politics of brackish aquaculture form a second, less well quantified case: benefits of gher expansion and its ecological and livelihood costs accrue to different groups, and land acquisition has in places been coercive (Paprocki, 2021; Shameem et al., 2014). The clearest quantification of a recovery-governance deficit comes from Sadik et al. (2018): short-term restoration was prioritised over measures that would have altered the conditions producing the original losses. In an evidence base containing no comparable study, that is the strongest available indication that recovery as practised reproduces rather than reduces the exposure generating displacement, and the weight it can carry is correspondingly limited by being a single-upazila assessment. Where participation is unequal, and water-collection labour and salinity-related health burdens fall disproportionately on women (Sultana, 2010), the information base for decisions narrows along with its legitimacy (Eriksen et al., 2021).

6.3 The legal and institutional gap

No comprehensive entitlement framework specifically addressing climate-induced displacement was identified in the reviewed peer-reviewed and grey literature, although constitutional provisions provide a basis for rights-based policy development (Naser, 2015). This statement is bounded by the search: primary legislation, gazette notifications and the Bangladesh Code were not searched systematically (Section 3.1), so the finding is an absence in the reviewed literature rather than a demonstrated absence in law. It is in any case a policy gap, not a proven causal mechanism. One question is particularly unresolved: which institution should own post-event restoration, land protection and recovery support over the months in which households remain unable to return. That interval is L, as formalised in Section 3.4.

7. Discussion

The most transferable finding here is not about Bangladesh. Vertical land motion estimates for this delta disagree by up to an order of magnitude, and the disagreement is not an empirical dispute awaiting better instruments. Gauge reconstructions, InSAR and stratigraphy sample different depth intervals over different timescales with different footprints, and reporting them as competing estimates of a single parameter is a category error. The consequence is practical and immediate: a polder rehabilitation design keyed to a regional average is keyed to a quantity that does not describe the site it is meant to protect. Any deltaic setting where multiple methods have been applied to the same coast faces this problem, and the remedy, requiring that every reported rate carry its depth interval, timescale and footprint, is cheap.

Within the Bangladesh case, elevation loss is both the best-evidenced pathway and the largest in magnitude. Sediment-core, geodetic and stratigraphic methods converge on a relative deficit of 1.0–1.5 m inside the polders, and the mechanism is not in dispute: interrupting tidal sediment delivery while draining the interior starves the soil column and compacts what remains. What sets this finding apart is that it traces to a dated engineering decision rather than a diffuse forcing, and so to a choice that could have gone otherwise. What remains genuinely open is the spatial distribution of the deficit across the polder network. Nobody has mapped it.

Salinisation inverts that pattern: the direction of travel is settled and the attribution is not. Two sources of disagreement are usually conflated: real spatial heterogeneity in the dominant proximate mechanism, and methodological non-standardisation. Only the second is a defect; the first requires spatially explicit attribution. Compounding both is the endogeneity between aquaculture as a response to salinity and as a driver of it. The health consequence is comparatively well characterised at cohort scale, though the most-cited figure is a modelled exposure rather than a measurement, and the relationship has not been established at population scale or costed into any adaptation appraisal reviewed here.

The Sundarbans question concerns marginal protection lost per hectare of fragmentation rather than the average protection per hectare of area that Menéndez et al. (2020) estimate. The direction of that bias is known; its magnitude is not. Landscape-scale surge modelling incorporating canopy connectivity could estimate it with existing methods and existing data.

The mortality series shows that one institutional capability, warning and evacuation, was built deliberately and now performs well (Figure 6). The recovery series shows no comparable trajectory. Mortality reduction required a system with defined triggers, responsibilities and timelines; no equivalent system governs the repair interval. Of the four pathways examined, recovery latency is measured least, and the evidence rests on documented observations of non-recovery rather than measured durations, so every claim about it here is a lower bound. The measurement gap is nonetheless closable with a conventional panel design.

It is worth stating plainly where this evidence base is strong and where it is not, because the strength is uneven in ways that matter for how the findings should be used. Strong: the existence and approximate magnitude of the polder elevation deficit; the direction of salinisation; the global protective value of mangroves; the fall in cyclone mortality. Moderate: the extent and duration of waterlogging; Sundarbans area loss and shoreline retreat; the association between salinity and migration probability. Weak: attribution of salinisation among its candidate drivers; population-scale health effects of drinking-water salinity; every quantitative statement about governance. Contradictory: absolute subsidence rates, though for the methodological reason set out above rather than because the studies disagree about the world. Missing entirely: any household-level record of when return conditions were restored after any event on this coast, and any spatially explicit map of the elevation deficit across the polder network.

That last absence is where the two literatures meet. The biophysical work establishes that the landscape has been altered in ways that raise exposure, but its outcome variables are hectares and millimetres; the mobility work tracks households but its major panels sit outside the study region. Recovery latency falls at the junction, and measuring it needs both literatures applied to the same units at the same time.

8. Research gaps, priorities and limitations

8.1 Research gaps

The literature converges on a multi-causal interpretation in which hazard, engineering, governance, ecosystem condition and household resources interact, with physical-transformation evidence strongest and governance attribution weakest. Six gaps constrain stronger causal inference and more targeted policy design (Table 5). Figure 7 shows how evidence grade relates to study count across the reviewed streams.

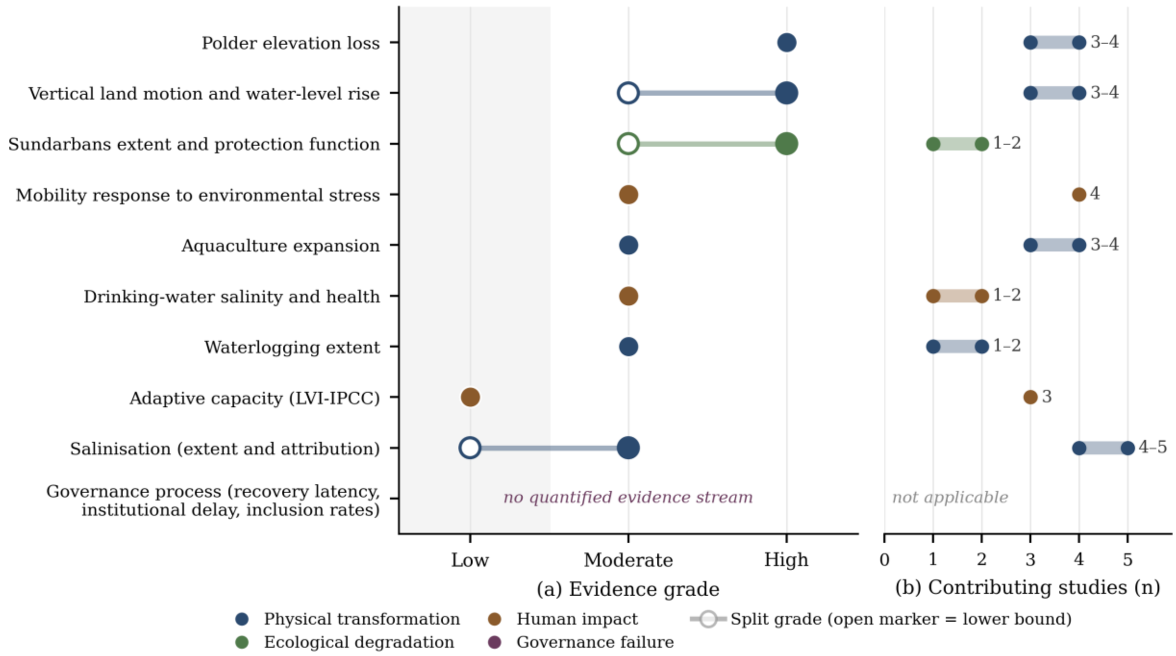

Figure 7. Evidence-strength profile of the reviewed evidence base, tabulated from Table 3. (a) Evidence grade by stream, with split grades drawn from the lower bound (open marker) to the upper bound (filled marker). (b) Number of contributing studies. The governance row carries no marker because no governance stream is quantified anywhere in the reviewed literature. Grade does not track study count: salinisation attribution has the largest study count and the lowest grade, so weak grading there reflects non-standardised operationalisation across individually sound studies, not a thin literature.

Table 5. Research gaps and priority research questions, by class.

Gap class	Specific gap	Why it matters	Research needed	Key literature
Mechanistic	Union-level attribution of displacement to specific drivers	District averages misallocate investment across wide within-district variation in risk	Cause-decomposition studies at union scale, event-specific	Ishtiaque et al. (2017); Auerbach et al. (2015)
Methodological	Non-standardised subsidence baseline	Estimates diverge by up to an order of magnitude, shifting RSLR projections (Figure 4)	Delta-wide harmonised measurement with explicit reporting of depth interval, timescale and footprint	Higgins et al. (2014); Becker et al. (2020); Wilson and Goodbred (2015); Nicholls et al. (2021)
Data	No longitudinal panel of displaced households	Recovery latency is right-censored in effectively all existing observations and cannot be estimated (Equations 1 to 3)	Five-year post-cyclone household panel with defined restoration criteria and survival-analytic treatment of censoring and competing risks	Chen and Mueller (2018); Call et al. (2017); Ayeb-Karlsson et al. (2016)
Health	Population-level dose-response for drinking-water salinity	Modelled dry-season sodium exceedance of 2.5 to 8 times WHO recommended maximum, but the measured biomarker is substantially lower and neither is costed into policy	Cohort studies linking directly measured exposure, health outcomes and mobility at population scale	Khan et al. (2011); Sultana (2010); Lam et al. (2022)
Ecological	Mangrove protection adjusted for fragmentation	Area-based accounting is expected to overstate residual protection where canopy is discontinuous; direction of bias known, magnitude unknown	Landscape-scale surge modelling incorporating canopy connectivity and event-specific attenuation	Menéndez et al. (2020); Jaman et al. (2023)
Governance and legal	No statutory definition of climate-displaced person identified; no institutional owner of recovery latency	If the recovery window is unowned, displaced households may convert to dispossessed. This is a hypothesis, not an established consequence	Legal-institutional design study mapping mandates, financing channels and accountability timelines, including a systematic search of primary legislation	Naser (2015); Kisinger and Matsui (2021); Eriksen et al. (2021)

8.2 Intervention priorities

The hazards and the sediment and water regime of the delta cannot be controlled. A substantial part of the vulnerability described here is nonetheless amenable to reduction, because several of the drivers closest to the impact are set by infrastructure, land-use and governance choices. Table 6 ranks four candidate interventions by expected mechanism, the strength of the evidence supporting that mechanism, and the principal uncertainty attaching to each. The ranking is by evidence strength and mechanism, not by cost-effectiveness, which the reviewed evidence does not permit anyone to assess.

Table 6. Priority ranking of interventions by expected mechanism, evidence strength and principal uncertainty. Ranked by evidence strength and mechanism, not by cost-effectiveness, which the reviewed evidence does not permit anyone to assess.

Intervention	Expected mechanism	Evidence strength	Principal uncertainty
Tidal River Management restoration	Restores sediment deposition inside beels, offsetting polder-induced elevation loss (§6.1)	Moderate to high	Distributional effects of basin selection; compensation for landowners in the receiving beel; long-run sediment supply
Embankment repair governance	Institutionalises the repair window, reducing the recovery latency that converts acute events into extended displacement (§5, §3.4)	Moderate to high for the mechanism; the reduction itself is a hypothesis	No measured baseline for L, so the size of the reducible interval is unknown; institutional mandate unassigned
Mangrove restoration, connectivity-focused	Reduces surge-exposed hinterland by rebuilding canopy connectivity rather than area alone (§4.3)	Moderate	Marginal protection per hectare of restored connectivity not estimated at Sundarbans scale
Planned relocation	Last-resort response where recovery-latency and restoration measures are infeasible	Low	Evidence on destination outcomes for coastal Bangladesh migrants is limited and mixed (Ahsan et al., 2024)

8.3 Limitations

Six constraints bound what this review can claim. Each is stated with its consequence, whatever mitigation was applied, and what would remove it.

The search was English-language only. The consequence is the exclusion of Bengali-language technical reporting, including BWDB and district-level assessments holding primary data with no English equivalent, which is likely to under-represent both engineering documentation and governance process. No mitigation was applied. Bengali-language searching would materially strengthen a subsequent iteration.

Screening and extraction were performed by one person without duplication, so no inter-rater statistic can be reported. The consequence is unquantified selection error. Records of uncertain eligibility were carried forward to full text rather than excluded, which biases residual error toward over-inclusion rather than silent omission. Duplicate screening would remove the limitation entirely.

The review is deliberately selective rather than exhaustive. The search was structured and is documented in full in Supplementary S1, but it was not designed to retrieve every relevant record. The consequence is that the absence of a finding here is not evidence that no study reports it, and this applies with particular force to the statutory claim in Section 6.3.

The evidence is heterogeneous in scale, outcome definition and method, and is not formally pooled, for the four reasons given in Section 3.3. The consequence is that comparisons across streams are qualitative and the evidence grades in Table 3 are ordinal judgements rather than measurements. Harmonised measurement, particularly of subsidence and of composite vulnerability indices, is the precondition for anything stronger.

Several governance and displacement mechanisms are supported by process evidence and convergent case studies rather than by measurement, and Section 6.2 in particular rests on a narrow base. The consequence is that the governance component of the conceptual framework in Figure 2 is the least empirically constrained part of it. Only primary research will change this.

The three-cyclone comparison is not a controlled event study. Track, surge height, landfall timing relative to the tide, and affected population all differ across the three events, and the mortality series is therefore a directional observation rather than an estimate of the effect of the preparedness system. A formal event study with a matched comparison would be required to make the causal claim that the descriptive series only suggests.

The grey literature retained is subject to no external peer review. It is identified as grey at every point of use and was retained only where it reported primary data or an official assessment unavailable in the peer-reviewed literature.

9. Conclusion

Coastal displacement in Khulna, Satkhira and Bagerhat is conventionally described as climate-related. The evidence assembled here supports a more differentiated reading, in which climatic hazards act together with engineered landscape transformation, ecosystem degradation, governance arrangements and household adaptive capacity. The single most robust quantitative finding is that relative elevation loss inside the polders, at roughly 20–30 mm yr^{-1} over approximately 50 years, exceeds the regional water-level trend of about 3 mm yr^{-1} by some seven to ten times.

A second finding is methodological and travels further than the case. Estimates of vertical land motion in this delta differ by up to an order of magnitude because gauge, InSAR and stratigraphic methods sample different depth intervals over different timescales. Treating them as rival estimates of one quantity misreads the disagreement, and reporting each rate with its depth interval, timescale and footprint would resolve it.

The conceptual contribution is to define recovery latency formally and to show why it cannot currently be estimated. Falling mortality across three cyclones demonstrates a substantial improvement in warning and evacuation. Documented observations of continuing non-recovery years after each event suggest no corresponding reduction in the time taken to restore the conditions that permit return, but because restoration is never recorded at household level against a defined criterion, every statement about that interval is a right-censored lower bound. The proposition is falsifiable and should be tested: a panel study that found displacement duration to track hazard severity rather than repair duration would refute it.

On governance, local ecological knowledge has demonstrably produced technically useful insight into drainage, sedimentation and land-surface recovery, seven years ahead of formal practice in the Tidal River Management case. This review does not establish that recognition failure causes maladaptation. It does document how limited participation, unequal benefit distribution and unassigned responsibility for the recovery interval have obstructed the uptake of locally generated solutions.

The delta's hazards and its sediment and water regime cannot be controlled. Several of the drivers closest to the impact can be, because they are set by infrastructure, land-use and governance choices rather than by climate. What the evidence most urgently requires is measurement of the one interval that nobody currently records.

Declarations

Funding. This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Conflict of interest. The author declares no competing interests.

Data availability. No new data were generated. All values reported are taken from, or arithmetically derived from, the cited sources; derivations are documented in Supplementary Material S2.3.

Author contributions. Sole author: conceptualisation, methodology, investigation, formal analysis, visualisation, writing of the original draft, and review and editing.

Use of generative AI. Generative AI tools were used for language editing and for checking internal consistency of numerical values and citations against their sources. No text, data, analysis, citation or conclusion was generated by such tools without author verification against the primary source. The author reviewed and approved all content and takes full responsibility for the integrity and accuracy of the manuscript.

References

Adger, W. N. (2006). Vulnerability. Global Environmental Change, 16(3), 268–281. https://doi.org/10.1016/j.gloenvcha.2006.02.006

Ahsan, M. N., Naim, J., Kumar, P., Okano, N., Alam, A., Chowdhury, S., Islam, M. T., Khatun, A., Nasrin, N., and Vink, K. (2024). Displaced by nature, driven by choice: Exploring the factors influencing environmental migrants' habitat preferences in coastal Bangladesh. Habitat International, 153, 103215. https://doi.org/10.1016/j.habitatint.2024.103215

Akber, M. A., Islam, M. A., Ahmed, M., Rahman, M. M., and Rahman, M. R. (2017). Changes of shrimp farming in south-west coastal Bangladesh. Aquaculture International, 25(5), 1883–1899. https://doi.org/10.1007/s10499-017-0159-5

Al Masud, M. M., Moni, N. N., Azadi, H., and Van Passel, S. (2018). Sustainability impacts of tidal river management: Towards a conceptual framework. Ecological Indicators, 85, 451–467. https://doi.org/10.1016/j.ecolind.2017.10.022

Al Masud, M. M., Värnik, R., Dogot, T., and Azadi, H. (2025). Sustainability index of tidal river management: A framework for measuring water sustainability in coastal areas. Water, 17(5), 648. https://doi.org/10.3390/w17050648

Auerbach, L. W., Goodbred Jr, S. L., Mondal, D. R., Wilson, C. A., Ahmed, K. R., Roy, K., Steckler, M. S., Small, C., Gilligan, J. M., and Ackerly, B. A. (2015). Flood risk of natural and embanked landscapes on the Ganges–Brahmaputra tidal delta plain. Nature Climate Change, 5(2), 153–157. https://doi.org/10.1038/nclimate2472

Awal, M. A. (2014). Water logging in southwestern coastal region of Bangladesh: Local adaptation and policy options. Science Postprint, 1(1), e00038. https://doi.org/10.14340/spp.2014.12A0001

Ayeb-Karlsson, S., van der Geest, K., Ahmed, I., Huq, S., and Warner, K. (2016). A people-centred perspective on climate change, environmental stress, and livelihood resilience in Bangladesh. Sustainability Science, 11(4), 679–694. https://doi.org/10.1007/s11625-016-0379-z

Baethge, C., Goldbeck-Wood, S., and Mertens, S. (2019). SANRA: A scale for the quality assessment of narrative review articles. Research Integrity and Peer Review, 4, 5. https://doi.org/10.1186/s41073-019-0064-8

Barnett, J., and O'Neill, S. (2010). Maladaptation. Global Environmental Change, 20(2), 211–213. https://doi.org/10.1016/j.gloenvcha.2009.11.004

Becker, M., Papa, F., Karpytchev, M., Delebecque, C., Krien, Y., Khan, J. U., Ballu, V., Durand, F., Le Cozannet, G., Islam, A. K. M. S., Calmant, S., and Shum, C. K. (2020). Water level changes, subsidence, and sea level rise in the Ganges–Brahmaputra–Meghna delta. Proceedings of the National Academy of Sciences, 117(4), 1867–1876. https://doi.org/10.1073/pnas.1912921117

Black, R., Bennett, S. R. G., Thomas, S. M., and Beddington, J. R. (2011). Climate change: Migration as adaptation. Nature, 478(7370), 447–449. https://doi.org/10.1038/478477a

Brammer, H. (2014). Bangladesh's dynamic coastal regions and sea-level rise. Climate Risk Management, 1, 51–62. https://doi.org/10.1016/j.crm.2013.10.001

Brown, S., and Nicholls, R. J. (2015). Subsidence and human influences in mega deltas: The case of the Ganges–Brahmaputra–Meghna. Science of the Total Environment, 527–528, 362–374. https://doi.org/10.1016/j.scitotenv.2015.04.124

Call, M. A., Gray, C., Yunus, M., and Emch, M. (2017). Disruption, not displacement: Environmental variability and temporary migration in Bangladesh. Global Environmental Change, 46, 157–165. https://doi.org/10.1016/j.gloenvcha.2017.08.008

Chen, J., and Mueller, V. (2018). Coastal climate change, soil salinity and human migration in Bangladesh. Nature Climate Change, 8(11), 981–985. https://doi.org/10.1038/s41558-018-0313-8

Clement, V., Rigaud, K. K., de Sherbinin, A., Jones, B., Adamo, S., Schewe, J., Sadiq, N., and Shabahat, E. (2021). Groundswell Part 2: Acting on Internal Climate Migration. World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/36248

Eriksen, S., Schipper, E. L. F., Scoville-Simonds, M., Vincent, K., Adam, H. N., Brooks, N., Harding, B., Khatri, D., Lenaerts, L., Liverman, D., Mills-Novoa, M., Mosberg, M., Movik, S., Muok, B., Nightingale, A., Ojha, H., Sygna, L., Taylor, M., Vogel, C., and West, J. J. (2021). Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? World Development, 141, 105383. https://doi.org/10.1016/j.worlddev.2020.105383

Fraser, N. (2000). Rethinking recognition. New Left Review, 3, 107–120.

Gain, A. K., Benson, D., Rahman, R., Datta, D. K., and Rouillard, J. J. (2017). Tidal river management in the south west Ganges-Brahmaputra delta in Bangladesh: Moving towards a transdisciplinary approach? Environmental Science and Policy, 75, 111–120. https://doi.org/10.1016/j.envsci.2017.05.020

GFDRR and Government of Bangladesh. (2008). Cyclone Sidr in Bangladesh: Damage, Loss and Needs Assessment for Disaster Recovery and Reconstruction. Global Facility for Disaster Reduction and Recovery, Dhaka.

Higgins, S. A., Overeem, I., Steckler, M. S., Syvitski, J. P. M., Seeber, L., and Akhter, S. H. (2014). InSAR measurements of compaction and subsidence in the Ganges–Brahmaputra Delta, Bangladesh. Journal of Geophysical Research: Earth Surface, 119(8), 1768–1781. https://doi.org/10.1002/2014JF003117

Ishtiaque, A., Sangwan, N., and Yu, D. J. (2017). Robust-yet-fragile nature of partly engineered social-ecological systems: A case study of coastal Bangladesh. Ecology and Society, 22(3), 5. https://doi.org/10.5751/ES-09186-220305

Jaman, T., Dharanirajan, K., and Sahoo, S. (2023). Are the Sundarbans, the world's largest mangroves region under threat? An ecosystem-based geospatial approach to assess changes past, present, and future in relation to natural and human-induced factors. Land Degradation and Development, 34(1), 125–141. https://doi.org/10.1002/ldr.4448

Khan, A. E., Ireson, A., Kovats, S., Mojumder, S. K., Khusru, A., Rahman, A., and Vineis, P. (2011). Drinking water salinity and maternal health in coastal Bangladesh: Implications of climate change. Environmental Health Perspectives, 119(9), 1328–1332. https://doi.org/10.1289/ehp.1002804

Khan, M. A., Hasan, K., and Kabir, K. H. (2022). Determinants of households' livelihood vulnerability due to climate induced disaster in southwest coastal region of Bangladesh. Progress in Disaster Science, 15, 100243. https://doi.org/10.1016/j.pdisas.2022.100243

Kisinger, C., and Matsui, K. (2021). Responding to climate-induced displacement in Bangladesh: A governance perspective. Sustainability, 13(14), 7788. https://doi.org/10.3390/su13147788

Lam, Y., Winch, P. J., Nizame, F. A., Broaddus-Shea, E. T., Harun, M. G. D., and Surkan, P. J. (2022). Salinity and food security in southwest coastal Bangladesh: Impacts on household food production and strategies for adaptation. Food Security, 14(1), 229–248. https://doi.org/10.1007/s12571-021-01177-5

Magnan, A. K., Schipper, E. L. F., Burkett, M., Bharwani, S., Burton, I., Eriksen, S., Gemenne, F., Schaar, J., and Ziervogel, G. (2016). Addressing the risk of maladaptation to climate change. WIREs Climate Change, 7(5), 646–665. https://doi.org/10.1002/wcc.409

Menéndez, P., Losada, I. J., Torres-Ortega, S., Narayan, S., and Beck, M. W. (2020). The global flood protection benefits of mangroves. Scientific Reports, 10, 4404. https://doi.org/10.1038/s41598-020-61136-6

Mutahara, M., Warner, J. F., Wals, A. E. J., Khan, M. S. A., and Wester, P. (2018). Social learning for adaptive delta management: Tidal River Management in the Bangladesh delta. International Journal of Water Resources Development, 34(6), 923–943. https://doi.org/10.1080/07900627.2017.1326880

Naser, M. M. (2015). Climate change and migration: Law and policy perspectives in Bangladesh. Asian Journal of Law and Society, 2(1), 35–53. https://doi.org/10.1017/als.2014.7

NAWG. (2020). Bangladesh: Cyclone Amphan Joint Needs Assessment, 31 May 2020. Need Assessment Working Group, Humanitarian Coordination Task Team, Dhaka.

Nicholls, R. J., Lincke, D., Hinkel, J., Brown, S., Vafeidis, A. T., Meyssignac, B., Hanson, S. E., Merkens, J.-L., and Fang, J. (2021). A global analysis of subsidence, relative sea-level change and coastal flood exposure. Nature Climate Change, 11(4), 338–342. https://doi.org/10.1038/s41558-021-00993-z

Paprocki, K. (2021). Threatening Dystopias: The Global Politics of Climate Change Adaptation in Bangladesh. Cornell University Press, Ithaca, NY.

Rahman, A. Z., Shamsudduha, M., Haq, M. I., Hanif, M., Islam, M. S., Islam, S. S., Biswas, A., and Taylor, R. G. (2026). Soil and river water salinity dynamics in coastal Bangladesh. Scientific Reports, 16, 1044. https://doi.org/10.1038/s41598-025-30639-5

Rigaud, K. K., de Sherbinin, A., Jones, B., Bergmann, J., Clement, V., Ober, K., Schewe, J., Adamo, S., McCusker, B., Heuser, S., and Midgley, A. (2018). Groundswell: Preparing for Internal Climate Migration. World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/29461

Sadik, M. S., Nakagawa, H., Rahman, M. R., Shaw, R., Kawaike, K., and Fujita, K. (2018). A study on Cyclone Aila recovery in Koyra, Bangladesh: Evaluating the inclusiveness of recovery with respect to predisaster vulnerability reduction. International Journal of Disaster Risk Science, 9(1), 28–43. https://doi.org/10.1007/s13753-018-0166-9

Saha, S. K. (2017). Cyclone Aila, livelihood stress, and migration: Empirical evidence from coastal Bangladesh. Disasters, 41(3), 505–526. https://doi.org/10.1111/disa.12214

Schipper, E. L. F. (2020). Maladaptation: When adaptation to climate change goes very wrong. One Earth, 3(4), 409–414. https://doi.org/10.1016/j.oneear.2020.09.014

Schlosberg, D. (2004). Reconceiving environmental justice: Global movements and political theories. Environmental Politics, 13(3), 517–540. https://doi.org/10.1080/0964401042000229025

Shameem, M. I. M., Momtaz, S., and Rauscher, R. (2014). Vulnerability of rural livelihoods to multiple stressors: A case study from the south-west coastal region of Bangladesh. Ocean and Coastal Management, 102(A), 79–87. https://doi.org/10.1016/j.ocecoaman.2014.09.002

SRDI. (2010). Saline Soils of Bangladesh. Soil Resource Development Institute, Ministry of Agriculture, Government of the People's Republic of Bangladesh, Dhaka.

Sultana, F. (2010). Living in hazardous waterscapes: Gendered vulnerabilities and experiences of floods and disasters. Environmental Hazards, 9(1), 43–53. https://doi.org/10.3763/ehaz.2010.SI02

Syvitski, J. P. M., Kettner, A. J., Overeem, I., Hutton, E. W. H., Hannon, M. T., Brakenridge, G. R., Day, J. W., Vörösmarty, C. J., Saito, Y., Giosan, L., and Nicholls, R. J. (2009). Sinking deltas due to human activities. Nature Geoscience, 2(10), 681–686. https://doi.org/10.1038/ngeo629

Tessler, Z. D., Vörösmarty, C. J., Grossberg, M., Gladkova, I., Aizenman, H., Syvitski, J. P. M., and Foufoula-Georgiou, E. (2015). Profiling risk and sustainability in coastal deltas of the world. Science, 349(6248), 638–643. https://doi.org/10.1126/science.aab3574

Turner II, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., Eckley, N., Kasperson, J. X., Luers, A., Martello, M. L., Polsky, C., Pulsipher, A., and Schiller, A. (2003). A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences, 100(14), 8074–8079. https://doi.org/10.1073/pnas.1231335100

UNDP. (2010). Cyclone Aila: Joint UN Multi-Sector Assessment and Response Framework. United Nations Development Programme, Dhaka.

Wilson, C. A., and Goodbred Jr, S. L. (2015). Construction and maintenance of the Ganges–Brahmaputra–Meghna delta: Linking process, morphology, and stratigraphy. Annual Review of Marine Science, 7, 67–88. https://doi.org/10.1146/annurev-marine-010213-135032

Appendix. Supplementary Material

Manufactured vulnerability in the Ganges–Brahmaputra–Meghna delta: engineered drivers and coastal displacement in south-west Bangladesh. A critical review

Arghya Protik Chowdhury

This appendix forms part of the same PDF as the manuscript above, in line with EarthArXiv's single-file requirement. Part S1 documents the review protocol in the detail that the compressed Methods section points to: the verbatim search strings, the eligibility criteria applied at full-text screening, the grey-literature sources consulted, the data-extraction template and the evidence-classification scheme. Part S2 reports descriptive statistics of the assembled evidence base and the derivations behind the quantitative figures in the main text. Every value here is taken from, or arithmetically derived from, figures already reported and cited in the main text; no new data are introduced.

Part S1. Review protocol

S1.1 Verbatim search strings

Databases were searched for the period 2010 to 2026. Block 1 specifies place, Block 2 mechanism and Block 3 outcome, with Boolean OR within blocks and AND between them.

Table S1.1. Verbatim search strings, field tags and database-specific limits.

Source	Field / syntax	String and limits
Web of Science Core Collection	TS =	(("coastal Bangladesh" OR "south-west* Bangladesh" OR "southwest* Bangladesh" OR Khulna OR Satkhira OR Bagerhat OR "Ganges-Brahmaputra" OR "GBM delta" OR Sundarban*) AND (polder* OR embankment* OR "tidal river management" OR salinis* OR saliniz* OR salinity OR shrimp OR gher OR aquaculture OR subsidence OR waterlog* OR "water logging" OR mangrove* OR accretion) AND (displac* OR migrat* OR mobilit* OR immobilit* OR relocat* OR vulnerab* OR maladapt* OR "adaptive capacity" OR recovery OR governance))
Scopus	TITLE-ABS-KEY =	The same three-block string, with the additional limits DOCTYPE(ar OR re OR ch) and LANGUAGE(English).
Google Scholar	Free text	Simplified two-block strings, because the platform does not reliably support field tags or long Boolean expressions. The first 100 results per string were screened by title, following the convention that relevance ranking degrades beyond that point. Used to identify grey literature and recent work not yet indexed elsewhere, not as a primary systematic source.

S1.2 Eligibility criteria applied at full-text screening

Reported in full because selectivity is the principal methodological vulnerability of a critical review: an unstated selection rule cannot be distinguished from selection bias.

Table S1.2. Eligibility criteria applied at full-text screening.

Dimension	Included	Excluded
Setting	Khulna, Satkhira or Bagerhat districts; or the wider GBM delta where the finding bears on the south-west coast	Other Bangladesh regions with no south-west relevance; other deltas except where used for explicit comparative framing
Phenomenon	Polder or embankment effects; salinisation; aquaculture conversion; mangrove change; subsidence or accretion; displacement, migration or immobility; adaptation governance	Studies of hazard meteorology alone with no land, livelihood or mobility outcome
Outcome	A measured or clearly interpretable quantity, or a documented governance process with an identifiable mechanism	Descriptive commentary or opinion with no empirical or process basis
Design	Empirical studies of any design; systematic and critical reviews; official damage, needs or inventory assessments	Editorials, conference abstracts without full text, predatory-venue output, undergraduate theses
Transparency	Method reported in sufficient detail to judge spatial scale, temporal coverage and measurement basis	Findings reported without a statement of how they were derived
Date	2010 to 2026 for database searching; earlier work admitted via citation chasing where it establishes a mechanism or baseline	Superseded editions where a later version exists
Language	English	Non-English, including Bengali-language technical reporting (see Section 8.3 of the main text)

S1.3 Grey-literature sources consulted

Grey literature was searched by named source rather than by string, because the relevant material is issued by identifiable institutions and is not consistently indexed. It was retained only where it reported primary data or an official damage or needs assessment unavailable in the peer-reviewed literature, and it is identified as such at every point of use in the main text. This list does not include a systematic search of primary legislation, gazette notifications or the Bangladesh Code, which bounds the legal claims in Section 6.3 of the main text.

- Global Facility for Disaster Reduction and Recovery (GFDRR)
- Soil Resource Development Institute (SRDI)
- Bangladesh Water Development Board (BWDB)
- Need Assessment Working Group, Humanitarian Coordination Task Team (NAWG)
- Internal Displacement Monitoring Centre (IDMC)
- UNDP Bangladesh
- The World Bank

Two of these sources yielded no retained record. BWDB material located during the search was either superseded by the peer-reviewed measurements used in Section 4.1 or available only in Bengali, and IDMC estimates for this coast were not disaggregated to a footprint comparable with the event-specific assessments already retained. Both are listed here because they were searched, not because they contributed a citation.

S1.4 Data-extraction template

Holding unit and measurement method as separate fields is what makes the method-divergence analysis in Section 4.1 and Figure 3 of the main text possible: it reveals when two estimates of nominally the same quantity describe different physical measurements.

Table S1.4. Structured data-extraction fields.

Field	Definition	Permitted values or notes
Bibliographic details	Author, year, venue, DOI	Free text
Study design	Design of the primary study	Empirical, review, official assessment
Spatial scale and named sites	Level of observation and place names	Union, upazila, district, delta, national, global
Temporal coverage	Observation window	Start and end year
Sample size or spatial extent	n, or area covered	Numeric with unit
Measured variable and unit	The quantity as reported	Numeric with unit; unit recorded separately
Reported value, range or effect estimate	As reported, not rescaled	Numeric
Measurement method	Instrument or inference route	Gauge, InSAR, stratigraphic, survey, panel, remote sensing, ethnographic
Range descriptor	What a reported range represents	Confidence interval / inter-site / inter-study / seasonal / unspecified
Modelled or measured	Whether the reported value was directly measured or derived from an assumption applied to other data	Measured / modelled / derived
Stated limitations	As stated by the source authors	Free text
Evidence category	Classification in Table S1.5	Physical transformation / Ecological degradation / Human impact / Governance failure

Ranges recorded as "unspecified" appear as such in Table 3 of the main text and are not treated as uncertainty bounds. The modelled-or-measured field is what allows Table 3 to distinguish the modelled sodium intake range from the measured urinary biomarker reported by the same study.

S1.5 Evidence classification scheme

Table S1.5. Evidence classification used to structure the synthesis in Sections 4 to 6 of the main text.

Evidence category	Quantitative indicator types	Where applied in the main text
Physical transformation	Elevation loss (m); elevation deficit rate (mm yr^{-1}); subsidence rate (mm yr^{-1}); land-use conversion (km^2 or ha)	§4.1 (polders); §4.2 (aquaculture conversion)
Ecological degradation	Mangrove area loss (ha); shoreline erosion rate (m yr^{-1}); protection-value loss (USD)	§4.3 (Sundarbans)
Human impact	Displacement counts; migration probability; exposure exceedance ratios; dose-response measures	§4.2 (health); §5 (cyclone comparison)
Governance failure	Recovery latency (months); institutional delay; inclusion rates in planning (%)	§6 (TRM, distributive exclusion, legal gap)

Part S2. Descriptive statistics of the evidence base and figure derivations

This part reports the descriptive structure of the assembled evidence base and documents every derivation behind the quantitative figures in the main text. Nothing here is inferential: no new parameter is estimated and no pooling is performed, for the reasons given in Section 3.3 of the main text. Values labelled "derived" are arithmetic on figures reported by the cited sources and carry the same caveats as those sources.

S2.1 Distribution of evidence grades across the evidence base

Table S2.1. Distribution of evidence grades by category, derived by tabulation from Table 3 of the main text.

Evidence category	Streams in Table 3	High	Moderate	Low	Split grade	Median n studies
Physical transformation	5	2	4	1	2	3.5
Ecological degradation	1	1	1	0	1	1.5
Human impact	3	0	2	1	0	3.0
Governance failure	0	0	0	0	0	—
All categories	9	3	7	2	3	3.5

Streams carrying a split grade are counted once in each of the two grade columns they span, so grade columns sum to more than the stream count. Median n uses the midpoint of each range reported in the "Studies (n)" column of Table 3. The governance row is empty by construction, not by oversight: no governance stream reaches the quantitative threshold for inclusion in the evidence matrix, which is itself the asymmetry reported in Sections 3.2 and 8.1 of the main text.

Two features of the table carry the substantive weight. First, only one of nine streams carries an unsplit High grade. The two other streams that reach High do so through a component that is either a regional aggregate, in the case of the 101-gauge water-level reconstruction, or a global valuation, in the case of mangrove flood-protection benefits. Neither is a local causal claim about this coast. Second, the two streams graded Low, salinisation attribution and adaptive-capacity measurement, are among the better-populated in study count: salinisation attribution has the largest count of any stream in the matrix. Weak grading there is therefore not a consequence of a thin literature. It reflects non-standardised operationalisation across studies that are individually sound, which is a different problem and requires a different remedy.

S2.2 Where the figures are

The charts that visualise these quantities are placed in the main text rather than here, so that the reader meets each one at the point in the argument it supports. Figure 3 of the main text plots the method-dependence of vertical land motion estimates. Figure 4 shows drinking-water sodium exposure against WHO dietary guidance together with the Sundarbans area-loss and shoreline-erosion trajectories. Figure 6 shows national cyclone mortality normalised by the population evacuated before landfall. Figure 7 plots the evidence-strength profile tabulated in Table S2.1 above. This section records only the derivations behind them.

S2.3 Derivations

Table S2.2. Derivations behind every quantity labelled "derived" in the main-text figures.

Quantity plotted	Derivation	Source values
Exceedance ratio, drinking-water sodium	ER = I_Na / WHO_Na (Equation 4 of the main text). Because intake is reported directly by the source, ER is computable from the reported range without separate estimation of concentration and ingestion rate, and no term normalised by body weight is introduced: the reference value is a per-person dietary recommendation, so numerator and denominator are both per person per day. ER is an exceedance against a population dietary recommendation, not a toxicological hazard quotient; sodium has no conventional reference dose.	Modelled intake 5–16 g d^{-1} in the dry season, obtained by applying an assumed consumption of 2 L d^{-1} to water-salinity records for 1998–2000 (Khan et al., 2011). WHO recommended maximum for adults ~2 g d^{-1}. ER = 2.5 to 8.
Measured urinary sodium, plotted alongside the modelled range	Not derived. Reported directly by the same study as a 24-hour urinary excretion mean with range, and plotted unaltered so that the modelled and measured quantities can be compared. It reflects total dietary sodium rather than drinking water alone, and is therefore not a validation of the modelled drinking-water figure.	3.4 g d^{-1}, range 0.4–7.7, n = 343 pregnant women, Dacope, dry season October 2009 to March 2010 (Khan et al., 2011).
Deaths per 100,000 evacuated	National mortality divided by the population evacuated before landfall, times 100,000. Aila is not computed because evacuation was not reported as a single figure, and it is recorded as not reportable rather than imputed.	Sidr: 3,406 deaths, ~3.0 million evacuated, giving ~113.5. Amphan: 26 deaths, >2.4 million evacuated, giving ~1.1. Both from Table 4 of the main text.
Shoreline erosion acceleration	Ratio of the two end-point rates reported for consecutive epochs.	−0.90 m yr^{-1} (1980–2000) and −5.81 m yr^{-1} (2000–2020), giving a 6.5-fold increase (Jaman et al., 2023).
Polder elevation deficit rate	Reported deficit divided by the interval since embankment closure. A differential against natural-island accretion, not an absolute subsidence rate; the denominator is approximate because construction was phased through the 1960s and 1970s.	1.0–1.5 m over approximately 50 years, giving 20–30 mm yr^{-1}. The deficit is reported by Auerbach et al. (2015) alone; Higgins et al. (2014) and Wilson and Goodbred (2015) support the mechanism rather than the value. Plotted in Figure 3 of the main text.
Ratio of deficit rate to regional water-level trend	Derived deficit rate divided by the regional water-level trend over a comparable period.	20–30 mm yr^{-1} against ~3 mm yr^{-1} (Becker et al., 2020), giving a factor of approximately 7 to 10.
Median study count by category	Midpoint of each range reported in the "Studies (n)" column of Table 3, then the median across streams in the category.	Ranges as reported in Table 3 and plotted in Figure 7(b) of the main text.

No derivation introduces a value that is not already reported and cited in the main text.

S2.4 What the figures do not show

No figure estimates recovery latency. Restoration intervals appear in the reviewed literature only anecdotally and at landscape scale, and no source records restoration at household or settlement level against a defined criterion, so the quantity is right-censored in effectively every observation. No figure pools estimates across methods, for the four reasons set out in Section 3.3 of the main text. And no figure attributes displacement to a specific driver at union scale, which remains the first of the six research gaps in Table 5.