A systems perspective for climate adaptation in deltas

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Deltas are complex and are among the most vulnerable landforms under climate change. Studying them collectively highlights common stressors that drive their most significant challenges. A holistic conceptual framing of a delta and its feeding river basin is fundamental to effective adaptation planning.

The world's river deltas are geologically young landforms, dating back to the mid-Holocene and the post-glacial sea-level stabilisation. Since then, deltas have hosted unique ecosystems and attracted human settlements due to the agricultural potential of their fertile soils, suitability for fisheries, and trade opportunities with access to large rivers and open seas[1]. Today, approximately 500 million people live within or adjacent to delta systems[1]. However, the world's largest deltas are under significant stress due to climatic and anthropogenic factors[2,3]. Likely global sea-level rise (SLR) projections range between 32 and 101 cm (SSP1-2.6 to SSP5-8.5) by 2100[4], but could be more extreme depending on the response of the Antarctic ice sheet, threatening low-lying delta systems. Climate change also amplifies the effects of droughts, floods, and declining water quality, posing increasing risks to human health and well-being. Approximately, 76 million people are directly exposed to a 100-year flood event from tropical cyclone activity globally, of which more than 40% live in deltas[5].

Deltas are also impacted by more direct anthropogenic stressors. Fluvial sediment supply to the world's deltas has been reduced by 30% on average, mainly due to upstream impoundments and downstream interventions, such as embanking, channelisation, and sand mining, further exacerbating deltaic exposure to climate hazards[6]. These interventions not only reduce or fully stop delta aggradation, they often lead to substantial morphological changes, such as riverbed, riverbank and coastal erosion, as well as shifts in hydrological regimes and elevation loss with accelerated relative sea-level rise (rSLR) due to land subsidence and lack of sedimentation. These morphological changes further expose the low-lying deltaic landforms to more flooding, salinisation, ecosystem loss, and inundation. Adaptation efforts to climate change and rSLR must therefore systematically incorporate local and regional drivers of change[7], that are nestled within a holistic and systematic approach that targets various interacting drivers across a range of spatial and temporal scales[8].

The concept of scale is of paramount importance when assessing the interacting driving forces. For example, rainfall is often driven by global patterns, but the resulting runoff is highly influenced by regional and local land use patterns and anthropogenic interventions and activities. Similarly, localised erosion can be attributed to changes in upstream fluvial sediment and discharge patterns driven by natural or human-induced shifts in the hydrological regime, but also by local interventions, such as sand mining. These contributing factors interact across different scales, and in the Ganges-Brahmaputra-Meghna (GBM) Delta, such interacting processes have been shown to transcend across four key scales: global, regional (catchment), deltaic, and community [9]. In many deltas, long-term strategic policy development is also defined within national administrative boundaries, as observed in the Mekong Delta[10], adding another scale of enquiry. Importantly, the interacting driving forces do not only operate at the abovementioned scales, but also across them; disentangling these complex dynamics enables the identification of context-specific challenges in every delta, a fundamental first step in defining appropriate adaptation solutions.

Critical hazards in deltas

Flooding, saltwater intrusion into surface and groundwater systems, land subsidence (and associated rSLR), sediment starvation, riverbed, riverbank and coastal erosion, hydrological regime shifts, water pollution, and the loss of biodiversity are among the most pressing hazards that threaten the livelihoods of millions of deltaic residents. Global climate change instigates changes that impact deltas and their natural balance via the shifting of hydrological and/or sediment regimes and fluctuations in elevation. Contrastingly, anthropogenic activities and interventions within the natural catchment-river-delta system typically occur at local scales but have far-reaching impacts. These anthropogenic drivers increasingly dominate the overall contemporary changes observed in delta systems worldwide (Figure 1).

For example, the vast majority of catchments are currently influenced by dams[6]. Although dams are local interventions, they interrupt the flow of water and sediment from upstream catchments to downstream reaches, significantly impacting the natural capacity of deltas to maintain subaerial and subaqueous morphological stability. Other local and delta-scale drivers, such as sand mining[10], groundwater extraction[8], poldering by reclaiming low-lying areas[11], and channel fixing, can be effective in meeting resources demand or addressing certain challenges at specific points in time and space; however, depending on the local conditions, these drivers can contribute to elevation loss and riverbed incision, enabling further ingression of the saltwater front, which can exacerbate soil and ecosystem degradation and impact water security and socio-economic development.

To develop effective adaptation plans tackling both the biophysical and socio-economic hazards in deltas, it is essential to map and develop a semi-quantifiable understanding of the contributions from the range of drivers at different spatial and temporal scales. Such analyses should define the most important processes and required models to understand the problems as the very first step in developing adaptation strategies; a step that is often absent or incomplete. We apply this to the cases of three mega-deltas – the Mekong, Ganges-Brahmaputra-Meghna, and the Nile– in a semi-quantitative manner based on existing knowledge (Box-1). This demonstrates how this framework can iteratively guide research or facilitate dialogue throughout the delta adaptation planning and implementation process. Specific solutions, such as those emerging from communities, stakeholders, experts, or government agencies, can be evaluated against this holistic understanding that addresses direct and indirect impacts of measures or strategies at different scales. Importantly, solutions or enabling conditions at smaller regional, national or local scales may have potentially higher implementation likelihood.

A systems perspective for adaptation

While climate change threatens the world's deltas, anthropogenic drivers - largely reflected in sediment starvation, resource extraction (sand, groundwater, hydrocarbon, etc.), profound land-use change, and hydrological regime shifts - can outpace climate change in the short to medium term. Nearly all local anthropogenic drivers result in measurable impacts within years to decades, emphasising the significance and relevance of local and regional drivers for effective and timely climate adaptation and policy development. The examples of the three deltas (Box-1) highlight the sensitivity of delta dynamics to the often uncertain local to regional socio-economic and geopolitical drivers, and the invaluable benefits of preserving the geomorphic stability of both the subaqueous and subaerial deltas.

Deltaic landscapes are highly complex, shaped by many interacting processes. Addressing climate-driven stressors of deltas in isolation, and disregarding parallel anthropogenic processes, can lead to an incomplete understanding, negative ripple effects elsewhere, and eventually insufficient socio-political drive to tackle the root causes of dominant drivers. The interconnectedness of biophysical and socio-economic processes in deltas makes it an extremely challenging landscape for decision makers, as implementing a measure in one part of the system can have unexpected consequences across the whole system, spanning spatial and temporal scales, as well as sectors.

In the context of global climate change and anthropogenic pressures, developing effective adaptation strategies for deltas (or any complex environmental system for that matter) is built on three pillars: 1) sound scientific system understanding, 2) informed communities (science-society interaction), and 3) political representation (research uptake and public interest). The first pillar requires a holistic, integrated system understanding to inform resilience-building decision making in the society-governance realm of interaction. This recognition is vital because the *implementation likelihood* and the potential on-the-ground impact increases at smaller scales. While it is essential to aim for multi-national initiatives and societal movements, the likelihood of success, and pace of implementation increases at smaller scales. Swift enforcement of effective policies may portray a possible sustainable future for deltas; inertia in translating new policy to effective adaptation measures can lead to further irreversible degradation of these vulnerable coastal systems and their associated socio-economic structures.

The key to sustainable and effective adaptation planning is to minimise disintegration across disciplines (e.g., various biophysical or socio-economic fields), temporal scales, and local, national, and international borders. A holistic understanding of a delta and its feeding river basin can facilitate constructive dialogues among key stakeholders and provide a basis for defining delta-specific adaptation strategies. Furthermore, it can highlight local/regional options with higher implementation likelihood nestled within a longer-term vision that provide more immediate benefits towards increasing longer-term climate resilience. It is critical that adaptation measures implemented today pave the way for scaling up and do not foreclose the future sustainability of deltaic systems.

Author's contributions

SE, as the corresponding author, coordinated various input from colleagues, conceptualized the commentary and visualizations, and led the authorship. GOE and RJN conceptualized the commentary, reviewed various versions and contributed to the text. AP, KS and PSJM reviewed the commentary, contributed to the text and helped conceptualizing the visualizations. KS reviewed the article and contributed to the text.

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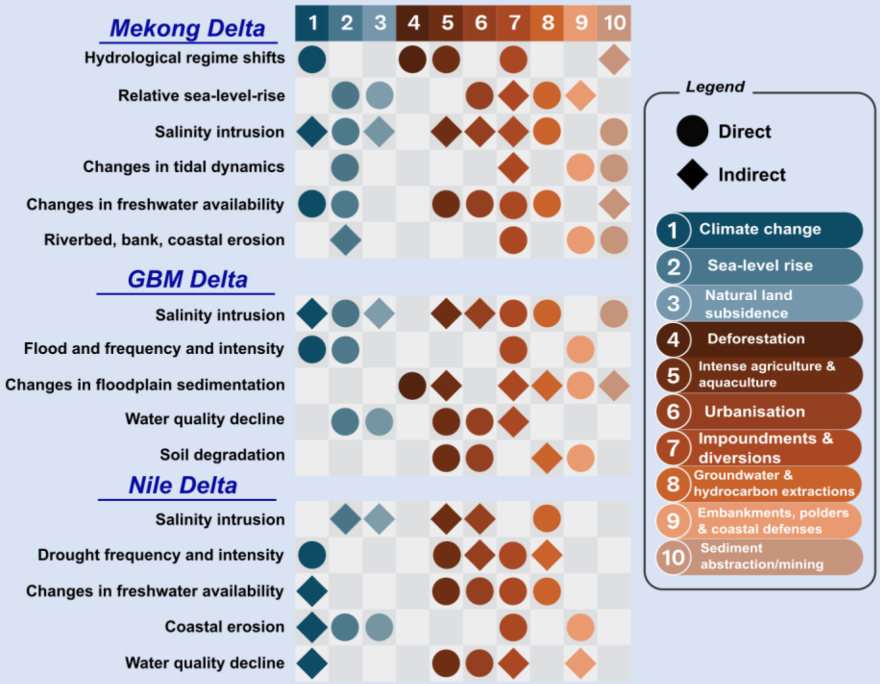
Competing interest statement

We, hereby, confirm that the authors declare no financial or non-financial competing interests.

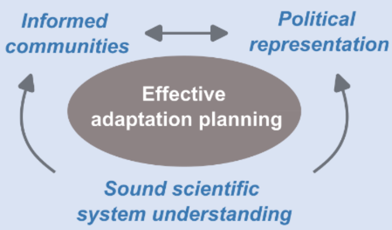
Box-1: *Cases of three mega-deltas*

We identified ten key drivers of change in deltas worldwide and elaborated on their different spatio-termporal impacts (Figure 2). Here, we utilise this framework in a semi-quantitative manner, based on existing research, for three globally important and relatively well-studied delta systems: the Mekong, the Ganges-Brahmaputra-Meghna (GBM), and the Nile deltas.



In the Mekong, upstream sediment entrapment and downstream sand mining leads to riverbed, riverbank, and coastal erosion, overall accelerated rSLR[12], changes in the hydrological cycle and increased salinity intrusion[13]. To date, only 5% of the observed salinity increase in the delta is driven by rSLR, with 95% driven by riverbed erosion due to anthropogenic sediment starvation[10]. Similar trends are portrayed in the cases of the GBM and the Nile deltas. In the GBM Delta, for instance, the reduced freshwater flows through the south-western part of Bangladesh have worsened salinity intrusion, which is contaminating surface and groundwater systems[14]. Consequently, rice production has shifted to aquaculture, further contaminating soils and has led to socio-economic disparities. In the Nile Delta, inefficient management of freshwater resources has resulted in similar trends of profound salinisation of surface and groundwaters, resulting in a water crisis and major disruption to the agriculture sector[15]. The development of upstream reservoirs in the Nile basin has dampened the natural hydrological variability of flows, which has exacerbated the risk of more extreme droughts, especially in the face of climate change. Hence, existing national and transboundary water management systems do not guarantee long-term water security for the delta.

The three examples highlight the sensitivity of the hydrogeomorphic stability of deltas to local and regional drivers of change. This stability is at the very core of building long-term resilience of deltaic socio-environmental systems to climate and anthropogenic change. A comprehensive systems understanding must lay the foundation of a constructive dialogue between the governance system and the communities it represents to help in developing effective adaptation and mitigation strategies.



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Captions for figures

Figure 1, **Climatic and anthropogenic drivers of change in the world's deltas**. Panel (A) provides a 3D view of the system, and panel (B) depicts a conceptual cross-section from the sea to the mountains, featuring the surface and groundwater variability along the river.

Figure 2, **A conceptual framework to support decision-makers in addressing biophysical and societal challenges in deltas**. Key drivers of change in river deltas divided into climate/natural and anthropogenic processes at various spatial and temporal scales (A), and their predominant direct and indirect impacts on the biophysical and socio-economic systems (tables on the right). These drivers are influenced by and shape the community and the governance systems. This contributes to potentially higher implementation likelihood at smaller scales of sub-national to national level (B). Note that sea-level rise is driven by climate change, but here we isolate it as a distinct phenomenon, while climate change in its totality impacts many different environmental and social indicators.