AGU ADVANCING EARTH AND SPACE SCIENCES

Reviews of Geophysics

REVIEW ARTICLE
10.1029/2024RG000846

Coastal Flooding in Asian Megadeltas: Recent Advances, Persistent Challenges, and Call for Actions Amidst Local and Global Changes

M. Becker[1], K. Seeger[2,3], A. Paszkowski[4], M. Marcos[5], F. Papa[6], R. Almar[6], P. Bates[7], C. France-Lanord[8], Md S. Hossain[9], Md J. U. Khan[6], M. A. Karegar[10], M. Karpytchev[1], N. Long[1], P. S. J. Minderhoud[3], J. Neal[7], R. J. Nicholls[11], and J. Syvitski[12]

[1]Littoral Environnement et Sociétés (LIENSs), UMR 7266 CNRS, La Rochelle Université, La Rochelle, France, [2]Institute of Geography, University of Cologne, Cologne, Germany, [3]Soil Geography and Landscape Group, Wageningen University & Research, Wageningen, The Netherlands, [4]Environmental Change Institute, University of Oxford, Oxford, UK, [5]IMEDEA (UIB-CSIC), Esporles, Spain, [6]Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS), Université Toulouse III, CNRS, CNES, IRD, Toulouse, France, [7]School of Geographical Sciences, University of Bristol, Bristol, UK, [8]Centre de Recherches Pétrographiques et Géochimiques, Université de Lorraine, CNRS UMR 7358, Vandoeuvre-lès-Nancy, Vandoeuvre, France, [9]School of Social & Environmental Sustainability, University of Glasgow, Dumfries, Scotland, [10]Institute of Geodesy and Geoinformation, University of Bonn, Bonn, Germany, [11]Tyndall Centre for Climate Change Research, University of East Anglia (UEA), Norwich, UK, [12]INSTAAR and CSDMS, University of Colorado, Boulder, CO, USA

Key Points:

- Urgent action is needed to address data gaps in monitoring coastal flooding in Asian megadeltas
- Integrated approaches, including in situ data, remote sensing and advanced modeling, are needed to understand coastal flooding impacts
- Unprecedented changes in Asian megadeltas call for integrated studies; decisions made today shape deltaic sustainability for decades

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

M. Becker,
mbecker@univ-lr.fr

Citation:

Becker, M., Seeger, K., Paszkowski, A., Marcos, M., Papa, F., Almar, R., et al. (2024). Coastal flooding in Asian megadeltas: Recent advances, persistent challenges, and call for actions amidst local and global changes. *Reviews of Geophysics*, *62*, e2024RG000846. https://doi.org/10.1029/2024RG000846

Received 18 APR 2024
Accepted 23 NOV 2024

Abstract Asian megadeltas, specifically the Ganges-Brahmaputra-Meghna, Irrawaddy, Chao Phraya, Mekong, and Red River deltas host half of the world's deltaic population and are vital for Asian countries' ecosystems and food production. These deltas are extremely vulnerable to global change. Accelerating relative sea-level rise, combined with rapid socio-economic development intensifies these vulnerabilities and calls for a comprehensive understanding of current and future coastal flood dynamics. Here we provide a state-of-the-art on the current knowledge and recent advances in quantifying and understanding the drivers of coastal flood-related hazards in these deltas. We discuss the environmental and physical drivers, including climate influence, hydrology, oceanography, geomorphology, and geophysical processes and how they interact from short to long-term changes, including during extreme events. We also jointly examine how human disturbances, with catchment interventions, land use changes and resource exploitations, contribute to coastal flooding in the deltas. Through a systems perspective, we characterize the current state of the deltaic systems and provide essential insights for shaping their sustainable future trajectories regarding the multifaceted challenges of coastal flooding.

Plain Language Summary Asian megadeltas, including the Ganges-Brahmaputra-Meghna, Irrawaddy, Chao Phraya, Mekong, and Red River deltas, are home to half of the world's deltaic population and play a critical role in Asian food production. However, these deltas are at high risk to climatic changes, with the vast majority of the world's coastal flood exposure observed in these systems. Rising sea levels and rapid socio-economic development worsen these vulnerabilities, necessitating a comprehensive understanding of coastal flooding dynamics across the five deltas. This review provides up-to-date insights on the current understanding and quantification of the drivers of coastal flood-related hazards. It examines environmental and biophysical factors, such as climate, hydrology, oceanography, geomorphology, and geophysical processes, and how these may interact during extreme events. The review also explores how human activities, like catchment interventions, land use changes, and resource exploitation, contribute to coastal flooding. By offering a systematic perspective, this review characterizes the current state of knowledge on these deltaic systems and provides valuable insights for shaping sustainable future trajectories in the face of the challenges posed by coastal flooding.

1. Introduction

Deltas are sedimentary depositional features situated where rivers enter permanent bodies of water (Bhattacharya, 2006; Goodbred & Saito, 2012; Moore & Asquith, 1971; Syvitski et al., 2022). Although their definitions vary, they are primarily shaped by river discharge, fluvial sediment load, and the dynamic reworking and interplay with marine processes, such as waves, tides, and coastal currents (Goodbred & Saito, 2012), as well as the influence of climate, precipitation, ecology, and intensive human activities (Nicholls et al., 2020). The constant supply of freshwater and nutrient-rich sediments result in diverse ecosystem services, including fertile soils, fisheries and aquaculture. Deltas have historically been foci for human settlement and trade (Paszkowski et al., 2021), the populations of which have adapted to the danger of flooding, the consequences of storm surges, significant tidal events, and excessive rainfall and runoff by learning to live with these hazards.

Nevertheless, increasing human interventions, growing populations and demands for resources, together with pressures from climate change, such as enhanced cyclone activity and relative sea-level rise (SLR), are pushing delta communities beyond their capacity to adapt, leading inexorably to loss and damage. In parallel, irrigation has continued to expand, agriculture has intensified, reflecting the relevance of these lands for large-scale food security (Darby et al., 2015; Nicholls et al., 2018; Schneider & Asch, 2020). Urbanization has accelerated (Santos & Dekker, 2020), and megacities (defined here as having 10+ million inhabitants) have sprung up on coastal lowlands of many deltas, with Bangkok, Kolkata, Dhaka, Shanghai, and Jakarta as examples (Nicholls et al., 2020). Today, it is estimated that between 340 and 500 million people live within deltas globally (Edmonds et al., 2020; Ericson et al., 2006; Scown et al., 2023; Syvitski et al., 2022) and many more in nearby surrounding areas. Ecosystem services and the economic potential that deltas provide, their estimated monetary value ranging from hundreds of billions to trillions of dollars per year (Giosan et al., 2014; Loucks, 2019), are juxtaposed with deltas also being global hotspots of risk, particularly of coastal flooding (Becker et al., 2023; Tessler et al., 2015). Coastal flooding refers to the inundation of land by seawater, which often also coincides with fluvial or pluvial flooding in delta systems (Figure 1).

Examples of high-impact coastal flooding events include Cyclone Bhola in 1970, which hit the Ganges-Brahmaputra-Meghna delta (>300,000 deaths; Frank & Husain, 1971), generating storm surges in excess of 9 m. Cyclone Nargis in 2008 swept across the entire Irrawaddy delta with a storm surge of 5 m and storm waves of an additional 2 m, causing a death toll of 140,000 people (Fritz et al., 2009; Pelling & Dill, 2010; Webster, 2008). More recently in 2020, Cyclone Amphan struck the coasts in West Bengal, India, and Bangladesh, impacting more than 2.6 million people and causing damages of up to US$13 billion, although the longer-term costs are still being calculated. If realized, this would make Amphan the costliest cyclone ever recorded in the North Indian Ocean (ADB, 2022; Khan et al., 2021). Depending on the basin, cyclone activity can coincide with heavy monsoon events that result in inundation from storm surges, from river flooding and breaching of riverbanks, and from heavy rainfall. With the growing threats of climate change and anthropogenic interventions, processes such as SLR, land subsidence, shoreline retreat and erosion, sediment starvation, and rapidly growing populations with increasing demands (Scown et al., 2023) are likely to exacerbate the exposure of people and assets to flood risks in deltas (Fanchette, 2022; IPCC, 2019).

This situation is especially relevant in South and Southeast Asian deltas, where 45% of the global deltaic population lives (Edmonds et al., 2020; Tellman et al., 2021). Five deltas in particular, namely the Ganges-Brahmaputra-Meghna, the Irrawaddy, the Chao Phraya, the Mekong, and the Red river deltas, are the rice bowls for most Asian countries (Schneider & Asch, 2020) and have diverse socio-economic settings, provide a variety of ecosystem services, and have all been highlighted as some of the most flood-prone and climate-vulnerable areas in the world (Scown et al., 2023).

In these five Asian deltas, ambitious socio-economic development objectives are leading to rapid changes in areas that are vulnerable to natural hazards (Arto et al., 2019), and where a solid understanding of the complexity of coastal flood risk dynamics is still lacking. Our ability to understand these dynamics is hampered by: (a) a lack of in situ measurements and difficulties in instrumenting observational sites; (b) a lack of integrated approaches in assessing these systems; and (c) complex interactions over a wide range of spatial and temporal scales. While significant funding and scientific attention have been allocated to the five deltas, a suite of best practices for using available information to conduct impact assessments of coastal flood hazards remains to be developed.

Traditional approaches to study coastal flooding in deltas generally focus on specific physical processes and rarely on their interactions, while neglecting longer-term and cumulative effects, uncertainties, human behavior and management, and ecosystem services (Figure 1). Additionally, approaches are often sectoral and fragmented, lacking an integrated and interdisciplinary perspective. Such issues become important when

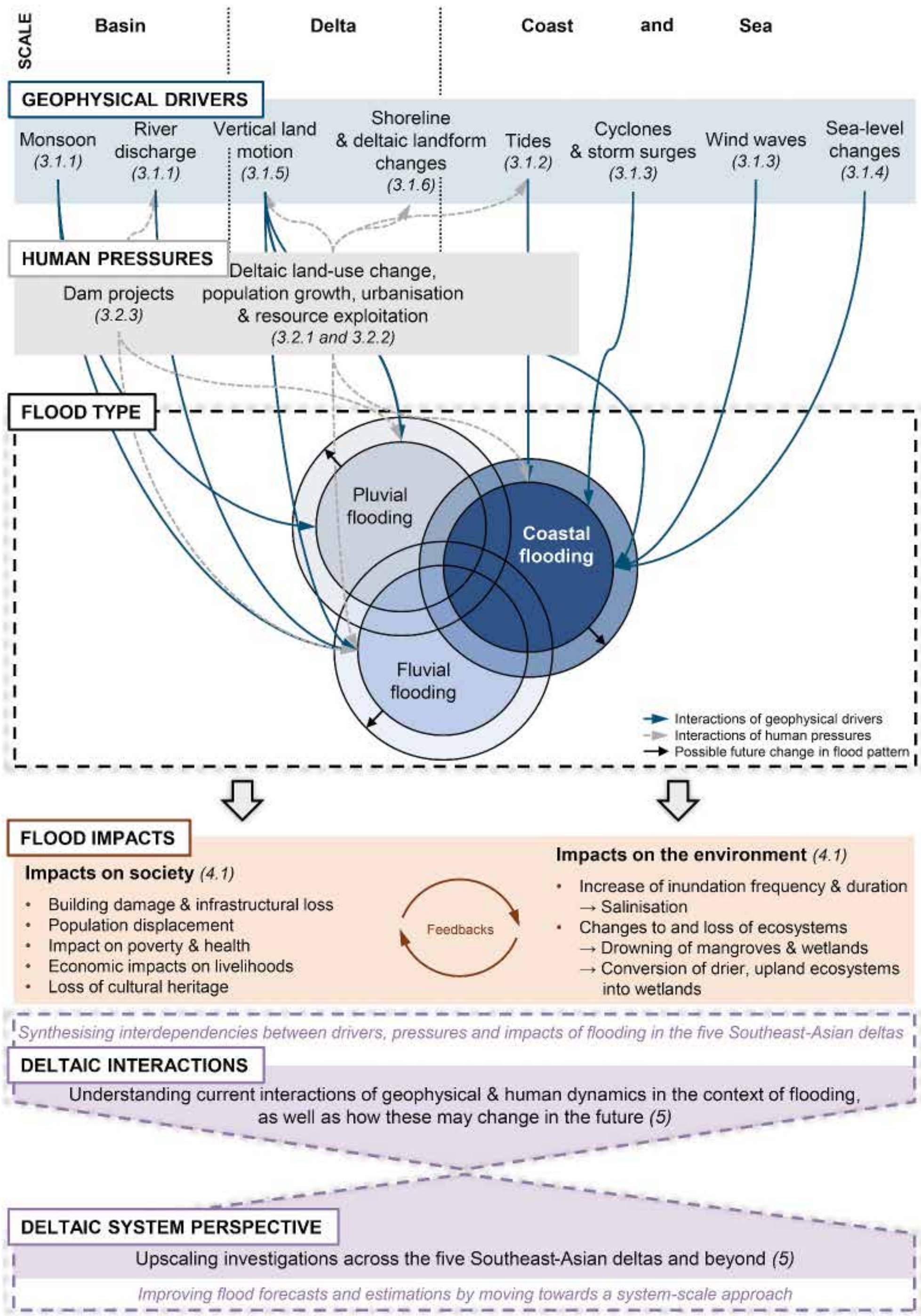

Figure 1. Conceptual framework of this review showing the interactions of geophysical drivers and human pressures in the context of flooding in deltaic systems. Numbers in italics refer to the relevant sections of this review.

these estimates (SLR, subsidence, flooded areas, etc.) are used as a basis for guiding adaptation strategies to coastal flood hazards. Thus, it is essential to get a better understanding of what processes, interactions, and impacts have been quantified, how, and across which spatial and temporal scales. Data collection, processing and analysis capabilities are improving at an impressive rate. The increasing quantity and quality of in situ observations, alongside the accessibility of remote sensing information and ever-growing model capabilities, is vast but also becoming ever more complex to apply. A clear understanding of what information can be used to quantify distinct deltaic processes and their interactions is lacking. Our review aims to provide a state-of-the-art understanding and define data and modeling requirements for addressing urgent scientific and policy-relevant questions in the five selected Asian megadeltas. Although the focus of this review is on the Ganges-Brahmaputra-Meghna, Irrawaddy, Chao Phraya, Mekong, and Red River deltas, the quantification of deltaic processes and interactions discussed herein is relevant to other major deltas in Asia (e.g., Yangtze, Yellow, Pearl) and beyond.

2. The Five Asian Megadeltas

2.1. Ganges-Brahmaputra-Meghna Delta

The Ganges-Brahmaputra-Meghna Delta is the largest delta in the world, 92,000 km^2 in size (Figure 2), and is formed by the Ganges, Brahmaputra, and Meghna Rivers that flow into the Bay of Bengal. The drainage basin covers 1.7 million km^2 that includes India, Nepal, China, Bhutan, and Bangladesh (Allison, 1998; Brown & Nicholls, 2015). For the Ganges, modern sediment fluxes (~300–450 Mt/yr) are similar to long-term averages over the Holocene (~308–426 Mt/yr), while sediment load in the Brahmaputra shows much higher variability (~500–650 Mt/yr at present compared to ~377–1119 Mt/yr over the Holocene) and reflects the river's sensitivity to changes in monsoon intensity and related sediment availability (Raff et al., 2023 and references therein). Goodbred and Kuehl (1998) estimated that about a third of this overall sediment flux is sequestered on the delta plains and the remainder is deposited on the delta shelf or transported to the Bengal fan. Human activities in the form of river diversions and dams upstream, as well as significant interventions within the delta itself (e.g., poldering), have recently led to substantial changes in river and sediment flows and transport capacities, impacting the overall geomorphic stability of parts of the delta (Paszkowski et al., 2021 and references therein).

Currently, approximately 147 million people live on the deltaic floodplains, with highest concentrations found in the megacities of Dhaka and Kolkata. Besides urban areas, the land is primarily used for agricultural production of irrigated and rain-fed crops, accompanied by rural settlements (Brown & Nicholls, 2015; Hoque et al., 2019). The deltaic landscape was tremendously altered during the 1960s to the 1980s, when vast areas were embanked to protect agricultural lands from flooding (R. Rahman & Salehin, 2013).

2.2. Irrawaddy (Ayeyarwady) Delta

The Irrawaddy River is a north–south-oriented fluvial system, originating from tributaries from the Himalaya, Shan Highland, Rakhine Mountains, and the Central Dry Zone in Myanmar (Figure 2). The river drains more than 60% of Myanmar (i.e., >421,000 km^2; Figure 2; Brakenridge et al., 2017) before branching into distributaries, forming a delta of approximately 33,000 km^2 in size, and debouching into the Andaman Sea. Sediment supply to the delta is estimated to be between 260 and 360 Mt/yr (Baronas et al., 2020; Milliman & Syvitski, 1992; Robinson et al., 2007). Detailed sediment discharges reveal that 20%–60% of the sediment is transported to the shelf during the monsoon season, where accumulation rates vary between 1 and 10 cm/yr (Glover et al., 2021; Kuehl et al., 2019).

The delta is home to approximately 13 million people, of which more than 5 million are based in Yangon City. Agricultural areas have expanded and intensified, by shifting from dry to irrigated crops, and together with increasing aquacultural production and urban growth, drove deforestation and mangrove loss, decreasing in surface area from 72% (1972) to 2% (Thi et al., 2012; Vogel et al., 2022). While deforestation in the catchment has raised fine sediment supply in the delta (Anthony et al., 2019), and the delta shoreline has been relatively stable for the last ~150 years (Hedley et al., 2010), upstream dam construction, sand mining, and dredging has reduced coarse sediment supply, exacerbating erosion and undermining the balance of the delta in the face of SLR (Anthony et al., 2019; D. Chen et al., 2020).

2.3. Chao Phraya Delta

Fed by four tributaries from northern Thailand, the Chao Phraya River catchment is 164,000 km^2 and discharges into the Gulf of Thailand (Figure 2; Sayama et al., 2015; Sinsakul, 2000). The flux of suspended sediment to the delta is around 1.5 Mt/yr (Park et al., 2021). This is much lower than that of the other Asian deltas of this study

10.1029/2024RG000846

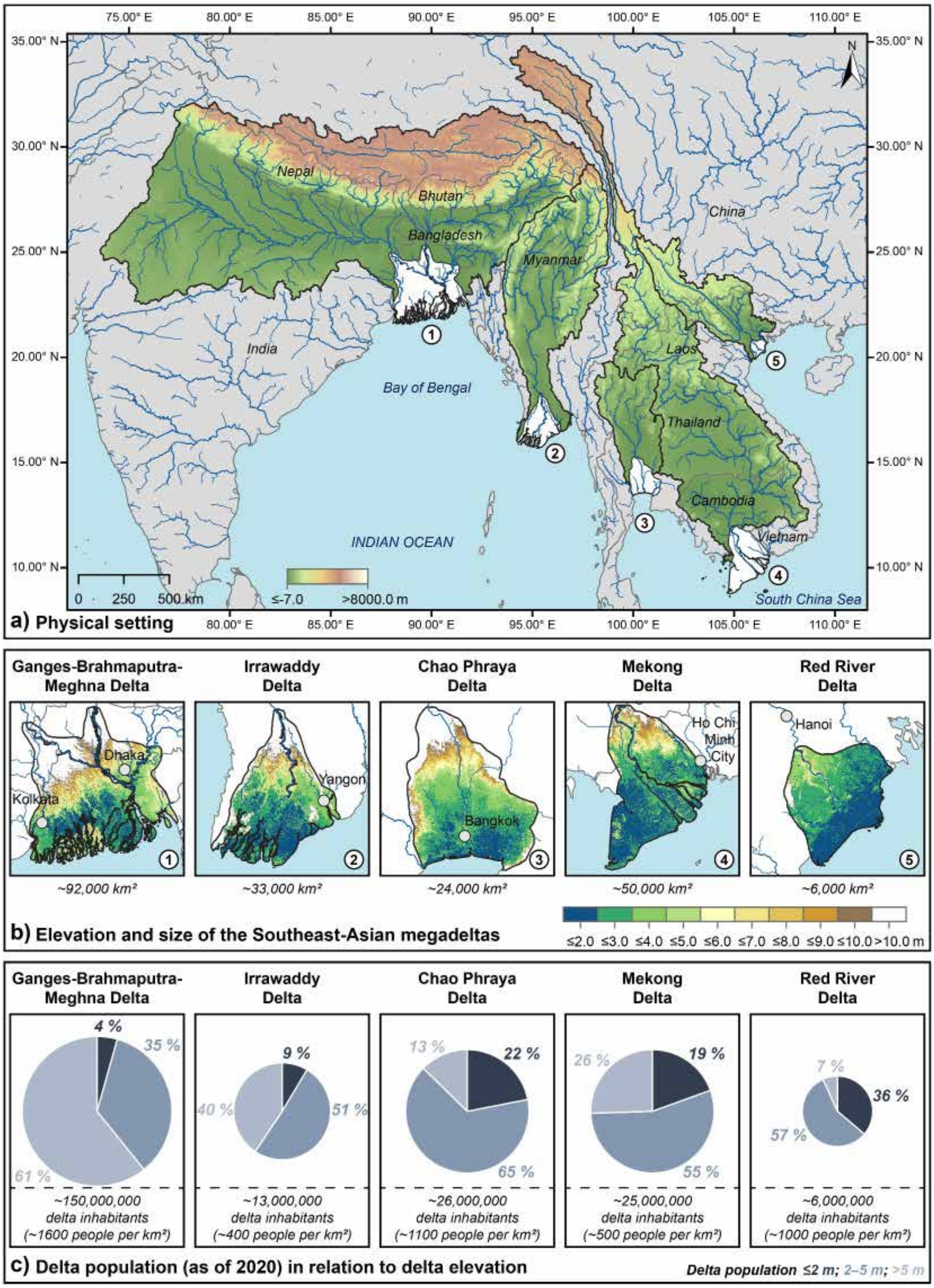

Figure 2. Setting of the five Asian deltas reviewed in this study. Elevation for river basins (a) and the deltas (b) are shown based on FABDEM relative to EGM2008 (Hawker et al., 2022). Population data for each delta by elevation (c) was derived from the WorldPop 2020 data set (WorldPop, 2018). The size of the circles reflects the overall population of the deltas. The delta polygons are based on delta extents provided by Tessler et al. (2015). The river network is derived from the HydroSHEDS data set (https://www.hydrosheds.org/).

that are fed by high rates of mountain erosion. The sequestration of a large part of the river sediment in upstream floodplains also limits the sediment influx to the delta, making it even more fragile to changing dynamics taking place.

In contrast to other deltas considered in this review, the Chao Phraya Delta is highly urbanized, with more than 11 million people living in the megacity of Bangkok (World Population Review, 2023). Palaeoenvironmental reconstructions in Bangkok indicate first intense agricultural practices occurring around 1660 CE, which were accompanied by the expansion of urban, industrial, and aquacultural activities during the 20th century (Punwong et al., 2023), thereby replacing agricultural, shrub, and bare lands (Hara et al., 2005; Thi et al., 2012). Although these areas are relevant for flood retention, conversion into built-up/industrial areas has led to increased flood exposure and vulnerability (Carpenter, 2012; Likitswat & Sahavacharin, 2023; Thi et al., 2012; Van Oldenborgh et al., 2012). Dam construction on the tributaries of the Chao Phraya River reduced sediment load from 30 Mt/yr before 1965 to less than 5 Mt/yr by the 1990s (Winterwerp et al., 2005), which, when combined with excessive groundwater withdrawal, has resulted in widespread and significant subsidence in the delta (Aobpaet et al., 2013).

2.4. Mekong Delta

Originating as the Lancang River in the Tibetan Plateau of China, the Mekong River stretches over approximately 5,000 km until it enters the South China Sea in Vietnam, thereby covering an area of 810,000 km^2 (Mekong River Commission, 2019) across China, Myanmar, Laos, Thailand, Cambodia and Vietnam (Figure 2; Mallick, 2022). The 50,000 km^2 Mekong Delta (Tessler et al., 2015) forms the third largest delta plain in the world (Anthony et al., 2015), and is located in Cambodia and southern Vietnam (Figure 2). The delta receives around 37 Mt/yr of sediment, based on measurements from 2009 to 2016 (Thi Ha et al., 2018). This is exceptionally low compared to the other mountain-source basins and is linked to major damming at several points in the river basin. The pre-dam flux of suspended sediment to the delta was above 150 Mt/yr for the period 1986–1993, illustrating the profound impact that dams have had on sediment delivery to the delta by 2016 (Thi Ha et al., 2018; Walling, 2009).

The Mekong Delta is home to approximately 18 million people (up to 25 million when adjacent Ho Chi Minh city is considered; Figure 2) and both its landscape and morphodynamics have been significantly altered over time. Since Vietnam's transition to a market economy in 1986, the delta has undergone vast agricultural intensification, urbanization and industrialization. With initial focus on rice cultivation, other land uses like aquaculture, cash crops, urban expansion and industrial intensification have strongly increased in the 21st century (Minderhoud et al., 2018).

2.5. Red (Hong) River Delta

The 6,000 km^2 Red River Delta in northern Vietnam constitutes the smallest of the five Southeast Asian deltas studied herein, although its drainage basin is of similar size to the Chao Phraya Delta (i.e., around 164,000 km^2; Figure 2; Ve et al., 2021), and covers parts of China, northern Vietnam and small areas of Laos (Figure 2). The Red River originates in the mountains of the Yunnan province in southern China and is mainly fed by the Da, Lo, and Thao rivers, sourced in the Chinese uplands (T. H. Dang et al., 2010).

Currently, the delta is home to more than 6 million people. The Red River Delta has become the most important region for economic activities in northern Vietnam (Mai et al., 2009) and records some of the highest land conversion rates in the country, mainly from agriculture to urban (Thien et al., 2023; Tuan, 2022). In addition, agriculture highly depends on hydraulic infrastructure (such as dikes, sluice gates, polders and irrigation systems, including pumping stations) to protect against saline intrusion, and fertilizers to maintain soil fertility (M. T. Nguyen et al., 2019 and references therein). Although water regulation due to dam construction along the Red River and its tributaries caused substantial changes in freshwater discharge and sediment supply (Gao et al., 2015), only one of five dams was responsible for reducing sediment flux by more than 60% (Ve et al., 2021). In contrast, deforestation and other land-use-land-cover changes increased sediment load in the river system and, together with land reclamation projects in the intertidal zone, contributed to a new coastal morphodynamic equilibrium (Ve et al., 2021).

3. Recent Advances in Understanding and Quantifying the Drivers of Coastal Flood Hazards in the Five Deltas

3.1. Main Geophysical Drivers

The complexity of interactions in the five Asian deltas merits unpicking the driving forces behind those interactions, and how they can be measured and quantified. This section delves into the predominant geophysical drivers shaping the Asian megadeltas, with key messages summarized in Table 1.

3.1.1. The Monsoon and River Discharge

The Asian megadelta region experiences a tropical monsoon climate, characterized by heavy rainfall, often in the form of intense downpours. This leads to seasonal increases in river discharge, can overwhelm the capacity of rivers and drainage channels, and can lead to waterlogging in low-lying deltaic plains. The Asian monsoon system comprises two distinct subsystems: the South Asian (or Indian) monsoon system and the East Asian monsoon system. The seasonal variation in river discharge (Figure 3a) of the Ganges-Brahmaputra-Meghna (annual average: ∼40,000 m^3/s, Papa et al., 2010) and Irrawaddy (∼14,000 m^3/s, Milliman & Haq, 1996) systems are subject to glacial and snowmelt from the Himalaya and the Tibetan Plateau in the fall, winter and spring, while the Indian monsoon precipitation is the major contributor to summer flow (Chowdhury & Ward, 2004; Jian et al., 2009; M. P. Rao et al., 2020; Shaman et al., 2005). The annual flood pulse resulting from a seasonal monsoon climate is also the main characteristic of river discharge in the Mekong (annual average ∼13,500 m^3/s, Räsänen et al., 2016), Chao Phraya (890 m^3/s, G. S. Nguyen et al., 2022) and the Red River (∼4,300 m^3/s, Luu et al., 2010), with distinct low flows in December–May and high flows in June–November.

Studies on river discharge often rely on in situ observations and measurements (Fekete et al., 2015) obtained from gauging networks that have been installed for several decades. For the Ganges-Brahmaputra-Meghna system, hydrological observations across Bangladesh and the delta have been collected by the Bangladesh Water Development Board and the Bangladesh Inland Water Transport Authority since the early 1920s (www.bwdb.gov.bd/; https://biwta.gov.bd/), but public access to these records remains limited (Jian et al., 2009; Papa et al., 2010), which is also the case for India. Similarly, for the Irrawaddy (Furuichi et al., 2009), the Mekong (Binh et al., 2020), Red River (Vinh et al., 2014) and Chao Phraya (Park et al., 2021), several institutional sources provide in situ water level and discharge information but the time series can be irregular, incomplete, not up-to-date, and/or not freely accessible, despite being published in the scientific literature.

Satellite altimetry-derived discharge time series are available over the Ganges and Brahmaputra rivers, as well as their combined discharge before entering the delta for the period 1993–2022 (monthly basis) and for 2008–2022 (10-day basis) (Papa et al., 2010, 2012). A similar approach was applied in the Irrawaddy River system (Frappart et al., 2015), for which an altimetry-derived discharge time series from 1993 provides complementary information to the traditional gauge data available on the Global Runoff Data Center (GRDC) website, as well as the Mekong River (Birkinshaw et al., 2010), for which a long-term and continuous record (1993–2022) is available (Biancamaria et al., 2017). Over the Mekong, river discharges from satellites are tested at various locations across the basin (Kim et al., 2019). For the Red River and Chao Phraya, no such satellite-derived methodology has yet been applied to estimate discharge, despite the availability of new estimates covering rivers worldwide (Belloni et al., 2021).

Other satellite techniques, such as imagery observations in the visible or infra-red (Landsat, Moderate Resolution Imaging Spectroradiometer (MODIS), Sentinel-2), or from passive microwave imagery (Kettner et al., 2021, https://floodobservatory.colorado.edu/technical.html), are also currently being used to estimate discharge, based on rating curves paired with river width variations and in situ or modeled discharge data (Riggs et al., 2023; Tarpanelli et al., 2013, 2019). Elmi et al. (2024) combined satellite imagery- and altimetry-derived river width and water height observations to extend the monthly discharge time series for inactive GRDC stations globally.

The launch of the Surface Water Ocean Topography (SWOT, Fu et al., 2024) satellite mission in December 2022 promises to add substantially to our ability to understand water level and discharge variations in megadeltas. SWOT is an imaging altimeter that produces near-complete spatial data on water level, river slope, and inundation using Ka-band radar interferometry at high resolution (Biancamaria et al., 2016). The mission science requirements specify a water height accuracy of <10 cm and slope accuracy of 1.7 cm/km when averaging over water areas greater than 1 km^2, and the nominal orbit will result in repeat measurements every 10.5 days

Table 1
Geophysical Drivers Overview: What We Know, What Gaps Remain, and the Key Challenges in Coastal Flood Assessments in the Asian Megadeltas

What we know	Gaps in terms of observations and/or models	Key challenges to be addressed in the context of Asian megadeltas
3.1.1 Monsoon and river discharge		
Coastal flooding poses significant challenges as it often coincides with pluvial and fluvial flooding due to seasonal increases in discharge, which can exceed the capacity of rivers and drainage channels and cause waterlogging	• **Limited long-term records**: The limited and incomplete record of long-term discharge observations make it challenging to observe past discharge trends • **Lack of recent and up-to-date data**: The availability of recent and up-to-date time series data on river discharge is limited, making it challenging to assess current conditions and trends accurately • **Limited availability of simultaneous in- situ and altimetry data**: In the Red River and Irrawaddy River, the application of satellite altimetry data to in situ observations has not yet been done, which limits the spatial and temporal understanding of discharge trends in these deltas • **Incomplete gauge coverage within deltas**: Within deltas, there is incomplete gauge coverage of distributary *channels*, which are important for accurately estimating river discharge. This can result in uncertainties when assessing the overall river discharge and when setting up hydrodynamic models for deltas • **Difficulty in observing channel bathymetry**: Current satellite systems *face* difficulties in directly observing channel bathymetry, which is necessary for understanding river dynamics and accurately estimating river discharge	• **Identify and address the primary challenges in obtaining comprehensive discharge data for coastal flood analysis** by conducting research to improve methods, data sharing protocols, and monitoring systems • **Investigate how the lack of data from rivers affects coastal flood modelling and prediction accuracy**. Develop *strategies* to mitigate these impacts, such as incorporating alternative data sources or developing statistical models to estimate missing data • **Apply existing approaches of combining** in situ *and satellite altimetry data to estimate discharge* in the Red River and *Irrawaddy* River systems. Incorporate lessons from other deltas • **Overcome altimetry limited spatial coverage and temporal sampling challenges**, particularly in the context of the SWOT mission. More resources *need* to be allocated to increase in situ data collection and monitoring systems in order to ground-truth global data sets • **Enhance our understanding and modelling of the complex interactions between backwater effects**, *river flows*, *tides*, *and storm surges* that contribute to coastal flooding in megadeltas, developing integrated modeling approaches
3.1.2 Tides		
Tides are a major driver of coastal flooding in Asian deltas, interacting with factors such as river discharge, topographic and bathymetric changes, SLR, and storm surges. This interaction greatly influences the region's coastal processes and flood dynamics	• **Limited observational data**: The scarcity of coastal tide gauges and the challenges associated with obtaining *accurate* tide measurements from coastal altimetry data impede our understanding of tidal patterns and their contribution to coastal flooding • **Difficulty in observing nearshore bathymetry**: Due to observational challenges, the nearshore bathymetry is often not *well* monitored. Global bathymetric data used in modeling often exhibit biases in shallow deltaic coastlines, which significantly impacts models' ability to capture tidal fluctuations, and thus coastal flooding • **Gap in current flood hazard assessment approaches**: Neglecting the interactions between tides and other factors in modeling and analyses can lead to an over- or *underestimation* of extreme coastal flood impacts	• **Assess whether the impact of tides on coastal flooding in the Asian megadeltas has been over- or underestimated** by studying the tide-surge *interactions* • **Investigate how climate change-induced SLR amplifies the influence of tides**, leading to *increased* risks of coastal flooding in Asian megadeltas • **Allocate resources to deploy more tide gauges**, in order to ground-truth against advancing altimetry technologies (SWOT) and reprocessing data with improved algorithms • **Explore the application of remote sensing and numerical modelling to improve the observation of bathymetry and topography** over nearshore areas of the *Asian* megadeltas • **Bridge the gap between the coastal ocean**, *estuaries and tidal channels through cross-scale numerical modelling to account for all relevant interactions with tides*. This *requires* improved model accuracy, validated results with field observations, and the incorporation of local knowledge
3.1.3 Tropical cyclones, storm surges and wind-waves		
The Asian megadeltas are exposed to various intensities of tropical cyclones, ranging from frequent and intense storms in the Red River and Ganges-Brahmaputra-Meghna deltas, to fewer but more intense cyclones in the Irrawaddy delta,	• **Limited in- situ data availability**: Similar to the limitations faced *in* tide and discharge observations, challenges exist for observations of storm surges and waves. Similarly, the lack of nearshore topographic-bathymetric observation impedes storm surge	• **Collect and validate high-quality data on cyclones, surges and waves in the Asian megadeltas to improve the accuracy and reliability of hydrodynamic models**, deploying additional

10.1029/2024RG000846

Table 1
Continued

as well as tropical storms and depressions in the Mekong and Chao Phraya deltas, respectively	modeling and a comprehensive understanding of coastal flood extents and magnitudes • **Satellite altimetry as a tool to observe storm surges**: Although satellite altimetry has shown success in observing storm surges in the Bay of Bengal, its use is not common due to sparse spatial and temporal sampling • **Coupled tide-surge-wave model**: Coupled tide-surge-wave models are necessary for proper simulation of storm surges in shallow areas, but often not used in application. Modeling of compound flooding, coming from storm surges and associated extreme rainfall, is also missing • **Effective approach to monitor extreme water-levels**: Utilizing an altimetry multi-mission approach has proven effective in monitoring water level extremes in the Mekong Delta	monitoring systems and utilizing advanced remote sensing technologies • **Identify and incorporate the key parameters and interactions that are crucial for accurately simulating cyclone and wave behaviour in the Asian megadeltas into hydrodynamic models** (such as tidal dynamics, sediment transport, coastal morphology, and local bathymetry) • **Conduct comprehensive studies to evaluate the potential impacts of climate change on cyclone frequency, intensity, and resulting coastal flooding** in Asian megadeltas • **Explore the potential of satellite missions** such as CFOSAT, SWOT, Sentinel-1/2/3/6, and PACE platforms to enhance coastal *flooding* monitoring capabilities
3.1.4 Sea-level change		
Over 1993–2023, altimetry data shows absolute SLR ranging between 3.5 and 5 mm/yr along most coastal areas of the five deltas	• **Limited in- situ data availability**: Limited *data* poses challenges in observing sea-level changes, which affects our understanding of the baseline water level prior to extreme events	• **Establish a comprehensive network of sea and water level monitoring stations** in the Asian megadeltas • **Foster collaboration among countries and institutions in the region to share sea/water level data and** collaborate on data collection and analysis • **Integrate relative SLR into coastal modelling systems to** improve the accuracy of coastal flood prediction • **Improve advancements in data processing algorithms and calibration/validation techniques** to *enhance* the accuracy and resolution of coastal altimetry measurements
3.1.5 Vertical land motion and land elevation dynamics		
Land subsidence in the Asian megadeltas can exceed global or regional sea-level rise rates VLM in the Asian megadeltas is a complex response to various processes occurring at different temporal and spatial scales Vertical errors and artifacts in global DEMs significantly undermine the reliability and precision of SLR and coastal flood exposure assessments in the Asian megadeltas	• **Sparse or no coverage of GNSS sites and RSET-MH set-up**, limiting the ability to measure subsidence and/or land aggradation. GNSS has the potential to *provide* valuable insights, as is the case for the Mekong Delta and the Chao Phraya River Delta, which have good GNSS coverage but inaccessible data • **Limited availability of extensive modelling studies** beyond 1D calculations in the Asian megadeltas due to the requirement of detailed local subsurface data and a complex setup • **Improvement of global DEMs**: Studies have utilized machine learning algorithms and satellite LiDAR data to enhance older published DEMs, yet the *vertical* reference of elevation data to local sea-level remains underrepresented and needs further attention • **Artiefacts and discrepancies in global DEMs**: Global DEMs may differ substantially from local elevation data, *resulting* in height residuals caused by limited training data. The coarse spatial resolution of available high-accuracy data in the Asian megadeltas often challenges its use for flood risk assessments	• **Increase the availability of GNSS data in flood-prone areas of Asian megadeltas** to better understand VLM's impact on coastal flooding • **Facilitate the sharing of VLM data among researchers, institutions, and government agencies** through open-access *platforms* and collaborative agreements • **Develop standardisedstandardized guidelines for documenting and reporting VLM rates** to ensure consistent and reliable data collection across studies and localities • **Encourage researchers to thoroughly document and justify the selection of VLM rates**, providing clear *explanations* of data sources, methodologies, and assumptions made • **Encourage researchers to collaborate and share insights to enhance modelling studies beyond 1D calculations**, integrating detailed local subsurface data • **Address the dynamic nature of topographic elevations in deltas by regularly updating DEMs** to ensure the improvement of elevation-informed coastal flood hazard assessments

Table 1
Continued

3.1.6 Sediment, shoreline and deltaic landform changes		
Sediment fluxes vary significantly among Asian megadeltas. Ganges, Brahmaputra, and Irrawaddy rivers carry substantial sediment loads, while the Mekong, Red River, and Chao-Praya have reduced fluxes due to human activities The Mekong Delta coastline experiences the most significant erosion rates, while the Irrawaddy Delta also undergoes erosion in substantial portions. Coastal erosion rates in Chao Phraya and the Red River deltas are comparatively lower. In the Ganges-Brahmaputra-Meghna Delta, shoreline progradation continues to dominate	• **Limited in- situ data availability**: Sediment fluxes to and from deltas remain approximate due to challenges in maintaining long-term surveys, political restrictions on data display, and technical difficulties, particularly in tidal zones of the deltas • **Erosion dynamics using satellite imagery**: Utilizing satellite imagery to analyse erosion dynamics can be laborious *and* often requires manual delineation to detect changes over time, posing challenges for comprehensive analysis • **Limited ground-truthing potential**: Due to the limited in situ data on sediment dynamics and erosion and accretion processes, ground-truthing of satellite-derived change detection is a challenge	• **Allocate resources to deploy more sediment gauges across the five Asian megadeltas** to better understand the changing patterns of sediment flux to the deltas • **Facilitate the sharing of sediment data among researchers, institutions, and government agencies** through open-access platforms and collaborative agreements, particularly for trans-boundary basins

(Fu et al., 2024). A non-sun synchronous orbit with a steep inclination (78°) was chosen for the SWOT mission, as such an orbit minimizes tidal aliasing and ensures that over the mission lifetime of at least 3 years, the full spectrum of tidal states at a given site can be sampled. The accuracy, spatial resolution, coverage and sampling frequency of the measurements will allow river discharge to be inferred in the absence of ground gauge data for rivers wider than 100 m (Durand et al., 2023).

3.1.2. Tides

The Asian megadeltas are exposed to a range of tidal fluctuations with diverse tidal characteristics (Figure 3b). The tides in the Ganges–Brahmaputra-Meghna and Irrawaddy deltas are semidiurnal (Krien et al., 2016; Sindhu & Unnikrishnan, 2013). The Mekong Delta experiences a mixed semidiurnal/mixed diurnal regime. Along the Chao Phraya and Red River deltas, the tide is more distorted with a diurnal regime. In terms of tidal amplitude, the Irrawaddy coastline experiences the largest tidal range among the Asian megadeltas, where amplitudes can exceed 5 m (P. S. Rao et al., 2005). A similar, albeit a bit smaller, tidal range is observed along the Ganges-Brahmaputra-Meghna delta coastline. The mean tidal range along the Chao Phraya and Red River deltas is relatively lower, at around 2 m (Figure 3b). The vast seasonal river discharges of the Mekong, Ganges, and Brahmaputra rivers (Section 3.1.1, Figure 3a) can lead to compounding impacts. As the tide propagates along the estuary inside the delta, it interacts with the narrowing river coastline and the discharge of the rivers (Khan et al., 2020; Rodrigues do Amaral et al., 2023). In the Ganges-Brahmaputra-Meghna and the Irrawaddy deltas, tides are observed to propagate approximately 200–300 km inland (Figure S1 in Supporting Information S1; Hedley et al., 2010; Khan et al., 2020) and in the Mekong Delta, tides could reach distances of 200–300 km upstream (T. C. Nguyen et al., 2023). During the wet season, the tide can substantially contribute to the estuarine and riverine water levels and contribute to coastal flood hazards.

Seasonal sea-level variation causes measurable changes in tides. For example, the M2 tidal constituent at the mouth of the Ganges-Brahmaputra-Meghna increases by about 7 cm during the monsoon season (Tazkia et al., 2017) and it is also significantly modulated in response to sea-level changes at interannual and longer time scales (Rose et al., 2022). Consequently, fluvial flooding during the wet season experiences a stronger backwater effect, potentially exacerbating fluvio-tidal coastal flooding (Mirza, 2003). Conversely, during the dry season, reduced river flows allow the tide to push the salt wedge further inland, which leads to saltwater intrusion into deltaic coastal areas (Akter et al., 2020; Sherin et al., 2020). This problem is exacerbated due to tidal amplification along the river/estuary (Eslami et al., 2019; Khan et al., 2020). Such amplification is supercharged by man-made control structures (such as dikes and polders), which force the tide to propagate further upstream with higher amplitudes (van Maren et al., 2023).

In addition, in macro-tidal regions with large continental shelves, like the Ganges-Brahmaputra-Meghna and Irrawaddy deltas, a significant contribution from tide-surge interaction is expected (Horsburgh & Wilson, 2007; Idier et al., 2019). Such interactions are often neglected in modeling and analyses (e.g., Wood et al., 2023), which

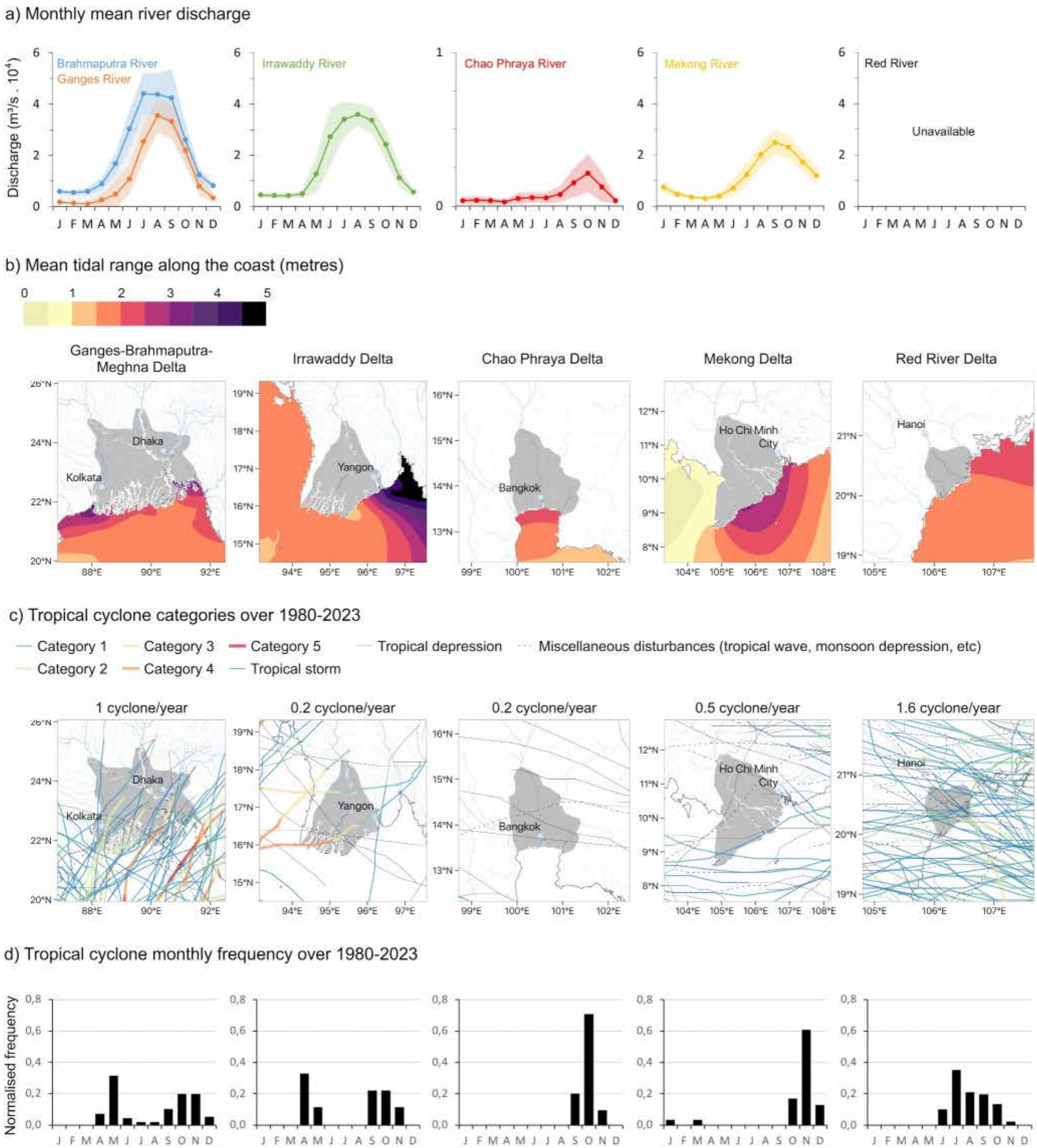

Figure 3. Summary of geophysical drivers of coastal flood risk in the Asian megadeltas: (a) monthly river discharge in the major rivers ±1 standard deviation (shaded areas), based on altimetry (Papa et al., 2010, 2012); (b) Mean tidal range (meters) from the open ocean to the coast of the deltas, excluding the river channels, as modeled in the FES2014 tidal atlas (Lyard et al., 2021); (c) spatial distribution of tropical cyclones passing through a 100 km radius of each of the deltas, based on IBTrACS data from 1980 to 2023 (Knapp et al., 2010, 2018); (d) monthly tropical cyclone frequency. Note: the discharge plots in (a) exclude the Red River discharge as this information is not publicly available. In addition, the Ganges and Brahmaputra rivers have been separated for legibility and identification of seasonal variation within each river. The legend items in (c) represent the tropical cyclone category based on the Saffir-Simpson scale. The river network is derived from the HydroSHEDS data set (https://www.hydrosheds.org/).

can lead to overestimations of extreme flood impacts (Arns et al., 2020). Climate-change induced rising mean sea-levels further exacerbate the impact of tides in these deltas. It is also shown that in a resonant estuary, like the Ganges-Brahmaputra-Meghna, tidal range amplifies in par with SLR; a 1 m SLR may change mean high water by twice as much in the estuary (Khan et al., 2020; Rose & Bhaskaran, 2022).

Tidal fluctuations and trends are typically observed via tide gauges, recording tidal patterns at high frequency (typically hourly or less). Similar to discharge data (Section 3.1.1), only a few coastal tide gauges, in many cases only one or two stations per delta, provide publicly available information across the Asian megadeltas (Haigh et al., 2023). In order to advance our understanding of past and future tidal trends, coastal ocean circulation models have become the de facto tools (Krien et al., 2016; Sindhu & Unnikrishnan, 2013), also measuring salinity propagation (Bricheno & Wolf, 2018), storm surges (Khan et al., 2021; Krien et al., 2017; Tasnim et al., 2015; Wood et al., 2023; Section 3.1.3), and coastal flooding (Khan et al., 2021, 2022). The main challenge that remains is obtaining a truthful representation of the bathymetry, particularly at the nearshore shallower regions (Krien et al., 2016). For example, the development of dedicated regional bathymetry over the northern Bay of Bengal revealed a strong shallow bias (2 and 3 m) in the global bathymetric data, and led to a 3–5 fold improvement compared to the global tidal atlas (Krien et al., 2016, 2019).

The utilization of satellite-based high-resolution optical imagery with wave-based techniques enables the estimation of coastal bathymetry in regions characterized by fluctuating water turbidity and suspended sediments, as these techniques rely on shallow-water propagation over a flat bottom (Almar et al., 2021; Cesbron et al., 2021; Daly et al., 2022). This approach offers promising opportunities for studying the Asian megadeltas. Emerging new techniques, such as satellite-derived bathymetry leveraging deep learning algorithms, as demonstrated by Sagawa et al. (2019) and Al Najar et al. (2023), hold significant potential in deriving a better bathymetry. In addition, future space missions, like the Constellation Optique 3D mission (https://co3d.cnes.fr/, to be launched in 2025) are expected to provide global coverage of stereoscopic data with 50 cm resolution.

3.1.3. Tropical Cyclones, Storm Surges, and Wind-Waves

Tropical cyclones are termed as cyclones in the Northern Indian Ocean, including the Bay of Bengal, and as typhoons in the West Pacific, including in the South China Sea. Figure 3c illustrates the historical tropical cyclone tracks passing within 100 km of each Asian megadelta and their along-track intensity as reported in the International Best Track Archive for Climate Stewardship data set over the period 1980–2023 (Knapp et al., 2010, 2018). The largest number of tropical cyclones are recorded over the Red River Delta (67 cyclones, 1.56 cyclones/year) and Ganges-Brahmaputra-Meghna Delta (42 cyclones, 0.98 cyclones/year). However, the Ganges-Brahmaputra-Meghna Delta shows much more propensity to be hit by a tropical cyclone (Category-1 or higher on the Saffir Simpson Hurricane Wind Scale, wind speeds >118 kmph, https://www.nhc.noaa.gov/aboutsshws.php). In the Irrawaddy Delta, only a few cyclones have reported to make landfall (9 cyclones in 43 years), but half of the landfalling cyclones are of Category-1 or higher. The cyclones that have passed the Mekong Delta are of tropical storm strength (maximum wind speeds between 63 and 118 kmph), and all the cyclones through the Chao Phraya Delta are of tropical depression strength (maximum wind speeds not exceeding 62 kmph).

Waves also play a significant role in coastal flooding in the Asian megadeltas, contributing to the severity and extent of inundation events (Laignel et al., 2023). Waves can lead to increased overtopping of coastal defenses, such as seawalls and embankments, allowing floodwaters to penetrate further inland during storm surge events. Waves can also erode coastal landforms and structures, weakening natural and man-made defenses against flooding (Anthony, 2015; Woodroffe et al., 2006). Given the complex interplay between waves, tides, storm surges, and river discharge in the Asian megadeltas, understanding the role of waves in coastal flooding is crucial for effective disaster management and adaptation strategies.

Observations of storm surges and waves are limited by in situ data scarcity and public accessibility. As is the case for river discharge (Section 3.1.1) and tides (Section 3.1.2), satellite altimetry has emerged as a valuable tool for observing water level extremes and storm surges in coastal regions, although with the same limitations as discussed above. Boergens et al. (2019) highlight the benefits of utilizing long-repeat orbit missions in a multi-mission approach to monitor water level extremes in the Mekong River Basin, showcasing the effectiveness of satellite altimetry for hydrological research. Similarly, Antony et al. (2014) demonstrate the utility of satellite altimetry in observing storm surges in the Bay of Bengal, providing valuable insights for disaster management and coastal protection strategies. Khan et al. (2021) present a case study focusing on Supercyclone Amphan in the Bay of Bengal, emphasizing the role of satellite observations, including altimetry, in enhancing storm surge and inundation forecasting systems in the Ganges-Brahmaputra-Meghna Delta. Looking ahead, satellite missions, such as the China France Oceanography Satellite (CFOSAT, Hauser et al., 2021), SWOT, or Sentinel-1 radar and optical Sentinel-2, and the Plankton, Aerosol, Cloud, Ocean Ecosystem mission (https://pace.gsfc.nasa.gov/), offer further potential for advancing our understanding of coastal dynamics and enhancing our ability to monitor and manage coastal hazards effectively.

3.1.4. Sea-Level Change

Along coastlines, relative SLR (i.e., sea level rise with respect to the Earth's surface) is most critical. Relative SLR results from the combination of geocentric (or absolute) sea level changes and vertical land motion, which is driven by both natural processes and human pressures (see Section 3.1.5). In deltaic areas, anthropogenic subsidence amplifies climate-induced mean SLR and often becomes the dominant mechanism of increasing relative sea level (Fox-Kemper, 2021). This increase in relative sea level exacerbates coastal flood risks, as the potential for inundation during high tides, storm surges, and extreme weather events is heightened.

The global average mean SLR has been estimated at 1.7 mm/year since 1900 (Fox-Kemper, 2021) and has accelerated since the 1970s (Dangendorf et al., 2019), with ongoing rates exceeding 3.6 mm/year during the last 30 years, as observed by satellite altimetry (http://www.aviso.altimetry.fr/). There is an unequivocal human fingerprint in global SLR (e.g., Becker et al., 2014; Marcos et al., 2017). Rates of sea level change vary regionally, mostly because of uneven thermal expansion and heat redistribution within the ocean (e.g., Hamlington et al., 2020). In the wide ocean region of the Asian megadeltas, sea level has risen by 15 cm since the early 20th century (i.e., average rate of 1.1 mm/yr), according to the mean sea level reconstruction by Dangendorf et al. (2019). After 1970, the rate of mean sea level rise in the region has accelerated by up to 2 mm/yr. Over the altimetric period (since 1993), linear mean sea level trends calculated from satellite altimetry observations display spatial patterns linked to regional processes, with rates ranging between 3.5 and 5 mm/yr along most of the coastal areas of the five deltas (Figure S2 in Supporting Information S1) (Cazenave & Moreira, 2022). The rates of SLR in the open ocean contrast with those derived from coastal tide gauges (Becker et al., 2019). For example, in the Ganges-Brahmaputra-Meghna delta, rates of relative SLR from in situ measurements exceed 3 mm/yr since 1970 (Becker et al., 2020). Similarly, Pham et al. (2024) found significantly higher relative SLR in the Mekong Delta calculated from tide gauge records along the Vietnamese coastline than in the open ocean, for the altimetry period. These differences highlight the major role of land subsidence in deltas, as well as the differences between the coastal region and the open ocean.

3.1.5. Vertical Land Motion and Land Elevation Dynamics

Vertical land motion (VLM) is the upward or downward motion of a land surface horizon relative to a fixed datum. Coastal subsidence, which is downward VLM (Shirzaei et al., 2021; Törnqvist & Blum, 2024) instigates elevation loss, which, if not compensated by new sediments (organically and/or inorganically derived), leads to increased flood exposure in coastal lowlands. The contribution of land subsidence to local and regional relative SLR and coastal flooding in delta plains is often considerable, and its magnitude can be equal to or exceed the present and projected global or regional sea-level changes (Becker et al., 2020; Gehrels et al., 2011; Nicholls et al., 2021; Piecuch et al., 2018; Syvitski, 2008). VLM in deltas is a complex response to a broad array of processes occurring over a wide range of spatial and temporal scales (Figure 4). Natural processes that cause VLM include tectonics, Glacial Isostatic Adjustment (GIA), Sediment Isostatic Adjustment (SIA), natural sediment compaction, and peat oxidation. Long-term VLM, such as GIA, SIA, and natural sediment compaction at larger depths, are often linear on centennial time scales and govern the local and regional short-term and seasonal to decadal natural VLM dynamics in the order of mm/yr. However, human-caused or accelerated VLM processes, often related to land-use change (Section 3.2.2) or resource extraction (e.g., groundwater withdrawal, Section 3.2.2), can create non-linear VLM, with annual rates in the range of multiple cms–dm/yr (e.g., Galloway & Burbey, 2011; Karegar et al., 2015; Oelsmann et al., 2024).

Shallow subsidence originating from sediment compaction and dewatering of Holocene deposits in the upper 20–30 m can be measured in situ using Rod Surface Elevation Tables with Marker Horizons (RSET-MH) (Jankowski et al., 2017; Webb et al., 2013) and/or Global Navigation Satellite System (GNSS) interferometric reflectometry

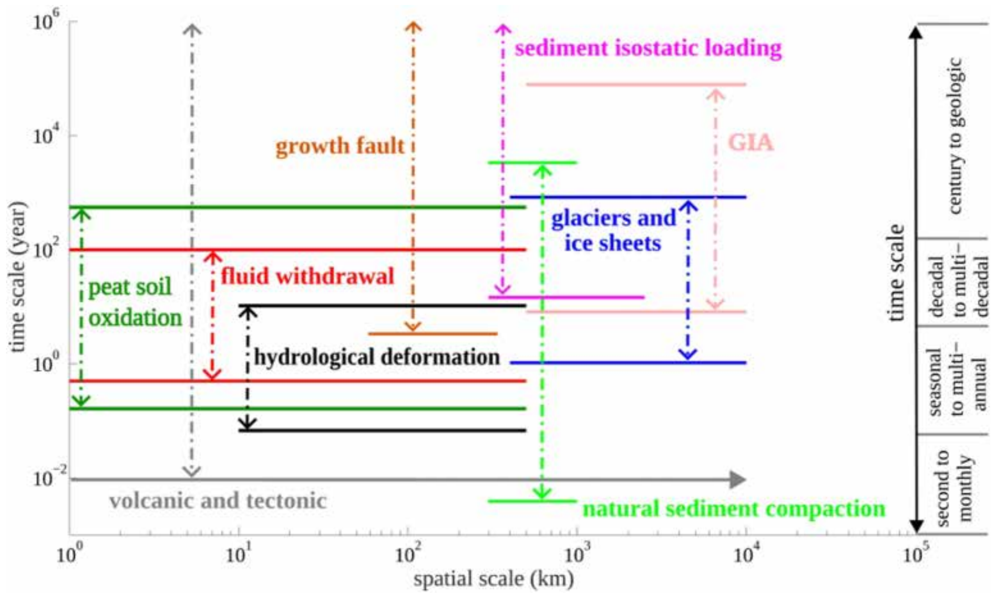

Figure 4. Spatial and temporal scales of processes causing coastal VLM.

(Karegar et al., 2020, 2023). In the Ganges-Brahmaputra-Meghna Delta, RSET-MH measurements, although very scarce, yield average shallow subsidence rates ranging between 5 mm/yr in the polder areas and 8.7 mm/yr in the natural Sundarbans of the delta plain (Akter et al., 2024). In 2019, a larger network of 22 RSET-MH sites (Figure 5) was established in the tidal plain of the Ganges-Brahmaputra-Meghna delta (Wilson et al., 2021), but longer time series are needed to obtain robust shallow compaction rates. The Mekong Delta also contains a growing RSET-MHs network (first one installed in 2010), but results so far are only published for three sites in coastal mangrove forests indicating shallow compaction rates of up to a staggering 42 mm/yr at one site, but these rates are based on short data record (3 years) and include large uncertainty (Lovelock et al., 2015).

Deeper subsidence, driven, for example, by GIA, SIA, deep sediment compaction, tectonic and groundwater over-extraction, can be measured using monitoring techniques like GNSS reference stations (Karegar et al., 2015, 2016, 2020). Available GNSS sites in the Ganges-Brahmaputra-Meghna delta show subsidence rates of 4–8 mm/yr (Steckler et al., 2022). Unfortunately, the availability of GNSS data in the Ganges-Brahmaputra-Meghna, Irrawaddy and Red River deltas is very limited, with sparse or no coverage (Figure 5). Although Vietnam and Thailand have relatively dense GNSS reference networks, data accessibility for the Mekong and Chao Phraya deltas remains an issue that hinders accurate measurements of VLM (Figure 5).

InSAR is a powerful remote sensing technique for measuring VLM with high spatial resolution (Candela & Koster, 2022). InSAR can be applied across the Asian megadeltas (Erban et al., 2014; Higgins, 2016), but it faces challenges due to the decorrelation caused by dense vegetation cover (Umarhadi et al., 2021). The capabilities of InSAR are illustrated in Figure 5 for the Asian megadeltas (Wu et al., 2022). As evident from Figure 5, the city of Yangon in the Irrawaddy Delta is experiencing subsidence of up to 90 mm/yr (2017–2023) and up to 20 mm/yr of subsidence occurs in Bangkok (2015–2021) and Dhaka (2014–2020), likely caused by localized groundwater over-extraction (see Section 3.2.2). A recent study showed that combining GNSS rates with InSAR rates improves the spatio-temporal resolution of VLM for studies on relative SLR and related flood hazards (Sherpa et al., 2023).

Viscoelastic Earth models provide estimates of the present VLM contribution from long-term processes such as GIA and SIA caused by ice, water, and sediment loading. The Asian megadeltas are all situated "far-field" from the Pleistocene ice sheets, thus the impact should be minor. However, modeled meltwater loading of the ocean basin could generate mantle currents that act to lift the adjacent continental margins up (Tamisiea & Mitrovica, 2011) and thus, all five Asian megadeltas could have experienced an uplift from GIA. Using Peltier's model (ICE-6G; Peltier et al., 2015), uplift rates of about 0.3–0.4 mm/yr for the Ganges-Brahmaputra-Meghna, Irrawaddy and Chao Phraya deltas, and 0.2–0.3 mm/yr for the Mekong and Red River deltas were estimated. Faster

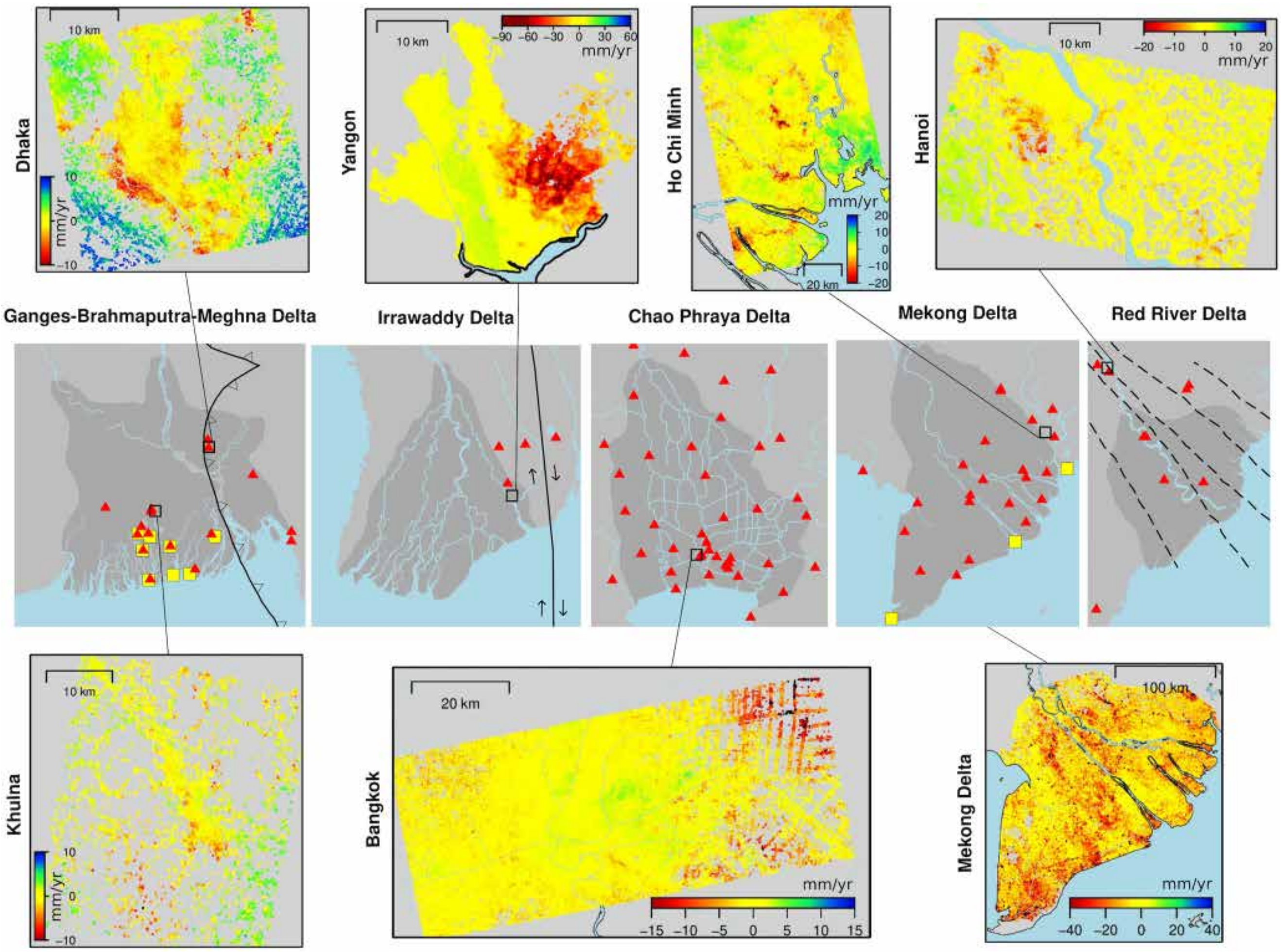

Figure 5. VLM observations available across the five Asian megadeltas. The middle panel shows locations of GNSS continuously operating reference stations (red triangles) and RSET-MH sites (yellow squares). Most of the GNSS station data is not publicly available. GNSS stations are from Steckler et al. (2016, 2022); Steckler and Scott (2020), for the Ganges-Brahmaputra-Meghna Delta; from VNGEONET (http://vngeonet.vn) for the Mekong and Red River deltas, from the National Thai CORS data center (https://www.cdg.co.th/website/en/industries/cors-data-center/) for the Chao Phraya Delta, and from Myanmar GNSS CORS network established in 2011 (handled by Myanmar Earthquake Committee) for the Irrawaday Delta. The raw GNSS data for the Irrawaday Delta from 2011 to 2017 are publicly available through the Earth Observatory of Singapore's scientific data set (https://earthobservatory.sg/). RSET-MH sites for the Mekong Delta are from Lovelock et al. (2015) and from Wilson et al. (2021) for the Ganges-Brahmaputra-Meghna Delta. The Indo-Burma subduction zone is shown by a black line with triangles in the Ganges-Brahmaputra-Meghna Delta. The Sagaing Fault is a major right-lateral strike-slip fault striking north-south to the eastern edge of the Irrawaddy Delta. Major fault lines in the Red River are shown with dashed lines. The upper and lower panels illustrate VLM derived in Line-of-Sight from Sentinel-1 A/B satellites for major cities shown with unfilled squares. VLM rates in Dhaka (2014–2020), Ho Chi Minh City (2017–2021), Hanoi (2015–2021), Khulna (2014–2021) and Bangkok (2015–2021) are from Wu et al. (2022). VLM rates in Yangon City (2017–2023) are from Seeger et al. (2023). VLM rates in the Vietnamese Mekong Delta (2014–2019) are from Copernicus Emergency Management Service—Risk and Recovery Mapping activation 062. The delta polygons are based on delta extents provided by Tessler et al. (2015).

uplift rates due to GIA are predicted by Lambeck's model (Lambeck et al., 2014, 2017; see Text S1 in Supporting Information S1) in the Ganges-Brahmaputra-Meghna Delta (0.6–1 mm/yr) and Mekong and Red River deltas (0.7–0.8 mm/yr), whereas slower uplift rates are estimated in the Irrawaddy Delta (0–0.4 mm/yr) and negligible rates in the Chao Phraya Delta. The modeled GIA rates depend on the chosen type of viscoelasticity, mantle layering, viscosity values, lithospheric thickness, etc (see Text S1 in Supporting Information S1 for details). Nevertheless, it is worth highlighting agreement between the models that the GIA induces uplift rates of an order of magnitude smaller than VLM generated by other natural and anthropogenic drivers, such as shallow sediment compaction or gas/water extraction.

Holocene sedimentation can lead to SIA, contributing to a proportion of present-day long-term subsidence in the Asian megadeltas (Ferrier et al., 2015; Ivins et al., 2007; Karpytchev et al., 2018). The present contribution of SIA in the Ganges-Brahmaputra-Meghna Delta, obtained from models, induces subsidence in the range of 1 and

2 mm/yr, which is further amplified in the east by tectonic faults in the delta (Karpytchev et al., 2018; Krien et al., 2019). However, it is generally rather difficult to isolate the contribution of SIA from VLM observations in deltas, as it is often dominated by shallow sediment compaction and other effects (Grall et al., 2018; Teatini et al., 2011; Törnqvist et al., 2008).

Most of the Asian megadeltas do not have extensive VLM modeling studies available beyond 1D calculations (e.g., Erban et al., 2014; Karlsrud et al., 2017), as they require detailed local (subsurface) data and are demanding to set up. The exception is the Mekong delta, for which in recent years several models were built. The contemporary contribution of natural compaction was modeled for a 2D transect of the southern part of the Mekong delta (Zoccarato et al., 2018), revealing that observed shallow compaction rates (up to >4 cm/yr in the top 20 m; Lovelock et al., 2015) may well be caused by natural autocompaction (hydrologically delayed consolidation and creep) resulting from extremely rapid delta progradation over past centuries.

Land elevation and topography are either measured directly by land leveling and GNSS, or are measured remotely via aircrafts or satellites (optical, radar, LiDAR) and interpolated to a digital elevation model (DEM). High-quality elevation data at high horizontal and vertical accuracy is not available for the majority of the world's coastlines. This results in the use of global satellite-derived DEMs, such as the Shuttle Radar Topography Mission (SRTM, Rabus et al., 2003) and ALOS World 3D (AW 3D, Tadono et al., 2016) for assessing coastal flooding in lowlands, such as in the Irrawaddy Delta (ICHAM, 2016). However, these global DEMs suffer from large vertical errors and artifacts that impact the quality of coastal flood exposure assessments (Minderhoud et al., 2019; Seeger et al., 2023). Recent studies aimed to improve older DEMs by using machine learning algorithms, as shown with advances such as the CoastalDEM v2.1 (Kulp & Strauss, 2021; source DEM: SRTM; data acquired in 2000) and FABDEM (Hawker et al., 2022; source DEM: Copernicus DEM; data acquired in 2010–2015), or by new DEM generations using recently available satellite LiDAR data (Pronk et al., 2024; Vernimmen & Hooijer, 2023). All of these aim to enhance the much needed vertical accuracy (e.g., Gesch, 2018; Schumann & Bates, 2018).

Though equally important, the vertical reference of elevation data to local sea-level is still underrepresented, but recent publications reveal that there is increasing awareness and advancements (Hauser et al., 2023; Minderhoud et al., 2019; Seeger et al., 2023; Vernimmen et al., 2020). For example, with their local TopoDEM, which is based on directly measured data from topographic maps, Minderhoud et al. (2019) showed that the Mekong delta is only approximately 0.8 m above local mean sea-level, while the global SRTM and MERIT DEMs significantly overestimate the delta elevation by more than 2 m. Even larger discrepancies have been documented for the Irrawaddy Delta, where an in-depth comparison of currently available DEMs found uncertainties ranging between 0.1% and 50% of the deltaic area, which could result in between 6,200 and 3.8 million more people being exposed to inundation due to a 1 m SLR by 2100 or sooner, depending on the DEM used (Figure 6 and Figure S3 in Supporting Information S1; Seeger et al., 2023).

Finally, the topography of deltas is not constant; it dynamically responds to changes in sediment accumulation or subsidence-induced elevation loss and morphological changes. Consequently, the actuality of DEMs is critical to represent recent elevation and morphology (such as channel networks). This issue is particularly relevant for outdated DEMs, such as the SRTM or its post-processed versions (e.g., CoastalDEM) with source data from 2000, that no longer adequately reflect the present-day deltaic landscape. Besides the need for actual elevation data sets, DEMs require regular updates, integrating information on sedimentation dynamics and VLM, which then also need to be incorporated into existing elevation-informed coastal flood hazard assessments.

3.1.6. Sediment, Shoreline, and Deltaic Landform Changes

Despite their importance, estimates of sediment fluxes to and from deltas remain relatively approximative due to difficulties in obtaining long-term surveys, political restrictions to display data, or technical difficulties in assessing reliable sediment fluxes, particularly in tidal zones of deltas. The most complete surveys of sediment delivery are typically undertaken alongside constructions of important infrastructure, such as bridges and dams. A significant portion of such assessments is not available to the public and remains as gray literature. In addition, sediment gauging is not always part of a longer hydrological monitoring survey. For instance, for the Ganges-Brahmaputra-Meghna Delta, there is no public data set on the Indian side of the delta, and Bangladesh has not released sediment concentration data since the mid-nineties (M. Rahman et al., 2018). This situation hampers the capacity to measure long-term trends in sediment transport and deposition and how these have been responding to

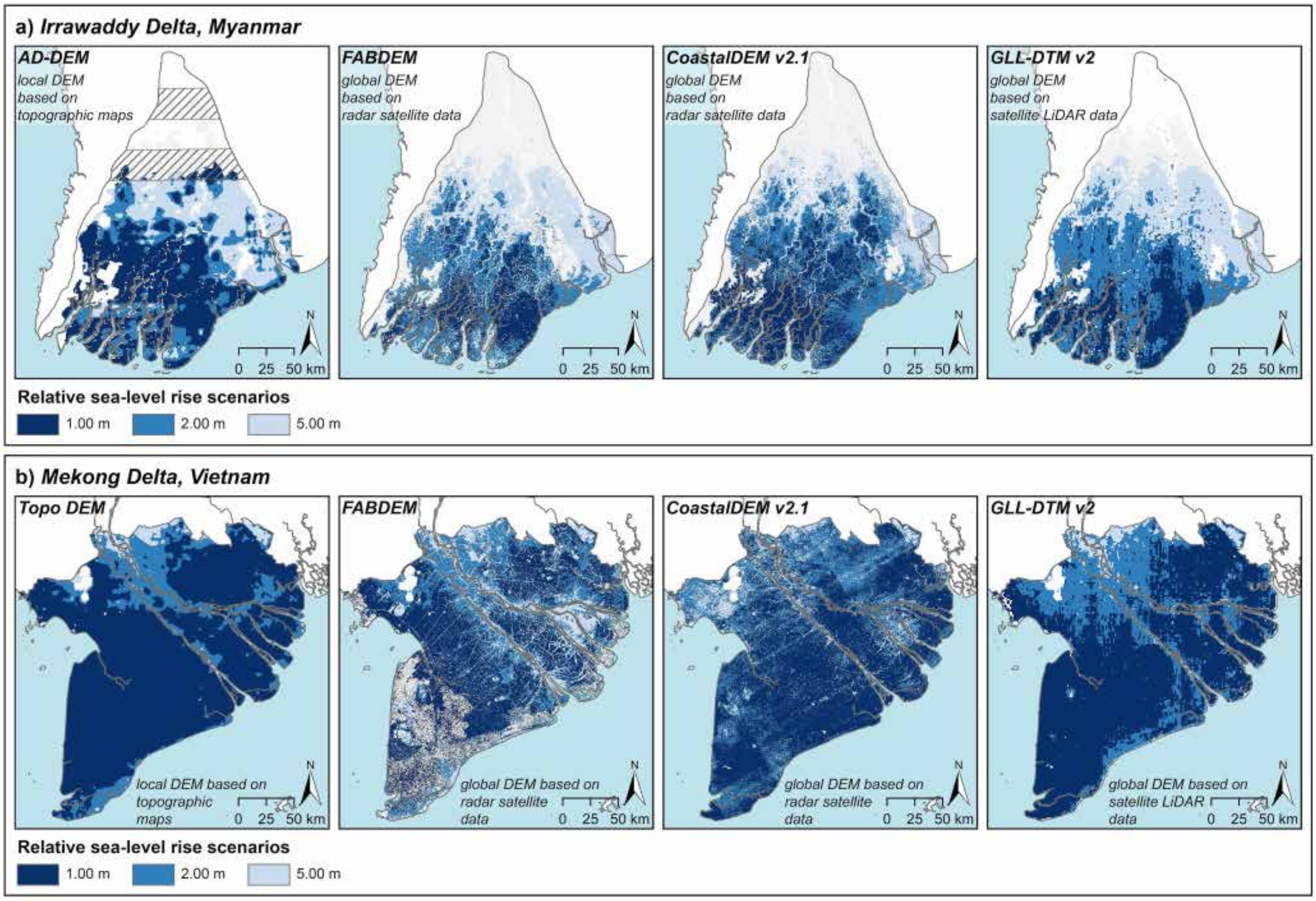

Figure 6. Projected area below sea-level following relative SLR scenarios of 1, 2, and 5 m for the (a) Irrawaddy, and (b) Mekong Delta, as indicated by different local, radar satellite, and satellite LiDAR DEMs referenced to local continuous mean sea-level (Hawker et al., 2022; Kulp & Strauss, 2021; Minderhoud et al., 2019; Seeger et al., 2023; Vernimmen & Hooijer, 2023). Areas in the AD-DEM containing interpolation artifacts are marked with hatching (see also Seeger et al., 2023).

anthropogenic activities and climate variability, factors that are critical for effective decision making going forward. Alternative approaches have been adopted based on river discharge data coupled to models of sediment transport, calibrated with in situ velocity profiling and water column suspended load sampling (Baronas et al., 2020; Lupker et al., 2011). Sediment transport has also recently been more integrated into semi-distributed physically based hydrological models, such as the INCA (INtegrated CAtchment) model, allowing predictive assessments on the future of sediment transport (e.g., Bussi et al., 2021; Dunn et al., 2019).

Satellite imagery (e.g., Landsat) has been extensively used to assess landform changes of large river systems, as well as their deltas and coastlines, with some key examples in the Asian megadeltas including Kummu et al. (2008), Lam-Dao et al. (2011), Li et al. (2017), and Marchesiello et al. (2019) for the Mekong River and its coastal deltaic areas, and Baki and Gan (2012), Hossain et al. (2013), and Dewan et al. (2017) for the large river systems in the Ganges-Brahmaputra-Meghna Delta. These studies found that in the Mekong delta, erosion is a profound and widespread hazard. At present, 50%–66% of the entire deltaic coastline experiences erosion, with rates reaching up to 50 m per year in some areas (Anthony, 2015; Li et al., 2017; Marchesiello et al., 2019). Contrastingly, along the coastline of the Ganges-Brahmaputra-Meghna Delta, land creation continues to exceed land erosion, but this is highly spatially heterogeneous, with erosion more prominent further away from the river mouth (Paszkowski et al., 2021 and references therein). In the Irrawaddy delta, Anthony et al. (2019) and D. Chen et al. (2020) use Landsat imagery to delineate areas of eroding channels and coastlines, and find that from 1974 to 2019, between 42% and 49% of the delta's shoreline underwent erosion, with the most significant erosion observed in the western areas, where maximum rates reached 19.3 m per year (D. Chen et al., 2020). Similarly, in the Chao Phraya and Red River deltas, erosion hazards seem to be widespread but less severe, with mean annual coastal erosion rates of approximately 10 m along the most severe areas in both deltas (Bidorn et al., 2021; Saito et al., 2007).

Despite the unique opportunities provided by remotely sensed data, using satellite imagery for analysing erosion dynamics can be laborious, requiring the manual delineation of images to detect changes over time. Therefore, automating this process is of great value. Passalacqua et al. (2013) initially developed a statistical framework to automatically extract deltaic channel networks from satellite imagery in order to determine key attributes, such as channel width and island geometries, and analyse their statistical behavior. Isikdogan et al. (2015, 2017) developed this approach further by establishing a model called RivaMap, that automatically extracts complex deltaic distributaries and braided rivers from satellite imagery at multiple scales. Jarriel et al. (2020) further built on the RivaMap model to create the DeepWaterMap model, which enables more detailed quantification of deltaic changes and why these may be occurring and what their impacts are. They applied the DeepWaterMap model to the Ganges-Brahmaputra-Meghna deltaic channel network and found that anthropogenically modified embanked parts of the delta have higher rates of geomorphic instability than the adjacent natural Sundarban mangrove forest (see Jarriel et al., 2020 for further detail on the approach). This modeling approach has now been applied to 48 deltas across the world to assess the patterns and rates of channel changes within river deltas (Jarriel et al., 2021). Finally, Boothroyd et al. (2021) illustrate the power of Google Earth Engine in transforming the spatiotemporal quantification of fluvial geomorphological dynamics, emphasizing that it enables research on the wider riverscape (i.e., water, sediment, and vegetation) to take place at higher spatial resolutions, over greater spatial extents, and at finer temporal resolutions than ever before. Thus, via the integration of satellite imagery, Google Earth Engine, data-driven modeling, and GIS analyses, landform changes in the typically inaccessible and relatively data-scarce Asian megadeltas can be characterized and quantified continuously, as more remotely sensed data becomes available (Boothroyd et al., 2021; Piégay et al., 2020; Shamsuzzoha & Ahamed, 2023).

To conclude Section 3.1, it is important to highlight the critical value of local knowledge in the assessment and quantification of the aforementioned geophysical drivers. Leveraging technological advances and combining these with local knowledge is the only way to obtain a nuanced understanding of how these processes drive coastal flooding on the ground. Typically passed down through generations, this wisdom offers invaluable insights into flood hazard patterns and traditional adaptation strategies, as well as their evolution, in response to such hazards. By entwining this deep-rooted understanding with advanced methods of data collection and assessment, more targeted and context-specific resilience measures can be developed.

3.2. Main Human Pressures

Alongside the complex interactions of the key natural drivers of change in the five Asian deltas discussed in Section 3.1, anthropogenic activities have played increasingly dominant roles in shaping deltaic dynamics. These range from extensive land use change, such as urbanization, to resource exploitation, and large-scale infrastructure, such as dams or diversions, constructed within the river catchments of these important five deltas. This section delves into the predominant anthropogenic pressures in the Asian megadeltas, with the key messages summarized in Table 2.

3.2.1. Population, Economy, and Megacities

Population growth has emerged as a significant driver of coastal flood risk in the low elevation coastal zone, as it expanded human settlement into highly exposed coastal zones (Figure 2c; Reimann et al., 2023). The significant population growth and economic development in Asian megadeltas drive changes in land use patterns and encourage the construction of flood control infrastructure, coastal development projects, and water management practices. Such alterations can inadvertently disrupt natural water and sediment flow dynamics, disturb ecosystems, and increase the risk of coastal regions to flooding.

The most dramatic population growth has occurred in the Chao Phraya Delta, nearly doubling in size (+81%) over the past 20 years, totaling almost 26 million inhabitants in 2020 (Table S1 in Supporting Information S1). This accounts for ∼37% of Thailand's total population, concentrated on less than 5% of the national land area, and reflects migration to the delta, especially to Bangkok. The population density in the delta has also doubled over two decades, reaching 1,100 inhabitants/km^2 in 2020 (Figure 2c). In contrast, the Red River Delta has seen little population change (1%) over the same period, reflecting that the large growing city of Hanoi is outside the delta limits, while the other four deltas all contain at least one major growing city (Figure 2c).

Table 2
Overview of the Main Human Pressures: What We Know, the Remaining Gaps, and Key Challenges Associated With Coastal Flood Assessments in the Asian Megadeltas

3.2.1 Population, economy and megacities

- Major cities in Asian megadeltas have experienced a threefold or more increase in urban population since 1950
- By 2030 (compared to 2010), the population in Yangon and Bangkok will likely increase by ∼50%, while Dhaka and Ho Chi Minh City are estimated to experience a population growth of over 80%
- Population growth, combined with economic growth, contributes to coastal flooding via urbanization, land use changes, groundwater extraction, infrastructure construction, flood protection structures, and sand mining

What we know	Gaps in terms of observations and/or models	Key challenges to be addressed in the context of Asian megadeltas
3.2.2 Deltaic land use/land cover changes		
Urbanization Transitioning from vegetated to urban areas reduces water absorption, impacting runoff and coastal flood hazards Since 1974, urbanization increased by ∼1,500% in the Irrawaddy Delta, specifically in Yangon, and by ∼300% in urban areas <5 m above mean sea level Since 1990, urban areas that lie below 5 m above mean sea level have increased by ∼72% in the Ganges-Brahmaputra-Meghna Delta, by 194% in the Chao Phraya Delta, and by 70%–80% in the two Vietnamese deltas	• **Knowledge gaps**: The intricate relationship between surface water and urbanization in Asian megadeltas remains largely unexplored, leaving significant knowledge gaps • **Lack of comprehensive analysis**: Integrating LULC data sets, derived from remote sensing products (such as population density and presence of built-up areas), and socioeconomic indicators in the Asian megadeltas, hinders a comprehensive understanding of the influence of urbanization on coastal flood dynamics	• **Evaluate and understand the effects of urbanizsation on coastal flooding in the Asian megadeltas**. The assessment should consider factors such as variations in peak discharge, runoff volume, changes in impervious surface areas, and the extent of coastal flooding • **Determine how quickly coastal flood dynamics respond to increased urbanizsation** to account for the fact that the combined effects of urbanization and climate change are accelerating in Asian megadeltas
Agriculture, aquaculture and mangrove losses Since the 1970s, in the mangrove regions of Asian megadeltas, significant land use change has been taking place, particularly to brackish water aquaculture Conversion of mangroves to aquaculture areas leads to a loss of ecologically important areas, as well as a series of interconnected consequences, including subsidence and erosion of coastlines, which directly contribute to coastal flooding	• **Assessing the cumulative effects** of agricultural practices, aquaculture activities, and mangrove retreat on coastal flooding, involves understanding their combined impacts and the underlying mechanisms through which they contribute to the dynamics of coastal flooding • It remains a challenge ***to attribute patterns in coastal flood dynamics to specific changes in land use***. Given the complexity of interacting factors, understanding is still limited on which LULC changes lead to the changes observed in flood dynamics	• **Improve hydrodynamic models that incorporate factors on land cover changes, water management practices, sediment dynamics, and tidal influences to accurately assess coastal flooding in Asian megadeltas and understand the interactions** between agriculture, aquaculture, mangrove retreat and coastal flooding • **Understand the role of mangroves in mitigating coastal flood extents**. This includes quantifying the ability of mangroves to attenuate wave energy, trap sediment, reduce erosion, and provide natural coastal flood protection
Groundwater extraction Groundwater depletion has been observed in all five Asian megadeltas Currently, cities and rural areas in the Asian megadeltas experience high land subsidence rates exceeding 1 cm/year due to groundwater over-extraction Extraction-induced land subsidence dominates the total subsidence signal in Asian megadeltas, particularly in their cities	• **Limited available information**: The Chao Phraya and Mekong deltas are the most well-documented, while the Red River and Ganges-Brahmaputra-Meghna deltas are partially documented. Groundwater monitoring is almost entirely missing in the Irrawaddy Delta.There are a lack of reliable estimates for groundwater abstraction in rural deltaic areas, and the extent of groundwater use for agricultural purposes remains unknown • **Nonlinear groundwater influence**: The link between subsidence and groundwater extraction is complex, influenced by various non-linear factors associated with human activities, which are still not fully understood • **Impacts of mitigation measures** could introduce unintended negative side effects due to limited understanding and estimation of their impacts	• **Improve monitoring networks** in undocumented and data-scarce areas, and ***strengthen regulations of groundwater abstraction*** rates across all five Asian megadeltas • **Investigate the highly non-linear nature** of groundwater extraction-induced land subsidence and its relationship with coastal flooding • **Install an in- situ subsidence monitoring network** to accurately track and understand the extent of land subsidence, to unravel urban differential subsidence into individual drivers and processes at different depths and determine the groundwater extraction-induced contribution to subsidence in Asian megadeltas • **Make projections of extraction-induced subsidence, based on different scenarios of future groundwater use**, as has been developed for the Mekong Delta • **Adopt a systems perspective**, including the relevant subsurface processes and feedback loops when designing miitigation strategies

Table 2
Continued

Sand mining Rapid socio-economic development in the region has created a substantial demand for river sand for construction, resulting in escalated rates of sand extraction Sand mining contributes to the deepening of river and estuary channels, causing erosion along riverbanks and coastal areas. It also alters geomorphology, deepens riverbeds, and impacts tidal dynamics within the delta	• **Incomplete monitoring**: Sand mining monitoring in Asian megadeltas is often insufficient, leading to gaps in tracking extraction rates, volumes, and locations. It is suspected that the reported volumes, obtained through legal licenses, do not capture the full extent of sand mining, including unreported or illegal extraction, which is believed to be much larger • **Uncertain coastal impacts**: Consequences of sand mining in Asian megadeltas, such as the long-term effects on river morphology, sediment transport, and coastal stability, are not yet fully understood. This knowledge gap limits the ability to accurately predict and mitigate potential impacts on coastal flooding	• **Develop modelling approaches in the Asian megadeltas to simulate the complex interactions of sand mining, sediment dynamics, and geophysical drivers** to assess these cumulative effects on elevation maintenance of deltas and coastal flooding • **Use remote sensing and deep learning techniques which aid in monitoring and assessment efforts** as they hold potential for quantifying sand mining activities and sediment budgets in Asian megadeltas that are not possible with the limited in situ data available • **Support Governments in strengthening regulations on sand mining activities** via more comprehensive monitoring and assessment systems
3.2.3 Upstream interventions (dams)		
Dam impacts on coastal flooding can be indirect but profound, regulating river flows and trapping sediments, which can influence and contribute to coastal flood dynamics Sediment dynamics in the Mekong and Red River deltas have already substantially reduced. In the Ganges-Brahmaputra-Meghna and the Irrawaddy deltas, the sustainability of future sediment loads is of concern, as the river basins face many planned dams. The Chao Phraya Delta seems not to be impacted by dams constructed upstream	• **Neglected role of dams**: Despite their potential significance, the inclusion of dams in coastal flood assessments in Asian megadeltas is often neglected • **Lack of comprehensive data** on dams, coupled with the difficulties in accurately estimating reservoir outflows and integrating dam characteristics into hydrodynamical models, contribute to the existing gaps in understanding the impacts of dams on coastal flooding in the deltas • **Remote sensing observations** have increasingly been used to assess water and sediment fluctuations as a result of upstream interventions, particularly within transboundary river systems where data sharing is particularly concerning. However, their use to monitor the impacts of dams is still limited	• **Conduct research to better understand the complexities of sediment transport in dam-affected river systems**. Develop methodologies to predict the magnitude and timing of sediment reduction caused by dams, considering both short-term and long-term impacts on coastal flooding • **Improve hydrodynamic models that incorporate dams and accurately simulate reservoir operations, water releases, and sediment dynamics**. This will enable a more comprehensive understanding of the interaction between dams and coastal flooding • **Utilizing remote sensing data in the Asian megadeltas** can provide a comprehensive understanding of the complex interactions between dam construction and coastal flooding, offering valuable insights into dam design, water levels and extent over time, and operational dynamics

When focusing on urban population changes in the Asian megadeltas, however, all large cities have grown threefold or more between 1950 and 2010 (Table S2 in Supporting Information S1). Gross Domestic Product has significantly increased since 1990 in all five Asian megadeltas (Table S1 in Supporting Information S1). Such changes have an impact on the damages that occur during floods: while fatalities due to coastal flooding have decreased over time as protection of deltaic regions improve, economic damages due to coastal flood events are on the rise (e.g., in Bangladesh, Alam & Dominey-Howes, 2015; Lumbroso et al., 2017). The economies of the deltas are growing rapidly, with service and manufacturing sectors gaining traction over more traditional agriculture and fishery activities (Arto et al., 2019).

3.2.2. Deltaic Land Use/Land Cover Changes

3.2.2.1. Urbanization

Increasing urbanization is leading to an increase in artificial and impervious surfaces, such as roads and buildings. In the Asian megadeltas, urban expansion is still ongoing. Figure 7 displays satellite-derived night light brightness maps, obtained from the National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite (NPP-VIIRS) Day/Night Band (Small & CIESIN, 2020), serving as a proxy for urban growth since 1992 (Small et al., 2018). In the Ganges-Brahmaputra-Meghna Delta (Figure 7a), a significant increase in brightness is observed in two densely populated megacities, Kolkata and Dhaka, and in their surrounding areas. Additionally, a significant developmental shift post-2002 is evident in the western part of the delta in India, in contrast to the remainder of the delta. The Chao Phraya Delta (Figure 7c), with Bangkok brightly lit in the center, shows a significant increase in

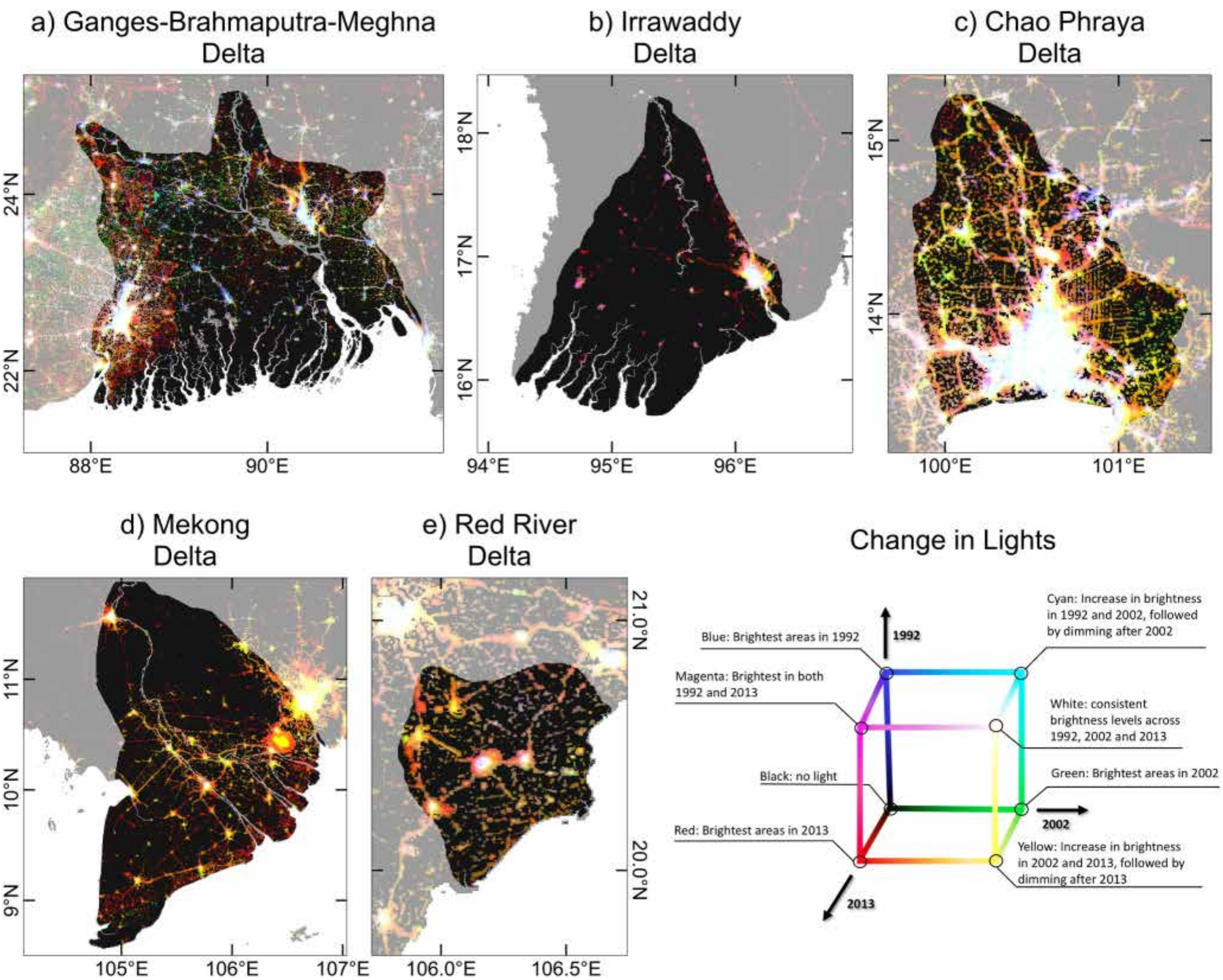

Figure 7. Spatial distribution and temporal evolution of nighttime lights between 1992 and 2013 from the National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite (NPP-VIIRS) Day/Night Band (Small & CIESIN, 2020) for (a) the Ganges-Brahmaputra-Meghna Delta, (b) the Irrawaddy Delta, (c) the Chao Phraya Delta, (d) the Mekong Delta, and (e) the Red River Delta. The delta polygons are based on delta extents provided by Tessler et al. (2015).

brightness after 2002 across the entire delta. In the Mekong and Red River deltas (Figures 7c and 7d), we observe a significant expansion of brightness across the deltas since 2002, emphasizing the interconnected spatial network of development. Analysing satellite images from 1974 to 2021, Vogel et al. (2022) revealed a 1,500% increase in urban areas in the Irrawaddy Delta, expanding from under 100 km^2 to about 1,640 km^2 by 2021 (∼5% of the delta area), primarily attributed to the development of Yangon City (Figure 7b). They also noted that urban areas located below 5 m in the delta have experienced a growth of ∼300%, making them more susceptible to flooding and the impacts of SLR. McGranahan et al. (2023), using a combination of the MERIT DEM and the degree of urbanization data set based on population density, built-up density, and total population, have shown that between 1990 and 2015, the urban area in the Bangladesh part of the Ganges-Brahmaputra-Meghna Delta has increased by 158% (∼72% < 5 m above sea level) and by 106% for the Chao Phraya Delta (∼194% < 5 m above sea level). They also estimated the changes in extents of built-up areas in land below 5 m in the two Vietnamese deltas, the Mekong and the Red River deltas, and observed a 70%–80% increase.

The conversion of vegetation into areas used for housing and industry diminishes the land's water absorption capacity, resulting in increased runoff, amplified peak flow discharges and their frequencies, and heightened risk of coastal flooding (Morita, 2016). The Chao Phraya Delta provides a prime example of this phenomenon. The completion of the Chao Phraya Dam in 1957 triggered rapid urbanization, transforming the coastal landscape and converting agricultural land, floodplains, and waterways into developed areas (World Bank, 2009). Historical floods in 1983 and 1995 in the Chao Phraya Delta highlighted the impact of urbanization on drainage capabilities and flood protection. The reduced drainage capacity, combined with tidal and meteorological factors, caused extensive flooding in Bangkok, leading to significant damages (Tang et al., 1992; Terry et al., 2021). Urban expansion also impacts the local hydrogeological conditions, as the phreatic water table is actively lowered through drainage to create favorable conditions for construction, resulting in increased shallow compaction (Minderhoud et al., 2018) and driving urban differential subsidence (de Wit et al., 2021), and increased groundwater extraction to meet the growing water demand from deeper layers (see section below).

3.2.2.2. Agriculture, Aquaculture, and Mangrove Losses

A range of land use/land cover (LULC) changes have been occurring in the agricultural sector, including the retreat of certain crops like rice, in favor of the development of aquaculture farms due to increased salinization, market orientation, and waterlogging. Vu et al. (2022), for example, show that in the Mekong delta, rice-growing areas increased from 2001 to 2015 and then declined until 2020, while aquaculture areas increased between 2001 and 2020. For the coastal part of this delta, M. H. Phan and Stive (2022) confirm that in 1973 aquaculture was virtually non-existent, and by 2020, it occupied 32% of the territory, to the detriment of vegetation zones (crops and mangroves). The mangrove area in the Mekong Delta has experienced a significant decline of 45% between 1973 and 2020, primarily attributed to factors such as aquaculture encroachment and coastal erosion (M. H. Phan & Stive, 2022). In the Chao Phraya Delta, 30%–40% of mangroves have been lost to shrimp farms (Hamilton, 2013), a trend that is also prevalent in the Red River Delta where 49% of mangroves have been covered to aquacultural land uses (Long et al., 2021). The high commercial value of shrimp cultivation in the Ganges-Brahmaputra-Meghna, the Chao Phraya and the Mekong deltas has also resulted in significant growth of this sector, now contributing ∼6% to Bangladesh's and ∼1% to Thailand's and Vietnam's Gross Domestic Product, respectively (Johnson et al., 2016; Lan, 2013; Szuster, 2003; Thu Trang & Loc, 2021). In the Irrawaddy Delta, mangrove coverage drastically declined by 72% between 1974 and 2021 (Vogel et al., 2022). This significant loss can similarly be attributed to the expansion of aquaculture, brine ponds, and agricultural areas.

The conversion of mangroves into aquaculture and agricultural areas across all Asian megadeltas leads to exacerbated erosion of coastlines and the loss of ecologically diverse and important areas, reduced retainment of sediments and organic matter by mangroves, leading to increased subsidence, changes in flow and sediment dynamics, and significant reduction in the natural absorption of coastal wave energy during extreme events, which all directly contribute to coastal flood impacts.

3.2.2.3. Groundwater Extraction

Groundwater extraction is significant in all five Asian megadeltas (Erkens et al., 2015), observed using both monitoring wells (Jasechko et al., 2024) or satellite-based estimates (Rodell et al., 2018), especially from the Gravity Recovery and Climate Experiment (GRACE) twin satellites (Rodell & Reager, 2023). GRACE makes it possible to map total water storage variations at the global and regional scales at 10-day to a monthly timescale since 2002, from which groundwater storage trends can be derived (J. Chen et al., 2016).

Widespread groundwater exploitation in the Chao Phraya Delta started in Bangkok in the 1950s for municipal and industrial purposes, which resulted in substantial land subsidence, with peak rates exceeding 10 cm/yr during the 1980s (Lorphensri et al., 2011; Phien-wej et al., 2006). By imposing strict groundwater policies and a gradual increase in groundwater taxation, the city managed to stop the overexploitation and the current groundwater extraction-induced subsidence in the city center has reduced to less than 1 cm/yr, with some parts seeming to experience a mild surface rebound due to groundwater recovery (e.g., Intui et al., 2022; Ishitsuka et al., 2014). However, past extraction-induced subsidence has caused the city to irreversibly lose more than 1 m in elevation, which has greatly increased the city's exposure to coastal floods (Phienwej & Nutalaya, 2005). While Bangkok has stabilized, large parts of the surrounding more rural areas of the Chao Phraya Delta still experience extraction-induced subsidence rates of up to 2 and 3 cm/yr (Pumpuang & Aobpaet, 2020).

Groundwater pumping in the Mekong Delta greatly increased following Vietnam's transition to a market economy in 1986, which instigated rapid land-use change, agricultural intensification and urbanization, all increasing groundwater demands and acceleration of land subsidence rates (Minderhoud et al., 2018). GRACE observations, along with both in situ measurements and hydrological models, recently revealed widespread groundwater depletion in the Mekong Delta Aquifer of the Lower Mekong region (Upadhyay et al., 2024). Over 2003–2016, groundwater storage has been declining at a rate of ∼0.68 cm/year, resulting in a total volume loss of 18.28 km^3 over the 14-year period, with depletion rates higher in the coastal regions of the delta (Upadhyay et al., 2024). InSAR-based estimates revealed subsidence rates in parts of the delta of 1–4 cm/yr during 2006–2010 (Erban et al., 2014) and delta-wide hydrogeomechanical modeling of groundwater extraction since 1991 revealed an acceleration in extraction-induced subsidence, with a delta-wide average of 1.1 cm/yr in 2015 and in some places exceeding 2.5 cm/yr (Minderhoud et al., 2017, best-estimate scenario). While policies to protect groundwater have recently been put in place, groundwater depletion still persists in many parts of the delta (Duy et al., 2021) and recent InSAR-based estimates (2014–2019) show peak rates of up to 5 and 6 cm/yr (Minderhoud, Hlavacova, et al., 2020), suggesting a continuation of the previous accelerating trend as projected for the business-as-usual extraction-induced subsidence scenarios (Minderhoud, Middelkoop, et al., 2020).

In the Ganges-Brahmaputra-Meghna Delta, declining groundwater levels (more than 1 m/yr during 1985–2005) of shallow aquifers in Bangladesh were reported in urban and peri-urban areas around Dhaka and in the north-central, northwestern, and southwestern parts the country due to intensive abstraction of groundwater during the dry-season for rice cultivation (Shamsudduha et al., 2009). These observations were later confirmed with declining trends in groundwater storage estimated from GRACE (Shamsudduha & Panda, 2019), which suggestively drives land subsidence, for example, in East Dhaka and Khulna (Higgins et al., 2014; Steckler et al., 2022).

Deciphering the impacts of groundwater extraction on land subsidence in the Irrawaddy Delta remains challenging, as groundwater monitoring only exists for a few artesian irrigation projects and in urban areas (Viossanges et al., 2017). Among the Southeast Asian cities, some of the highest abstraction rates are observed in Yangon City (Hashimoto et al., 2022), contributing 4–10 cm of subsidence per year (Seeger et al., 2023; van der Horst et al., 2018). For the more rural deltaic areas, reliable abstraction estimates are missing and groundwater use for cultivation (horticulture, aquaculture, etc.) is unknown (Viossanges et al., 2017).

3.2.2.4. Sand Mining

The rapid urbanization of the Asian megadeltas, as well as development nationally and regionally, has created a substantial demand for river sand for construction, resulting in escalated rates of sand extraction that often surpass the natural replenishment capacity of rivers (Kumar et al., 2023). In many of the river channels of the Asian megadeltas, particularly in the Mekong, Ganges-Brahmaputra-Meghna, and Irrawaddy deltas, sand is being extracted (D. Chen et al., 2020; Gruel et al., 2022; Hackney et al., 2020; Saito et al., 2007), partly under legal licenses with reported volumes, but presumably the real volumes including the unreported or illegal extractions are much larger (Bari & Haque, 2022; Yuen et al., 2024).

Sand mining leads to the deepening of river and estuary channels, can result in erosion of riverbanks and coastal areas, as well as modifications to the geomorphology, and affects the tidal dynamics in the delta (Park, 2024; Section 3.1.2). A data-driven, process-based modeling study in the Hau River in the Mekong Delta revealed the increase of tidal amplitude, and tidal propagation length, increasing the backwater effect upstream as a result of extensive sand mining (Eslami et al., 2019, 2021). Sediment mining is prevalent throughout the Irrawaddy Basin, with a particular emphasis on extracting coarse sand and gravel, which are valuable materials for construction purposes. According to D. Chen et al. (2020), the documented annual volume of sediment mining reached 20 million tonnes, ∼10% of the estimated total sediment load. However, the actual amount of unreported or illegal sand mining could be significantly higher, posing a substantial threat to the stability of the delta (WWF, 2018).

Gruel et al. (2022) used Sentinel-1 (10 m spatial resolution) and Landsat-8 imagery (30 m spatial resolution) over the Mekong Delta to detect vessels for sand extraction, and correlated these with locally measured bathymetric survey data. They estimated that sand mining in the Vietnam Mekong Delta increased by 25% from 2015 to 2020, reaching ∼47 Mm^3/year. Hackney et al. (2020) employed PlanetScope imagery (5 m spatial resolution) to estimate sand extraction volumes, tracking sand barges, in a specific section of the Upper Mekong Delta. They showed that extraction rates in 2020 (∼59 Mm^3) were nearly twice as high as previous estimates for sand extraction in this region and exceed the current best estimates for the entire Mekong Basin (∼50 Mm^3). Kumar et al. (2023) developed a cost-effective remote sensing-based deep learning framework for quantifying sand mining activities and budgets in the Mekong Delta. Their study reveals that sand mining increased by ∼52% between 2015 and 2022. Notably, the Lower Mekong Delta, where intensive mining activities are concentrated, accounts for nearly 90% of the total sand mining volume extracted within the entire delta. This automated remote sensing-based deep learning framework exhibits great potential for application in other Asian megadeltas.

3.2.3. Upstream Interventions

The impacts of dams on coastal flooding in the Asian megadeltas is typically indirect but profound. When dams regulate river flows and trap sediment, they modify natural flow patterns, disrupt hydrological regimes, and alter sediment transport processes, critical for coastal equilibrium. Improper dam operations, such as abrupt releases or excessive water storage, can result in sudden flood events in downstream reaches. When these releases coincide with coastal storms, flooding in delta systems can be widespread and severe. Nevertheless, the consideration of dams in coastal flood assessments is frequently overlooked due to limited data availability, as well as the complexities associated with estimating reservoir outflows and the challenges of incorporating dam features and operational decisions into hydrodynamical models (Boulange et al., 2021).

The most widely studied impacts of dams on sediment dynamics has been in the Mekong basin, given the extensive development of hydropower projects across the catchment. More than 50% of the annual sediment supply from the Mekong River basin is already trapped behind upstream dams (Kondolf et al., 2022). This sediment reduction, combined with approximately one-third of the pre-dam sediment influx currently being mined from riverbeds in Vietnam and Cambodia (Kondolf et al., 2022), is resulting in widespread and profound sediment starvation and accelerated subsidence in the lower Mekong delta, exacerbating coastal flooding and erosion. In the Red River basin, the construction of the Hoa Binh Dam in northern Vietnam in 1988 had a significant impact on the distribution of suspended sediment in the Red River delta. According to Vinh et al. (2014), despite a modest 9% decrease in water discharge, the annual suspended sediment flux at Son Tay, near Hanoi, experienced an average reduction of 61%.

Although the Ganges-Brahmaputra-Meghna delta is still currently classified as a stable delta (Brammer, 2014), if the planned 414 dams within the catchment are constructed, the sediment flux to the delta could reduce by 88% by the end of the century (Best, 2019; Dunn et al., 2019; Higgins et al., 2018; M. Rahman et al., 2018). This significant reduction in sediment supply will impact the delta's ability to maintain its elevation above sea-level and will increase its risk to coastal flooding in the future (Higgins et al., 2018; Paszkowski et al., 2021 and references therein; M. M. Rahman et al., 2022). The Chao Phraya and Irrawaddy deltas have also been observed to remain stable, with limited impacts felt by upstream dam construction. In the Chao Phraya River system, for instance, two large storage dams, one on the Ping River (Bhumibol Dam, 1964) and one on the Nan River (Sirikit Dam, 1972) have been found to not have had an impact on sediment delivery to the delta (Bidorn et al., 2021). In the Irrawaddy Basin, there are few dams, and the limited availability of sediment data makes it difficult to assess the impact of these dams on sediment fluxes to the delta. While Latrubesse et al. (2021) document the river's sediment delivery not being dramatically impacted so far, other studies report induced reductions of sediment load by up to 30% and substantial geomorphological changes (D. Chen et al., 2020; Lazarus et al., 2019; Syvitski et al., 2009). As the rate of dam construction increases alongside population growth and energy demand (mainly supplied by hydropower), planned projects could reduce sediment loads by an additional 19% (Tessler et al., 2018).

It is difficult to attribute changes taking place in delta systems to interventions made upstream. Recently, space observations have increasingly been used to assess water and sediment fluctuations as a result of upstream interventions (e.g., Foteh et al., 2018; Moragoda et al., 2023), particularly within transboundary river systems where data sharing is particularly challenging. The use of remote sensing technologies to monitor the impacts of dams is limited in the five Asian deltas and only a few studies exist. For instance, Zhang et al. (2014) combined a suite of satellite observations, namely water surface area estimations from MODIS and surface elevation measurements derived from the Geoscience Laser Altimeter System on board the Ice, Cloud, and land Elevation Satellite, in order to construct an area-elevation relationship and monitor changes in reservoir storage in South Asia, including some dams and associated reservoirs that feed into the Ganges-Brahmaputra-Meghna delta. Beveridge et al. (2020) use visible and Near Infra-Red reflectance from the Landsat satellite series to detect changes in suspended sediment concentrations as a result of recent dam constructions in a sub-basin of the Lower Mekong River system. In addition to analysing suspended sediment concentrations, the study also uses remotely sensed nighttime light data and land cover to better explain the potential impacts of settlements and land-use changes on the amount of sediment being trapped behind dams. T. D. Dang et al. (2018) used similar approaches of analysing suspended sediment concentrations for the rivers and channel networks of the Mekong delta.

4. Coastal Flood Mapping and Assessing Impacts in the Five Asian Deltas

All of the five Asian megadeltas are densely populated, with densities ranging from ∼400 people/km^2 in the Irrawaddy delta to ∼1,600 people/km^2 in the Ganges-Brahmaputra-Meghna delta (Figure 2c). These dense populations exposed to coastal flooding can result in profound impacts on lives and livelihoods of millions of people annually. Across the five Asian megadeltas, there are currently 113 million people living in the low elevation zones (≤5 m above sea level). Population numbers in these areas are expected to increase in the next decades, as Asia is projected to have the highest absolute growth of exposed populations by 2050 (Merkens et al., 2018). This makes assessments of coastal flood vulnerability and mitigation efforts more topical than ever.

At the same time, flooding is also fundamental to the very existence of these deltas, providing floodplain lands with nutrient-rich sediments, washing away pollutants and saline water, contributing to vertical land creation, and rejuvenating breeding grounds for aquatic plants and fish (Hui et al., 2022; Son et al., 2013). In the Mekong Delta, annual floods provide the region with an average estimated benefit of around US$8–10 million each year (Mekong River Commission, 2010; Son et al., 2013). However, as a result of the interplay between the drivers set out in Section 3, as well as the increasing climatic changes, flooding in the five Asian megadeltas has become much less predictable, putting current management measures and adaptive approaches to the test (Tellman et al., 2021). In response to these increasing challenges, more research has been centered around improving predictions of future coastal flood dynamics by developing new models, methods, and applications (Bates, 2022; Mosavi et al., 2018).

Studying and understanding coastal flooding in these deltas is paramount due to their critical role in enhancing climate resilience (Chan et al., 2024). Shaped by sediment deposition that keeps pace with relative sea-level rise, and with coastal vegetation forming a vital natural shield against flooding, deltaic landscapes protect nearby communities (S. Dasgupta et al., 2019). A comprehensive understanding of the dynamics of coastal flooding within these ecosystems allows for a deeper appreciation of their contributions to community safety, biodiversity preservation (Nicholls et al., 2018), and carbon sequestration (Lagomasino et al., 2019). This knowledge is essential for developing effective management strategies that enhance the resilience of delta regions in the face of increasing climate-related threats.

Section 3 illustrated how the Asian megadeltas studied here are prime global hotspots of coastal flooding, and provided insights into the dynamic interactions between riverine, coastal, and monsoonal processes with highly modified and densely populated human landscapes that shape flood hazards (Figure 8). These multifaceted driving forces can generate profound and widespread impacts on the deltaic environments and their inhabitants. This section summarizes the predominant impacts felt across the five Asian megadeltas and how these can be monitored and quantified.

4.1. Impacts of Coastal Flooding in the Five Asian Deltas

Given the significance of the five Asian megadeltas for agricultural production in the region (mainly rice), floods can substantially impact agricultural crops (either directly by damaging or indirectly by impairing growth conditions), local livelihoods, local and regional food security, and can result in significant economic losses (Figure 8; Brakenridge et al., 2017; N. Phan et al., 2019). For instance, the Mekong and Red River deltas are Vietnam's most important food baskets (N. Phan et al., 2019; Van Kien et al., 2020). In the Red River Delta, in 2018 during the Son-Tinh storm, ∼50% of the total rice area was inundated and damaged (N. Phan et al., 2019). Though less exposed to storm surges than the Red River Delta, the Irrawaddy Delta is also severely affected by coastal storm surges (Section 3.1.1). Tropical cyclone Nargis (2008), for instance, incurred a cost exceeding US$4 billion, equivalent to 21% of Myanmar's Gross Domestic Product in 2008 (World Bank, 2015). The agricultural sector suffered severe consequences as 4 million hectares of rice fields, constituting 57% of the country's total production, were damaged (Post-Nargis Joint Assessment, 2008). Analysis of MODIS-derived vegetation indices by Omori et al. (2021) revealed a 19% reduction in paddy fields compared to the previous year, primarily due to the extensive destruction of personal properties, including homes, crops, livestock, and critical infrastructure. Rice production recovery was estimated to take around 3 years (Omori et al., 2021). In 2015, exceptionally intense monsoon precipitation combined with tropical storm Komen caused countrywide flooding in Myanmar, with an unprecedented extent. The floods affected more than 1.6 million people (causing 132 fatalities) and ∼530,000 ha of land used for agriculture and aquaculture (Brakenridge et al., 2017; Government of the Union of Myanmar, 2015; IFRC, 2017).

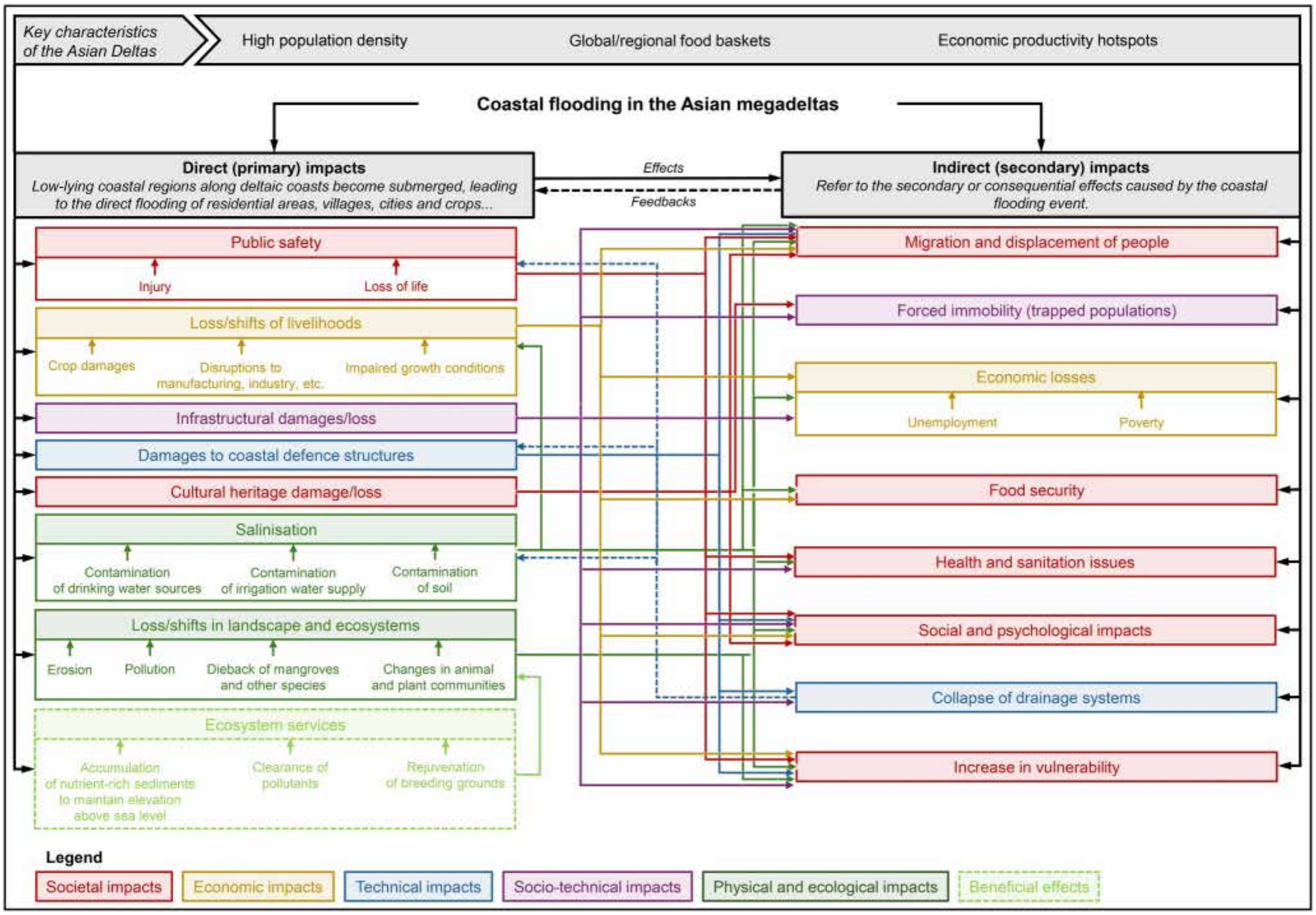

Figure 8. Direct and indirect societal, economic, technical, socio-technical, physical and ecological impacts as well as beneficial effects of flooding in the five Asian deltas. All these impacts show various interlinkages in the form of consequential effects and/or feedbacks, which are shown by arrows. Examples of these interlinkages are highlighted in the text.

As evident, coastal flooding in these deltas can significantly affect local livelihoods, particularly for rural resource-dependent populations. In these areas, homes are often temporary or semi-permanent structures, which can result in the complete loss of assets and homesteads during extreme flood events. The damage and disruptions from coastal flooding, as well as the increasing threats of saline intrusion, can therefore result in the loss of homes, the destruction of cultural heritage, rural unemployment, food insecurity, social unrest, conflicts, and forced migration (Figure 8; Adnan et al., 2019; Bernard et al., 2022; Johnson et al., 2016; Paszkowski et al., 2024; Singha et al., 2020). Coastal flooding events can also damage infrastructure assets and networks, such as transport networks, electricity, drinking water, wastewater treatment facilities, and communication services (Adshead et al., 2024). Such disruptions can lead to manufacturing, industry, and workforce disruptions, and inaccessibility to healthcare facilities or safe shelters, discontinuation of education, spread of infectious diseases in contaminated water, and profound psychological stress to victims (R. Dasgupta & Basu, 2023). Thus, coastal flooding can often generate significant setbacks in socio-economic development and can exacerbate poverty in these densely populated and highly resource-dependent Asian deltas (Figure 8; e.g., Adshead et al., 2024).

4.2. Coastal Flood Mapping and Modeling in the Five Asian Deltas

4.2.1. Remote Sensing for Flood Mapping and Impact Assessments

Flooded deltaic plains are exceptionally difficult to access during or immediately after flood events, which has historically resulted in errors and uncertainties being introduced in flood extent estimations and quantifications, and their impacts. Remote sensing technologies can help to address these challenges by providing large-scale and timely information on flood inundation without needing to access the flood localities, which can inform immediate relief support and underpin longer-term planning for flood management (Chawla et al., 2020; DeVries et al., 2020; Munawar et al., 2022; N. Phan et al., 2019; Singha et al., 2020; Tellman et al., 2021). As opposed to flood models, satellite-based remote sensing enables the direct observation of inundation, accounting for changes in land use, infrastructure, settlement, and climate (Kuenzer et al., 2015), which may not be reflected in flood extents generated by models (Coltin et al., 2016; Tellman et al., 2021). The Global Surface Water database (GSW, Pekel et al., 2016) provides a Landsat-based data set of open inland water worldwide, at 30 m resolution, and their characteristics (occurrences, water occurrence change intensity and changes) over more than 30 years (1984–2021, https://global-surface-water.appspot.com/map). Tellman et al. (2021) compiled 15 years of global flood data based on MODIS satellite imagery to inform improved flood risk management (database accessible here: https://global-flood-database.cloudtostreet.ai/).

Both the GSW (Pekel et al., 2016) and the global flood database (Tellman et al., 2021) are based on optical sensors that rely on daylight and weather conditions to acquire images and record flood inundation. Consequently, mapping of precipitation-induced or associated floods, such as storm surge or monsoon floodings, is challenging and can often only be conducted post-event, without monitoring inundation at time steps during the event (e.g., Lin et al., 2016). In contrast, radar imagery obtained by an active sensor (such as SAR) overcomes these challenges by sending pulses at longer wavelengths than optical sensors (i.e., in the range of microwaves). Being independent of sunlight and cloud cover, flood inundation can be fully captured by the radar satellite instrument over a large spatial extent and in a timely manner (e.g., Kuenzer et al., 2013). Particularly, the launch of the Sentinel-1 mission in 2014 has led to an increasing application of radar imagery in flood mapping (McCormack et al., 2022 and references therein; Pham-Duc & Nguyen, 2022). It provides high temporal (6–12 days) and horizontal resolution (10 m) imagery globally and has thus been used for emergency mapping, such as for the Copernicus Emergency Management Service (CEMS). The Sentinel data therefore provides valuable information for flood hazard assessments, especially when these and local data are difficult to access (Nghia et al., 2022; Pham-Duc et al., 2017; Seeger et al., 2024; Uddin et al., 2019). The satellite's frequent revisit time also allows for regular updates of flood information, as has been shown for the exceptional monsoon floods in Myanmar in 2015 (Myanmar Information Management Unit, 2015). For documenting floods at higher spatial resolutions, the SAR system of the TerraSAR-X mission is favorable and produces data at up to 1–3 m horizontal resolution (DLR, 2013), but—in contrast to Sentinel—requires activation to start operation.

The use of satellite imagery in assessments of flood damages thus enables the direct quantification of flood impacts via geospatial assessments. For instance, overlaying satellite-derived land use maps with satellite images of a flood event can estimate the destruction of flooding to agricultural or aquacultural production (Kotera et al., 2016; Liew et al., 2016; N. Phan et al., 2019). However, in deltaic systems the differentiation between intended (e.g., flooded rice fields or aquaculture) versus unintended flooding remains challenging and requires detailed local and contextual knowledge (e.g., Seeger et al., 2024; Torbick et al., 2017). In the absence of this information, the GSW database (Pekel et al., 2016) can be used to exclude permanent and nearly permanent water bodies covered by water >10 months per year.

In some cases, different spaceborne data sets can also be combined to obtain a higher resolution understanding of flood impacts. In the Chao Phraya Delta, for instance, Liew et al. (2016) used a combination of high-resolution images from SPOT 4, WorldView-2, and GeoEye-1 to spatially depict the spread of floodwater through Bangkok, identifying physical infrastructure and features that controlled the spread of the shallow flood, and analysed the sediment content within flood waters. Such assessments can also be combined with other data sets and models to analyse further implications of flood hazards, such as with a DEM to obtain information on flood depth, a parameter that is critical for flood risk assessments (Maranzoni et al., 2023; Van et al., 2024). Lu et al. (2016) used satellite imagery in combination with 6 million de-identified mobile phone users in Bangladesh to assess both immediate and longer-term migration patterns as a result of Cyclone Mahasen in 2013. Similarly, Ceola et al. (2014) and Mård et al. (2018) used nighttime satellite data over a 20-year period (1992–2013) to understand how flood impacts have affected the proximity of populations to river systems over time, as well as how structural flood protection infrastructure affects these dynamics.

4.2.2. Coastal Flood Modeling

Despite the many opportunities that remote sensing provides for flood observations and measurements, they are limited to retrospectively assessing floods and their associated impacts (i.e., measuring past flood impacts). In order to understand how flooding may behave in the future, models are required. These range from the more simple bathtub models to complex physical hydrodynamic models that can capture many different interacting processes.

The bathtub method is a commonly utilized GIS-based approach that uses the region below a specified elevation to identify large-scale flooded areas. This method relies on a high-resolution and accurate DEM as its primary input (Section 3.1.5). However, it has significant limitations as it may inaccurately indicate flooding in low-lying areas that are disconnected from the coast (such as polders). Moreover, bathtub models tend to overestimate coastal exposure to extreme flood levels as they do not account for the attenuation of water height over vegetated regions or over land with increasing distance from the ocean (Vafeidis et al., 2019; Vousdoukas et al., 2016). Despite these limitations and gross errors, the simplicity and ease of implementation of the bathtub method have led to its widespread use in numerous global-scale studies to assess coastal flooding due to future sea-level rise (Dullaart et al., 2021; Kirezci et al., 2020; Kulp & Strauss, 2019; Muis et al., 2016; Tay et al., 2022 among others), including research focused on the Asian megadeltas (e.g., Kanan et al., 2023; Mitra et al., 2023; Vernimmen & Hooijer, 2023; Vousdoukas et al., 2016). Although recent improvements have been made to the bathtub model, its projections have limited utility in deltas due to the flat, human-modified (e.g., poldering), and unconfined coastal floodplains and the failure of the bathtub method to account for erosion and sedimentation, which are particularly significant factors in deltas (Nienhuis & van de Wal, 2021).

In order to address some of these complexities, hydrodynamic models can be applied, which solve equations based on principles of mass and momentum conservation using numerical methods to simulate water movement over complex topographies and bathymetries. Unlike bathtub models, which conserve neither mass nor momentum, hydrodynamic approaches can properly represent flow connectivity and flood wave attenuation across vegetated surfaces and with distance from the sea and therefore solve the challenge of flood inundation prediction much better than static models, albeit at the expense of increased computational costs and reliance on up-to-date bathymetric data (see Bates, 2022 or Jafarzadegan et al., 2023 for a detailed discussion).

Numerous instances exist of the application of such models to estuaries and deltas. Indeed, over 50 years ago, one of the very first environmental applications of hydrodynamic modeling at a large scale was to the Mekong Delta (Zanobetti et al., 1970). Since then, there have been hundreds of numerical modeling studies using hydrodynamic approaches addressing a wide range of delta science problems, including understanding tide/surge/river flow interactions (e.g., Dube et al., 2009; Ramirez et al., 2016), flood hazard mapping (e.g., Yamazaki et al., 2014); erosion, water quality and salinity intrusion modeling (e.g., Attema & Hendriks, 2014; Cortese et al., 2024; Tran Anh et al., 2018), climate change impacts (e.g., Mitchell et al., 2022) and the development of near real-time warning systems (e.g., Khan et al., 2021). Nevertheless, while such models can provide accurate results when the bathymetry, terrain, boundary conditions and friction coefficients are known, in real life, all of these data inputs are uncertain or unavailable (see Section 3.1). While water level can be measured to within a few cm at gauges and to a few 10s of cm from satellite altimetry, measurements of surface water flux within channels and rainfall are only accurate to 10%–20%, even under ideal conditions (e.g., McMillan et al., 2012). Similarly, although modern DEMs are reasonably accurate for mapping bare-earth floodplain terrain (e.g., Hawker et al., 2022), channel bathymetry within deltas is scarce and may need to be inferred using additional algorithms and (sometimes strong) assumptions (e.g., Neal et al., 2021, see also Section 3.1.5). Lastly, the data used to calibrate and validate inundation models are not error free, with satellite-based estimates of flood inundation having a likely upper accuracy limit of 70%–80% (Horritt et al., 2001). As a result, there are fundamental limits to what inundation models can achieve, and caution is required to develop sound scientific inferences from their outputs (Bates, 2023).

5. Paving the Way for Future Research in the Five Asian Megadeltas

This review has provided a synthesis of the key natural and anthropogenic drivers of coastal flooding in the five Asian megadeltas, as well as how these have historically and more recently been quantified. We also reviewed how coastal flooding can be mapped and modeled and how the key impacts of flooding can be estimated. In this section, these different drivers are brought together to illustrate how all these processes are interconnected, emphasizing that a systems perspective, equalizing human and environmental compartments, is required for effective future delta management. Subsequently, we provide a summary of the state of knowledge in the five Asian megadeltas, highlighting the key gaps that remain in our current understanding of coastal flood dynamics. In this final section, we use the findings from the review to develop trajectories of future research ventures, focusing on how approaches used in some deltas can be applied in other deltas to answer critical questions regarding flood risk in these sensitive coastal systems.

5.1. A Deltaic Systems Perspective

The natural and anthropogenic drivers discussed in Section 3 all play critical roles in shaping unique flood dynamics in every locality of each delta system. However, interpreting and assessing these as individual drivers that act in isolation can be problematic, as they each only represent part of the wider interconnected system and key interactions that can exacerbate flood and other hazards are missed. For example, the construction of upstream dams can lead to reduced water and sediment flows to the delta (e.g., Binh et al., 2020), which results in a change in how much sediment is distributed and deposited on the delta's floodplains, affecting rates of elevation loss due to subsidence (e.g., Higgins et al., 2014; Minderhoud et al., 2017, 2018). Accelerated subsidence could result in saline water moving further inland, particularly during the dry season (e.g., Eslami et al., 2019, 2021; Park, 2024), which is further exacerbated by the upstream dams also reducing freshwater flows through the system (e.g., Eslami et al., 2021). The increased salinization of water sources in the delta typically lead to more groundwater pumping to meet freshwater demands (e.g., M. M. Rahman et al., 2019), leading to further localized subsidence (e.g., Erban et al., 2014). Such accelerated subsidence can then further exacerbate flood and erosion risk, disrupting lives and livelihoods, causing displacement and deepening poverty (e.g., J. Chen et al., 2022). These continuous feedback loops can lead to local populations getting trapped in cycles of risk, where the continuous setbacks caused by coastal flooding exceed communities' capacity to recover and adapt (Renaud et al., 2013).

In order to escape such risk cycles and develope more effective management approaches, decision-makers require targeted research that assesses these interacting dynamics in systematic ways by viewing deltas as dynamic socio-ecological systems (Brondizio et al., 2016; Nicholls et al., 2016; Sebesvari et al., 2016). By embracing a systems perspective, a more holistic and complete understanding of the intricate dynamics shaping these megadeltas can be achieved, including how these system dynamics may change in the future. For example, in order to effectively manage the increasing challenges of groundwater over-extraction in the Mekong Delta, decision makers need to know what would happen in the delta for a range of different future extraction scenarios. In response to this, (Minderhoud et al., 2017; Minderhoud, Middelkoop, et al., 2020) assessed the consequences of groundwater extraction, using a pre-established database of hydrogeological, groundwater, and VLM observations, and projected how subsidence may change in the future for a range of groundwater extraction scenarios in the Mekong Delta. In the lesser studied deltas, such as the Irrawaddy and the Red River deltas, such challenges are similarly present, but the required analyses are currently missing.

All five Asian deltas studied herein are undergoing changes due to multiple and incompletely understood drivers at unprecedented rates. Decisions made today will define deltaic sustainability for decades to come. It is therefore of paramount importance to advance integrated, interdisciplinary, and holistic studies, alongside continued disciplinary research, to support targeted and informed decision-making (Lázár et al., 2020; Paszkowski et al., 2021; Renaud et al., 2013). Currently, coastal flood management decisions in the five Asian deltas predominantly focus on recovering from and better preparing for future flood impacts. However, by allocating more resources and generating more knowledge on the root causes of coastal flooding, such as by quantifying the interactions discussed in this review, decision-makers can begin to target the multiple drivers of flood risk (amongst others, managing groundwater extraction, sand mining, damming, and land use, as well as climate change and SLR), rather than the impacts, which would fundamentally enhance their resilience to flood hazards in the long term.

5.2. Status of Coastal Flood Assessments in the Five Asian Megadeltas

When comparing the five Asian megadeltas, key observations emerge (Figure 9). The Ganges-Brahmaputra-Meghna and the Irrawaddy deltas exhibit high vulnerability to threats from extreme events, such as storm surges, cyclones, and salinization (see also Nicholls et al., 2020; Vogel et al., 2024). The future of these two deltas

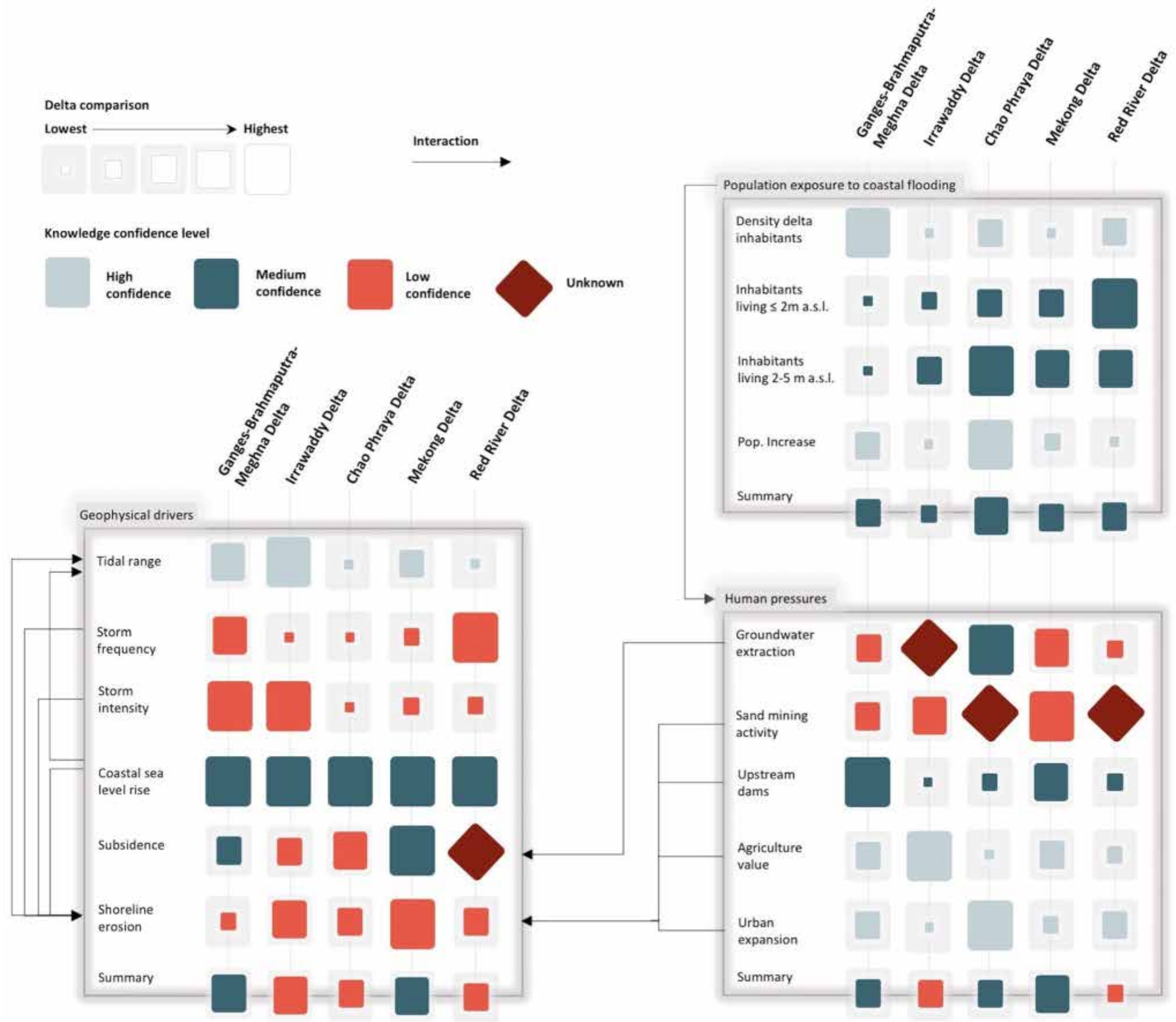

Figure 9. A systemic perspective on the status of knowledge of the main natural drivers and human pressures contributing to coastal flooding across the five Asian megadeltas. (a.s.l = above sea level).

is predominantly threatened by planned upstream dam construction, sand mining, groundwater extraction, relative SLR, and by the consequences of intense poldering and agricultural and aquacultural intensification. It is also important to note the challenges the Irrawaddy Delta faces due to the military takeover and outbreaks of violence since 2021, which disrupted aid and support initiatives and made efforts in vulnerability reduction and disaster risk management from regional to international levels more difficult, leading to huge uncertainties in present and future disaster risk management and its effectiveness (see also ACAPS, 2024; Vogel et al., 2024). This highlights the relevance of governance in coping with flooding, and the importance of its stability in preparing for managingfuture flood risk in deltas.

The Chao Phraya, Red River, and Mekong deltas are characterized by rapid urbanization, dam construction, sand mining, groundwater extraction and land-use changes (Figure 9). These deltas are primarily threatened by ongoing human development in areas exposed to coastal flooding, as well as in upstream reaches of the river systems. Across all five deltas, it is evident that human activities play a more critical role in shaping coastal flood dynamics in the immediate term, with climate change playing a more important role toward the end of the century. It is important to note that there are processes for which the contribution to coastal flooding is hardly understood in any of the five deltas; thus, their impacts may be underestimated so far. These include the impacts of sand mining on modifying sediment and flow dynamics, therewith forcing shoreline change, as well as the various driving forces of land subsidence, where the quantification is challenged by data scarcity, amongst others.

It is evident from this review that all processes are interconnected, but that a sustainable influx of sediment to the five deltas is critical to maintain above mean sea level. Dunn et al. (2019) modeled the future change in sediment flux to 49 deltas to the end of the century, including the five deltas studied herein. Despite differences in how the processes interact across the different deltas, all of the five deltas will face profound challenges in the future if all planned upstream interventions are implemented; in the Mekong, a 77% reduction in sediment influx to the delta could be expected by the end of the century, whilst for the Irrawaddy, Ganges-Brahmaputra-Meghna, Chao Phraya, and Red River systems, reductions of 56%, 48%, 14%, and 14% are expected, respectively (Dunn et al., 2019). If realized, these sediment reductions will likely exacerbate subsidence and coastal flooding in each delta and will put even the most effective management strategies to the test.

From this review, it has also become apparent that the Ganges-Brahmaputra-Meghna and the Mekong deltas are the most widely studied deltas in South and Southeast Asia (see confidence scale of Figure 9). This is likely due to these two deltas being the biggest, most populous, and regionally most important transboundary (crossing 5 and 6 countries each) river systems. The Irrawaddy and Red River deltas, on the other hand, are the least studied deltas of the five assessed in this review. A variety of gaps and uncertainties persist for the Irrawaddy and Red River deltas, where baseline information (groundwater, subsidence, and sediment transport, amongst others) is entirely missing or inaccessible. This leads to challenges in attributing causes and impacts between the various interacting processes, resulting in significant assumptions needing to be made in hydrodynamic models and spatial assessments of risk. There is therefore an urgent need to establish these baseline parameters, by advancing targeted activities (see next Section 5.3), in order to conduct well-informed projections about the future of these deltas.

5.3. Future Research Directions in the Five Asian Megadeltas

By focusing not only on what drivers impact coastal flooding in the five Asian megadeltas, but also on how these have been quantified, this review provides a unique opportunity to highlight the key requirements for advancing quantifications of processes, as well as to shed light on the transferability of methodologies and approaches from some deltas to others. In order to advance our understanding of the interconnected processes in the five Asian deltas, more resources need to be allocated toward comprehensive data collection and monitoring. Although the Mekong and Ganges-Brahmaputra-Meghna deltas are the most widely studied megadeltas in South and Southeast Asia, improved data collection and monitoring systems apply to all five deltas, and beyond. The key data requirements include, but are not limited to: (a) a more complete network of discharge and sediment gauges in deltaic river channels; (b) a comprehensive network of sea and water level monitoring stations, as well as tide gauges; (c) regular bathymetry measurements, particularly in the near-shore areas and deltaic channels; (d) a subsidence monitoring network to enable a detailed understanding of the different drivers of elevation loss and the contribution of groundwater abstraction; and (e) regular updating of DEMs to improve elevation information for hazard assessments. To ensure this data collection is meaningful and relevant, better dissemination and data sharing is critical.

While some approaches discussed in this review are solely based on open data from satellite observations, and thus can be directly transferred to other deltas, others involve more complex data inputs or local in situ information, challenging their direct transfer to more data-sparse and inaccessible deltas. Table 3 below provides the priorities for direct and indirect reapplications of available methodologies, tools, and data sets proven in at least one delta to be transferred and advance our understanding of particular processes in the less studied deltas. Given the readily accessible information that the direct reapplication suggestions entail, these recommendations are the low hanging fruit for future research in this field across the five Asian deltas, and beyond.

Table 3
Priorities for Transferable Methodologies Across the Five Asian Megadeltas

Process	Description of applicable methodology	Learning from which delta(s)	Apply to which delta(s)
Direct reapplication potential			
Elevation data	DEM uncertainty and suitability assessment. Obtaining the most accurate DEM and using water levels in the same vertical datum as the DEM is critical in assessments of flood risk	• Mekong (Minderhoud et al., 2019) • Irrawaddy (Seeger et al., 2023)	• Ganges-Brahmaputra-Meghna • Chao Phraya • Red River
Upstream catchment changes	Use near infra-red reflectance from Landsat satellite imagery as well as nighttime imagery to detect changes in suspended sediment concentrations as a consequence of upstream dams, changes in land use and settlement density	• Mekong (Beveridge et al., 2020; Dang et al., 2018)	• Red River • Irrawaddy • Ganges-Brahmaputra-Meghna
Sand mining	Apply an automated remote sensing-based deep learning framework for quantifying sand mining activities and sediment budgets	• Mekong (Gruel et al., 2022; Hackney et al., 2020; Kumar et al., 2023)	• Ganges-Brahmaputra-Meghna • Irrawaddy • Red River
Flood exposure assessment	Combine different (openly accessible) data sets of satellite imagery, (global) precipitation estimates and river discharge measurements with available information on the physical setting (e.g., land elevation, geomorphology) and society (e.g., population, land use) to create a first-order assessment of single and multiple flood hazard types	• Irrawaddy (Seeger et al., 2024)	• Chao Phraya • Ganges-Brahmaputra-Meghna • Mekong • Red River
Detailed flood mapping	Combine different spaceborne data sets (e.g., SPOT 4, WorldView-2, and GeoEye-1) to depict the spread of floodwater through urban environments at a very high resolution	• Chao Phraya (Liew et al., 2016)	Urban centers of: • Ganges-Brahmaputra-Meghna • Red River • Irrawaddy • Mekong
Indirect reapplication potential			
Discharge	Satellite altimetry-derived discharge time series, ideally at multiple locations in the river basin. Requires in situ measurements to be available as well	• Mekong (Biancamaria et al., 2017; Birkinshaw et al., 2010; Kim et al., 2019) • Irrawaddy (Frappart et al., 2015) • Ganges-Brahmaputra-Meghna (Papa et al., 2010, 2012)	• Red River • Chao Phraya
Vertical Land Motion (VLM)	Create 2D VLM models that go beyond 1D calculations to project scenarios of VLM. This requires detailed local subsurface data to be collected and can be technically demanding to set up	• Mekong (Lovelock et al., 2015; Minderhoud, Middelkoop, et al., 2020; Zoccarato et al., 2018)	• Ganges-Brahmaputra-Meghna • Red River • Chao Phraya • Irrawaddy

In addition to the recommendations in Table 3, we are also at an exciting moment where more satellite missions have recently been, or will soon be, launched that will offer openly available information on water and sediment dynamics at unprecedented spatial and temporal resolutions. These will be critical in monitoring changing coastal flood patterns and answering some of the most pressing questions across the five Asian megadeltas. It is imperative that these advances in remote sensing are also reflected in continued and enhanced efforts on data collection, as in situ data is absolutely vital to ground truth remote sensing observations and modeling studies. Lastly, research should be aware of delta management activities and priorities in each case. In some cases this may provide the funds and resources for these activities, and the science will be coproduced with relevant stakeholders.

6. Conclusion

This review has provided an in-depth presentation of the state-of-the-art understanding of coastal flood drivers, and how these can be assessed, for five critical Asian megadeltas, although the findings are relevant for deltas globally. In order to advance research in this region and build flood resilience in the face of future uncertainty, it is critical that efforts focus on filling data gaps and leverage remote sensing, including improvements in the accessibility to long-term, data sets, also in combination with reliable in situ observations. Satellite observations and modeling efforts have contributed to better characterizing coastal flooding in megadeltas, but challenges remain due to uncertainties and limitations in spatial and temporal resolutions. However, remote sensing, including new and upcoming missions, holds great potential, especially through knowledge transfer between deltas. Therefore, we recommend making existing in situ archives (such as for river discharge, sediment dynamics, or GNSS observations) openly available as data, while space agencies should continue to ensure free access to satellite observations.

This review has underscored the critical role that human activities play in shaping near-term coastal flood dynamics in deltas, while emphasizing the growing significance of climate change impacts in the long term. By integrating the discussed drivers and pressures across temporal and spatial scales, targeted and effective strategies can be developed to tackle coastal flooding in the Asian megadeltas and beyond, enhancing resilience and sustainability in the face of changing conditions. This will require embracing a systems perspective that includes both on-the-ground information and remote sensing advances to effectively address the intricate dynamics of coastal flooding in these systems, which is essential for breaking cycles of risk and enhancing the long-term resilience of deltaic communities.

Data Availability Statement

No new data was created or used for this research.

Acknowledgments
This research was supported by the International Space Science Institute (ISSI) in Bern, through ISSI International Team project #548: "Past, Present and Future of the Asian Mega-Deltas: The Role of Space Observations." This work also benefits from the support of the French CNES TOSCA program through the DeltAsia project. M.B., N.L., J.K., M.K., and F.P. were supported by the French Research Agency (ANR) under the DELTA project (ANR-17-CE03-0001). P.S.J.M. is supported by the Dutch Science Foundation (NWO) under the Drowning Deltas project (Veni-TTW-20231). K.S. is supported by the German Research Foundation (DFG) under the Rising Sea And Sinking Land project (project number 411257639). M.A.K was supported by DFG under SFB 1502/1-2022 (project number 450058266). The authors express their gratitude to K. Lambeck for providing the computations of his models for this review. The authors are grateful to A. Cazenave for providing valuable insights and helpful comments on the latest version of the manuscript.

References

ACAPS. (2024). MYANMAR—Three years post-coup: Recent developments and humanitarian situation. Retrieved from https://www.acaps.org/fileadmin/Data_Product/Main_media/20240220_ACAPS_briefing_note_Myanmar_three_years_post_coup_01.pdf

ADB. (2022). *Coastal towns climate resilience project: Report and recommendation of the president—People's Republic of Bangladesh: Coastal towns climate resilience project*. Asian Development Bank (ADB). Retrieved from https://www.adb.org/projects/documents/ban-55201-001-rrp

Adnan, M. S. G., Haque, A., & Hall, J. W. (2019). Have coastal embankments reduced flooding in Bangladesh? *Science of the Total Environment*, *682*, 405–416. https://doi.org/10.1016/j.scitotenv.2019.05.048

Adshead, D., Paszkowski, A., Gall, S. S., Peard, A. M., Adnan, M. S. G., Verschuur, J., & Hall, J. W. (2024). Climate threats to coastal infrastructure and sustainable development outcomes. *Nature Climate Change*, *14*(4), 344–352. https://doi.org/10.1038/s41558-024-01950-2

Akter, S., Ahmed, K. R., Marandi, A., & Schüth, C. (2020). Possible factors for increasing water salinity in an embanked coastal island in the southwest Bengal Delta of Bangladesh. *Science of the Total Environment*, *713*, 136668. https://doi.org/10.1016/j.scitotenv.2020.136668

Akter, S., Wilson, C. A., Bhuiyan, A. H., Akhter, S. H., Steckler, M. S., & Rana, M. M. (2024). Elevation dynamics between polders and the natural Sundarbans of the Ganges-Brahmaputra delta plain. *Estuaries and Coasts*, *47*(7), 1877–1892. https://doi.org/10.1007/s12237-024-01349-4

Alam, E., & Dominey-Howes, D. (2015). A new catalogue of tropical cyclones of the northern Bay of Bengal and the distribution and effects of selected landfalling events in Bangladesh. *International Journal of Climatology*, *35*(6), 801–835. https://doi.org/10.1002/joc.4035

Allison, M. A. (1998). Historical changes in the Ganges-Brahmaputra delta front. *Journal of Coastal Research*, 1269–1275.

Almar, R., Bergsma, E. W. J., Thoumyre, G., Baba, M. W., Cesbron, G., Daly, C., et al. (2021). Global satellite-based coastal bathymetry from waves. *Remote Sensing*, *13*(22), 4628. https://doi.org/10.3390/rs13224628

Al Najar, M., Thoumyre, G., Bergsma, E. W. J., Almar, R., Benshila, R., & Wilson, D. G. (2023). Satellite derived bathymetry using deep learning. *Machine Learning*, *112*(4), 1107–1130. https://doi.org/10.1007/s10994-021-05977-w

Anthony, E. J. (2015). Wave influence in the construction, shaping and destruction of river deltas: A review. *Marine Geology*, *361*, 53–78. https://doi.org/10.1016/j.margeo.2014.12.004

Anthony, E. J., Besset, M., Dussouillez, P., Goichot, M., & Loisel, H. (2019). Overview of the Monsoon-influenced Ayeyarwady River delta, and delta shoreline mobility in response to changing fluvial sediment supply. *Marine Geology*, *417*, 106038. https://doi.org/10.1016/j.margeo.2019.106038

Anthony, E. J., Brunier, G., Besset, M., Goichot, M., Dussouillez, P., & Nguyen, V. L. (2015). Linking rapid erosion of the Mekong River delta to human activities. *Scientific Reports*, *5*(1), 14745. https://doi.org/10.1038/srep14745

Antony, C., Testut, L., & Unnikrishnan, A. S. (2014). Observing storm surges in the Bay of Bengal from satellite altimetry. *Estuarine, Coastal and Shelf Science*, *151*, 131–140. https://doi.org/10.1016/j.ecss.2014.09.012

Aobpaet, A., Cuenca, M. C., Hooper, A., & Trisirisatayawong, I. (2013). InSAR time-series analysis of land subsidence in Bangkok, Thailand. *International Journal of Remote Sensing*, *34*(8), 2969–2982. https://doi.org/10.1080/01431161.2012.756596

Arns, A., Wahl, T., Wolff, C., Vafeidis, A. T., Haigh, I. D., Woodworth, P., et al. (2020). Non-linear interaction modulates global extreme sea levels, coastal flood exposure, and impacts. *Nature Communications*, *11*(1), 1918. https://doi.org/10.1038/s41467-020-15752-5

Arto, I., García-Muros, X., Cazcarro, I., González-Eguino, M., Markandya, A., & Hazra, S. (2019). The socioeconomic future of deltas in a changing environment. *Science of the Total Environment*, *648*, 1284–1296. https://doi.org/10.1016/j.scitotenv.2018.08.139

Attema, Y. H., & Hendriks, H. C. M. (2014). Delft3D model of the Ayeyarwady delta Myanmar. Retrieved from https://repository.tudelft.nl/islandora/object/uuid%3A7a8d35c0-bdf0-409e-98be-5ed22f161f0a

Baki, A. B. M., & Gan, T. Y. (2012). Riverbank migration and island dynamics of the braided Jamuna River of the Ganges–Brahmaputra basin using multi-temporal Landsat images. *Quaternary International*, *263*, 148–161. https://doi.org/10.1016/j.quaint.2012.03.016

Bari, E., & Haque, S. E. (2022). Legal and illicit sand mining practice in Bangladesh: Exploring supply chain and its value. *Journal of Illicit Economies and Development*, *4*(1), 44–57. https://doi.org/10.31389/jied.149

Baronas, J. J., Stevenson, E. I., Hackney, C. R., Darby, S. E., Bickle, M. J., Hilton, R. G., et al. (2020). Integrating suspended sediment flux in large Alluvial River Channels: Application of a synoptic rouse-based model to the Irrawaddy and Salween Rivers. *Journal of Geophysical Research: Earth Surface*, *125*(9), e2020JF005554. https://doi.org/10.1029/2020JF005554

Bates, P. D. (2022). Flood inundation prediction. *Annual Review of Fluid Mechanics*, *54*(1), 287–315. https://doi.org/10.1146/annurev-fluid-030121-113138

Bates, P. D. (2023). Fundamental limits to flood inundation modelling. *Nature Water*, *1*(7), 566–567. https://doi.org/10.1038/s44221-023-00106-4

Becker, M., Karpytchev, M., & Hu, A. (2023). Increased exposure of coastal cities to sea-level rise due to internal climate variability. *Nature Climate Change*, *13*(4), 367–374. https://doi.org/10.1038/s41558-023-01603-w

Becker, M., Karpytchev, M., & Lennartz-Sassinek, S. (2014). Long-term sea level trends: Natural or anthropogenic? *Geophysical Research Letters*, *41*(15), 5571–5580. https://doi.org/10.1002/2014GL061027

Becker, M., Karpytchev, M., & Papa, F. (2019). Chapter 7—Hotspots of relative sea level rise in the Tropics. In V. Venugopal, J. Sukhatme, R. Murtugudde, & R. Roca (Eds.), *Tropical extremes* (pp. 203–262). Elsevier. https://doi.org/10.1016/B978-0-12-809248-4.00007-8

Becker, M., Papa, F., Karpytchev, M., Delebecque, C., Krien, Y., Khan, J. U., et al. (2020). Water level changes, subsidence, and sea level rise in the Ganges–Brahmaputra–Meghna delta. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(4), 1867–1876. https://doi.org/10.1073/pnas.1912921117

Belloni, R., Camici, S., & Tarpanelli, A. (2021). Towards the continuous monitoring of the extreme events through satellite radar altimetry observations. *Journal of Hydrology*, *603*, 126870. https://doi.org/10.1016/j.jhydrol.2021.126870

Bernard, A., Long, N., Becker, M., Khan, J., & Fanchette, S. (2022). Bangladesh's vulnerability to cyclonic coastal flooding. *Natural Hazards and Earth System Sciences*, *22*(3), 729–751. https://doi.org/10.5194/nhess-22-729-2022

Best, J. (2019). Anthropogenic stresses on the world's big rivers. *Nature Geoscience*, *12*(1), 7–21. https://doi.org/10.1038/s41561-018-0262-x

Beveridge, C., Hossain, F., & Bonnema, M. (2020). Estimating impacts of dam development and landscape changes on suspended sediment concentrations in the Mekong River Basin's 3S tributaries. *Journal of Hydrologic Engineering*, *25*(7), 05020014. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001949

Bhattacharya, J. P. (2006). Deltas. In H. W. Posamentier & R. G. Walker (Eds.), *Facies models revisited* (Vol. 84, pp. 0–292). SEPM Society for Sedimentary Geology. https://doi.org/10.2110/pec.06.84.0237

Biancamaria, S., Frappart, F., Normandin, C., Blarel, F., Bourrel, L., Aumont, M., et al. (2017). Tonle Sap Lake water storage change over 24 years from satellite observation and its link with Mekong River discharge and climate events, *2017*, H42G-05. In *Presented at the AGU Fall Meeting Abstracts*.

Biancamaria, S., Lettenmaier, D. P., & Pavelsky, T. M. (2016). The SWOT mission and its capabilities for land hydrology. *Surveys in Geophysics*, *37*(2), 307–337. https://doi.org/10.1007/s10712-015-9346-y

Bidorn, B., Sok, K., Bidorn, K., & Burnett, W. C. (2021). An analysis of the factors responsible for the shoreline retreat of the Chao Phraya Delta (Thailand). *Science of the Total Environment*, *769*, 145253. https://doi.org/10.1016/j.scitotenv.2021.145253

Binh, D. V., Kantoush, S., & Sumi, T. (2020). Changes to long-term discharge and sediment loads in the Vietnamese Mekong Delta caused by upstream dams. *Geomorphology*, *353*, 107011. https://doi.org/10.1016/j.geomorph.2019.107011

Birkinshaw, S. J., O'Donnell, G. M., Moore, P., Kilsby, C. G., Fowler, H. J., & Berry, P. A. M. (2010). Using satellite altimetry data to augment flow estimation techniques on the Mekong River. *Hydrological Processes*, *24*(26), 3811–3825. https://doi.org/10.1002/hyp.7811

Boergens, E., Dettmering, D., & Seitz, F. (2019). Observing water level extremes in the Mekong River Basin: The benefit of long-repeat orbit missions in a multi-mission satellite altimetry approach. *Journal of Hydrology*, *570*, 463–472. https://doi.org/10.1016/j.jhydrol.2018.12.041

Boothroyd, R. J., Williams, R. D., Hoey, T. B., Barrett, B., & Prasojo, O. A. (2021). Applications of Google Earth Engine in fluvial geomorphology for detecting river channel change. *WIREs Water*, *8*(1), e21496. https://doi.org/10.1002/wat2.1496

Boulange, J., Hanasaki, N., Yamazaki, D., & Pokhrel, Y. (2021). Role of dams in reducing global flood exposure under climate change. *Nature Communications*, *12*(1), 417. https://doi.org/10.1038/s41467-020-20704-0

Brakenridge, G. R., Syvitski, J. P. M., Niebuhr, E., Overeem, I., Higgins, S. A., Kettner, A. J., & Prades, L. (2017). Design with nature: Causation and avoidance of catastrophic flooding, Myanmar. *Earth-Science Reviews*, *165*, 81–109. https://doi.org/10.1016/j.earscirev.2016.12.009

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

Bricheno, L., & Wolf, J. (2018). Modelling tidal river salinity in coastal Bangladesh. In *Ecosystem services for well-being in deltas: Integrated assessment for policy analysis*. Springer International Publishing. https://doi.org/10.1007/978-3-319-71093-8_17

Brondizio, E. S., Vogt, N. D., Mansur, A. V., Anthony, E. J., Costa, S., & Hetrick, S. (2016). A conceptual framework for analyzing deltas as coupled social–ecological systems: An example from the Amazon River Delta. *Sustainability Science*, *11*(4), 591–609. https://doi.org/10.1007/s11625-016-0368-2

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

Bussi, G., Darby, S. E., Whitehead, P. G., Jin, L., Dadson, S. J., Voepel, H. E., et al. (2021). Impact of dams and climate change on suspended sediment flux to the Mekong delta. *Science of the Total Environment*, *755*, 142468. https://doi.org/10.1016/j.scitotenv.2020.142468

Candela, T., & Koster, K. (2022). The many faces of anthropogenic subsidence. *Science*, *376*(6600), 1381–1382. https://doi.org/10.1126/science.abn3676

Carpenter, G. (2012). *Thailand flood 2011 one year retrospective*. Marsh & McLennan. Retrieved from https://www.Guycarp.Com/Content/Dam/Guycarp/En/Documents/Dynamic-Content/Thailand%20Flood%202011_One%20Year%20Retrospective.Pdf

Cazenave, A., & Moreira, L. (2022). Contemporary sea-level changes from global to local scales: A review. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *478*(2261), 20220049. https://doi.org/10.1098/rspa.2022.0049

Ceola, S., Laio, F., & Montanari, A. (2014). Satellite nighttime lights reveal increasing human exposure to floods worldwide. *Geophysical Research Letters*, *41*(20), 7184–7190. https://doi.org/10.1002/2014GL061859
Cesbron, G., Melet, A., Almar, R., Lifermann, A., Tullot, D., & Crosnier, L. (2021). Pan-European satellite-derived coastal bathymetry—Review, user needs and future services. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.740830
Chan, F. K. S., Paszkowski, A., Wang, Z., Lu, X., Mitchell, G., Tran, D. D., et al. (2024). Building resilience in Asian mega-deltas. *Nature Reviews Earth & Environment*, *5*(7), 522–537. https://doi.org/10.1038/s43017-024-00561-x
Chawla, I., Karthikeyan, L., & Mishra, A. K. (2020). A review of remote sensing applications for water security: Quantity, quality, and extremes. *Journal of Hydrology*, *585*, 124826. https://doi.org/10.1016/j.jhydrol.2020.124826
Chen, D., Li, X., Saito, Y., Liu, J. P., Duan, Y., Liu, S., & Zhang, L. (2020). Recent evolution of the Irrawaddy (Ayeyarwady) Delta and the impacts of anthropogenic activities: A review and remote sensing survey. *Geomorphology*, *365*, 107231. https://doi.org/10.1016/j.geomorph.2020.107231
Chen, J., Famigliett, J., Scanlon, B., & Rodell, M. (2016). Groundwater storage changes: Present status from GRACE observations. *Surveys in Geophysics*, 207–227. https://doi.org/10.1007/978-3-319-32449-4_9
Chen, J., Mueller, V., Durand, F., Lisco, E., Zhong, Q., Sherin, V. R., & Saiful Islam, A. K. M. (2022). Salinization of the Bangladesh Delta worsens economic precarity. *Population and Environment*, *44*(3), 226–247. https://doi.org/10.1007/s11111-022-00411-2
Chowdhury, M. D. R., & Ward, N. (2004). Hydro-meteorological variability in the greater Ganges–Brahmaputra–Meghna basins. *International Journal of Climatology*, *24*(12), 1495–1508. https://doi.org/10.1002/joc.1076
Coltin, B., McMichael, S., Smith, T., & Fong, T. (2016). Automatic boosted flood mapping from satellite data. *International Journal of Remote Sensing*, *37*(5), 993–1015. https://doi.org/10.1080/01431161.2016.1145366
Cortese, L., Donatelli, C., Zhang, X., Nghiem, J. A., Simard, M., Jones, C. E., et al. (2024). Coupling numerical models of deltaic wetlands with AirSWOT, UAVSAR, and AVIRIS-NG remote sensing data. *Biogeosciences*, *21*(1), 241–260. https://doi.org/10.5194/bg-21-241-2024
Daly, C., Baba, W., Bergsma, E., Thoumyre, G., Almar, R., & Garlan, T. (2022). The new era of regional coastal bathymetry from space: A showcase for west Africa using optical Sentinel-2 imagery. *Remote Sensing of Environment*, *278*, 113084. https://doi.org/10.1016/j.rse.2022.113084
Dang, T. D., Cochrane, T. A., Arias, M. E., & Tri, V. P. D. (2018). Future hydrological alterations in the Mekong Delta under the impact of water resources development, land subsidence and sea level rise. *Journal of Hydrology: Regional Studies*, *15*, 119–133. https://doi.org/10.1016/j.ejrh.2017.12.002
Dang, T. H., Coynel, A., Orange, D., Blanc, G., Etcheber, H., & Le, L. A. (2010). Long-term monitoring (1960–2008) of the river-sediment transport in the Red River Watershed (Vietnam): Temporal variability and dam-reservoir impact. *Science of the Total Environment*, *408*(20), 4654–4664. https://doi.org/10.1016/j.scitotenv.2010.07.007
Dangendorf, S., Hay, C., Calafat, F. M., Marcos, M., Piecuch, C. G., Berk, K., & Jensen, J. (2019). Persistent acceleration in global sea-level rise since the 1960s. *Nature Climate Change*, *9*(9), 705–710. https://doi.org/10.1038/s41558-019-0531-8
Darby, S. E., Dunn, F. E., Nicholls, R. J., Rahman, M., & Riddy, L. (2015). A first look at the influence of anthropogenic climate change on the future delivery of fluvial sediment to the Ganges–Brahmaputra–Meghna delta. *Environmental Sciences: Processes & Impacts*, *17*(9), 1587–1600. https://doi.org/10.1039/C5EM00252D
Dasgupta, R., & Basu, M. (2023). Mental health and socio-psychological manifestations of cyclone-induced water insecurity in the Indian Sundarban delta. *International Journal of Disaster Risk Reduction*, *98*, 104085. https://doi.org/10.1016/j.ijdrr.2023.104085
Dasgupta, S., Islam, M. S., Huq, M., Khan, Z. H., & Hasib, M. R. (2019). Quantifying the protective capacity of mangroves from storm surges in coastal Bangladesh. *PLoS One*, *14*(3), e0214079. https://doi.org/10.1371/journal.pone.0214079
DeVries, B., Huang, C., Armston, J., Huang, W., Jones, J. W., & Lang, M. W. (2020). Rapid and robust monitoring of flood events using Sentinel-1 and Landsat data on the Google Earth Engine. *Remote Sensing of Environment*, *240*, 111664. https://doi.org/10.1016/j.rse.2020.111664
Dewan, A., Corner, R., Saleem, A., Rahman, M. M., Haider, M. R., Rahman, M. M., & Sarker, M. H. (2017). Assessing channel changes of the Ganges-Padma River system in Bangladesh using Landsat and hydrological data. *Geomorphology*, *276*, 257–279. https://doi.org/10.1016/j.geomorph.2016.10.017
de Wit, K., Lexmond, B. R., Stouthamer, E., Neussner, O., Dörr, N., Schenk, A., & Minderhoud, P. S. J. (2021). Identifying causes of urban differential subsidence in the Vietnamese Mekong delta by combining InSAR and field observations. *Remote Sensing*, *13*(2), 189. https://doi.org/10.3390/rs13020189
DLR. (2013). TerraSAR-X [Dataset]. Retrieved from https://www.dlr.de/en/research-and-transfer/projects-and-missions/terrasar-x
Dube, S. K., Jain, I., Rao, A. D., & Murty, T. S. (2009). Storm surge modelling for the Bay of Bengal and Arabian Sea. *Natural Hazards*, *51*(1), 3–27. https://doi.org/10.1007/s11069-009-9397-9
Dullaart, J. C. M., Muis, S., Bloemendaal, N., Chertova, M. V., Couasnon, A., & Aerts, J. C. J. H. (2021). Accounting for tropical cyclones more than doubles the global population exposed to low-probability coastal flooding. *Communications Earth & Environment*, *2*(1), 1–11. https://doi.org/10.1038/s43247-021-00204-9
Dunn, F. E., Darby, S. E., Nicholls, R. J., Cohen, S., Zarfl, C., & Fekete, B. M. (2019). Projections of declining fluvial sediment delivery to major deltas worldwide in response to climate change and anthropogenic stress. *Environmental Research Letters*, *14*(8), 084034. https://doi.org/10.1088/1748-9326/ab304e
Durand, M., Gleason, C. J., Pavelsky, T. M., Prata de Moraes Frasson, R., Turmon, M., David, C. H., et al. (2023). A framework for estimating global river discharge from the surface water and ocean topography satellite mission. *Water Resources Research*, *59*(4), e2021WR031614. https://doi.org/10.1029/2021WR031614
Duy, N. L., Nguyen, T. V. K., Nguyen, D. V., Tran, A. T., Nguyen, H. T., Heidbüchel, I., et al. (2021). Groundwater dynamics in the Vietnamese Mekong Delta: Trends, memory effects, and response times. *Journal of Hydrology: Regional Studies*, *33*, 100746. https://doi.org/10.1016/j.ejrh.2020.100746
Edmonds, D. A., Caldwell, R. L., Brondizio, E. S., & Siani, S. M. O. (2020). Coastal flooding will disproportionately impact people on river deltas. *Nature Communications*, *11*(1), 4741. https://doi.org/10.1038/s41467-020-18531-4
Elmi, O., Tourian, M. J., Saemian, P., & Sneeuw, N. (2024). Remote sensing-based extension of GRDC discharge time series—A monthly product with uncertainty estimates. *Scientific Data*, *11*(1), 240. https://doi.org/10.1038/s41597-024-03078-6
Erban, L. E., Gorelick, S. M., & Zebker, H. A. (2014). Groundwater extraction, land subsidence, and sea-level rise in the Mekong Delta, Vietnam. *Environmental Research Letters*, *9*(8), 084010. https://doi.org/10.1088/1748-9326/9/8/084010
Ericson, J. P., Vörösmarty, C. J., Dingman, S. L., Ward, L. G., & Meybeck, M. (2006). Effective sea-level rise and deltas: Causes of change and human dimension implications. *Global and Planetary Change*, *50*(1), 63–82. https://doi.org/10.1016/j.gloplacha.2005.07.004
Erkens, G., Bucx, T., Dam, R., de Lange, G., & Lambert, J. (2015). Sinking coastal cities. *Proceedings of IAHS*, *372*, 189–198. https://doi.org/10.5194/piahs-372-189-2015

Eslami, S., Hoekstra, P., Kernkamp, H. W. J., Nguyen Trung, N., Do Duc, D., Nguyen Nghia, H., et al. (2021). Dynamics of salt intrusion in the Mekong Delta: Results of field observations and integrated coastal–inland modelling. *Earth Surface Dynamics*, *9*(4), 953–976. https://doi.org/10.5194/esurf-9-953-2021

Eslami, S., Hoekstra, P., Nguyen Trung, N., Ahmed Kantoush, S., Van Binh, D., Duc Dung, D., et al. (2019). Tidal amplification and salt intrusion in the Mekong Delta driven by anthropogenic sediment starvation. *Scientific Reports*, *9*(1), 18746. https://doi.org/10.1038/s41598-019-55018-9

Fanchette, S. (2022). Delta vulnerability linked to climate and environmental changes: Metropolization challenges in Asian and nile deltas. In A. Deboulet & W. Mansour (Eds.), *Middle eastern cities in a time of climate crisis* (pp. 91–110). CEDEJ—Égypte/Soudan. https://doi.org/10.4000/books.cedej.8574

Fekete, B. M., Robarts, R. D., Kumagai, M., Nachtnebel, H.-P., Odada, E., & Zhulidov, A. V. (2015). Time for in situ renaissance. *Science*, *349*(6249), 685–686. https://doi.org/10.1126/science.aac7358

Ferrier, K. L., Mitrovica, J. X., Giosan, L., & Clift, P. D. (2015). Sea-level responses to erosion and deposition of sediment in the Indus River basin and the Arabian Sea. *Earth and Planetary Science Letters*, *416*, 12–20. https://doi.org/10.1016/j.epsl.2015.01.026

Foteh, R., Garg, V., Nikam, B. R., Khadatare, M. Y., Aggarwal, S. P., & Kumar, A. S. (2018). Reservoir sedimentation assessment through remote sensing and hydrological modelling. *Journal of the Indian Society of Remote Sensing*, *46*(11), 1893–1905. https://doi.org/10.1007/s12524-018-0843-6

Fox-Kemper, B. (2021). Ocean, cryosphere and sea level change. In *AGU Fall Meeting Abstracts* (Vol. 2021, p. U13B-09). Retrieved from https://ui.adsabs.harvard.edu/abs/2021AGUFM.U13B..09F/abstract

Frank, N. L., & Husain, S. A. (1971). The deadliest tropical cyclone in history? *Bulletin of the American Meteorological Society*, *52*(6), 438–445. https://doi.org/10.1175/1520-0477(1971)052<0438:TDTCIH>2.0.CO;2

Frappart, F., Papa, F., Marieu, V., Malbeteau, Y., Jordy, F., Calmant, S., et al. (2015). Preliminary assessment of SARAL/AltiKa observations over the Ganges-Brahmaputra and Irrawaddy Rivers. *Marine Geodesy*, *38*(sup1), 568–580. https://doi.org/10.1080/01490419.2014.990591

Fritz, H. M., Blount, C. D., Thwin, S., Thu, M. K., & Chan, N. (2009). Cyclone Nargis storm surge in Myanmar. *Nature Geoscience*, *2*(7), 448–449. https://doi.org/10.1038/ngeo558

Fu, L.-L., Pavelsky, T., Cretaux, J.-F., Morrow, R., Farrar, J. T., Vaze, P., et al. (2024). The surface water and ocean topography mission: A breakthrough in radar remote sensing of the ocean and land surface water. *Geophysical Research Letters*, *51*(4), e2023GL107652. https://doi.org/10.1029/2023GL107652

Furuichi, T., Win, Z., & Wasson, R. J. (2009). Discharge and suspended sediment transport in the Ayeyarwady River, Myanmar: Centennial and decadal changes. *Hydrological Processes*, *23*(11), 1631–1641. https://doi.org/10.1002/hyp.7295

Galloway, D. L., & Burbey, T. J. (2011). Review: Regional land subsidence accompanying groundwater extraction. *Hydrogeology Journal*, *19*(8), 1459–1486. https://doi.org/10.1007/s10040-011-0775-5

Gao, J., Dai, Z., Mei, X., Ge, Z., Wei, W., Xie, H., & Li, S. (2015). Interference of natural and anthropogenic forcings on variations in continental freshwater discharge from the Red River (Vietnam) to sea. *Quaternary International*, *380–381*, 133–142. https://doi.org/10.1016/j.quaint.2015.01.007

Gehrels, W. R., Dawson, D. A., Shaw, J., & Marshall, W. A. (2011). Using Holocene relative sea-level data to inform future sea-level predictions: An example from southwest England. *Global and Planetary Change*, *78*(3), 116–126. https://doi.org/10.1016/j.gloplacha.2011.05.013

Gesch, D. B. (2018). Best practices for elevation-based assessments of sea-level rise and coastal flooding exposure. *Frontiers in Earth Science*, *6*. https://doi.org/10.3389/feart.2018.00230

Giosan, L., Syvitski, J., Constantinescu, S., & Day, J. (2014). Climate change: Protect the world's deltas. *Nature*, *516*(7529), 31–33. https://doi.org/10.1038/516031a

Glover, H. E., Ogston, A. S., Fricke, A. T., Nittrouer, C. A., Aung, C., Naing, T., et al. (2021). Connecting sediment retention to distributary-channel hydrodynamics and sediment dynamics in a tide-dominated delta: The Ayeyarwady Delta, Myanmar. *Journal of Geophysical Research: Earth Surface*, *126*(3), e2020JF005882. https://doi.org/10.1029/2020JF005882

Goodbred, S. L., & Kuehl, S. A. (1998). Floodplain processes in the Bengal Basin and the storage of Ganges–Brahmaputra river sediment: An accretion study using 137Cs and 210Pb geochronology. *Sedimentary Geology*, *121*(3), 239–258. https://doi.org/10.1016/S0037-0738(98)00082-7

Goodbred, S. L., & Saito, Y. (2012). Tide-dominated deltas. In R. A. Davis, Jr. & R. W. Dalrymple (Eds.), *Principles of tidal sedimentology* (pp. 129–149). Springer Netherlands. https://doi.org/10.1007/978-94-007-0123-6_7

Government of the Union of Myanmar. (2015). Post-disaster needs assessment of floods and landslides.

Grall, C., Steckler, M. S., Pickering, J. L., Goodbred, S., Sincavage, R., Paola, C., et al. (2018). A base-level stratigraphic approach to determining Holocene subsidence of the Ganges–Meghna–Brahmaputra Delta plain. *Earth and Planetary Science Letters*, *499*, 23–36. https://doi.org/10.1016/j.epsl.2018.07.008

Gruel, C.-R., Park, E., Switzer, A. D., Kumar, S., Loc Ho, H., Kantoush, S., et al. (2022). New systematically measured sand mining budget for the Mekong Delta reveals rising trends and significant volume underestimations. *International Journal of Applied Earth Observation and Geoinformation*, *108*, 102736. https://doi.org/10.1016/j.jag.2022.102736

Hackney, C. R., Darby, S. E., Parsons, D. R., Leyland, J., Best, J. L., Aalto, R., et al. (2020). River bank instability from unsustainable sand mining in the lower Mekong River. *Nature Sustainability*, *3*(3), 217–225. https://doi.org/10.1038/s41893-019-0455-3

Haigh, I. D., Marcos, M., Talke, S. A., Woodworth, P. L., Hunter, J. R., Hague, B. S., et al. (2023). GESLA version 3: A major update to the global higher-frequency sea-level dataset. *Geoscience Data Journal*, *10*(3), 293–314. https://doi.org/10.1002/gdj3.174

Hamilton, S. (2013). Assessing the role of commercial aquaculture in displacing mangrove forest. *Bulletin of Marine Science*, *89*(2), 585–601. https://doi.org/10.5343/bms.2012.1069

Hamlington, B. D., Gardner, A. S., Ivins, E., Lenaerts, J. T. M., Reager, J. T., Trossman, D. S., et al. (2020). Understanding of contemporary regional sea-level change and the implications for the future. *Reviews of Geophysics*, *58*(3), e2019RG000672. https://doi.org/10.1029/2019RG000672

Hara, Y., Takeuchi, K., & Okubo, S. (2005). Urbanization linked with past agricultural landuse patterns in the urban fringe of a deltaic Asian mega-city: A case study in Bangkok. *Landscape and Urban Planning*, *73*(1), 16–28. https://doi.org/10.1016/j.landurbplan.2004.07.002

Hashimoto, R., Kazama, S., Hashimoto, T., Oguma, K., & Takizawa, S. (2022). Planning methods for conjunctive use of urban water resources based on quantitative water demand estimation models and groundwater regulation index in Yangon City, Myanmar. *Journal of Cleaner Production*, *367*, 133123. https://doi.org/10.1016/j.jclepro.2022.133123

Hauser, D., Boni, R., Minderhoud, P. S., Teatini, P., Woillez, M.-N., Almar, R., et al. (2023). A scoping study on coastal vulnerability to relative sea-level rise in the Gulf of Guinea. In *AFD Research Papers* (Vol. 283, pp. 1–42).

Hauser, D., Tourain, C., Hermozo, L., Alraddawi, D., Aouf, L., Chapron, B., et al. (2021). New observations from the SWIM radar on-board CFOSAT: Instrument validation and ocean wave measurement assessment. *IEEE Transactions on Geoscience and Remote Sensing*, *59*(1), 5–26. https://doi.org/10.1109/TGRS.2020.2994372

Hawker, L., Uhe, P., Paulo, L., Sosa, J., Savage, J., Sampson, C., & Neal, J. (2022). A 30 m global map of elevation with forests and buildings removed. *Environmental Research Letters*, *17*(2), 024016. https://doi.org/10.1088/1748-9326/ac4d4f

Hedley, P. J., Bird, M. I., & Robinson, R. A. J. (2010). Evolution of the Irrawaddy delta region since 1850. *The Geographical Journal*, *176*(2), 138–149. https://doi.org/10.1111/j.1475-4959.2009.00346.x

Higgins, S. A. (2016). Advances in delta-subsidence research using satellite methods. *Hydrogeology Journal*, *24*(3), 587–600. https://doi.org/10.1007/s10040-015-1330-6

Higgins, S. A., Overeem, I., Rogers, K. G., & Kalina, E. A. (2018). River linking in India: Downstream impacts on water discharge and suspended sediment transport to deltas. *Elementa: Science of the Anthropocene*, *6*, 20. https://doi.org/10.1525/elementa.269

Higgins, S. A., Overeem, I., Steckler, M. S., Syvitski, J. P. M., Seeber, L., & 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

Hoque, M. Z., Cui, S., Xu, L., Islam, I., Tang, J., & Ding, S. (2019). Assessing agricultural livelihood vulnerability to climate change in coastal Bangladesh. *International Journal of Environmental Research and Public Health*, *16*(22), 4552. https://doi.org/10.3390/ijerph16224552

Horritt, M. S., Mason, D. C., & Luckman, A. J. (2001). Flood boundary delineation from Synthetic Aperture Radar imagery using a statistical active contour model. *International Journal of Remote Sensing*, *22*(13), 2489–2507. https://doi.org/10.1080/01431160116902

Horsburgh, K. J., & Wilson, C. (2007). Tide-surge interaction and its role in the distribution of surge residuals in the North Sea. *Journal of Geophysical Research*, *112*(C8). https://doi.org/10.1029/2006JC004033

Hossain, M. A., Gan, T. Y., & Baki, A. B. M. (2013). Assessing morphological changes of the Ganges River using satellite images. *Quaternary International*, *304*, 142–155. https://doi.org/10.1016/j.quaint.2013.03.028

Hui, T. R., Park, E., Loc, H. H., & Tien, P. D. (2022). Long-term hydrological alterations and the agricultural landscapes in the Mekong Delta: Insights from remote sensing and national statistics. *Environmental Challenges*, *7*, 100454. https://doi.org/10.1016/j.envc.2022.100454

ICHAM. (2016). International Centre for Water Hazard and Risk Management (ICHARM), Public Works Research Institute (PWRI), CTI Engineering International Co., Ltd., CTI Engineering Co., Ltd, and PASCO CORPORATION: Republic of the Union of Myanmar: Transformation of Urban Management—Flood Management Component, Asian Development Bank Technical Assistance Consultant's Report, Final Report Annexes 1–7 (p. 159). Retrieved from https://www.adb.org/sites/default/files/project-documents/46496/46496-001-tacr-en_1.pdf

Idier, D., Bertin, X., Thompson, P., & Pickering, M. D. (2019). Interactions between mean sea level, tide, surge, waves and flooding: Mechanisms and contributions to sea level variations at the coast. *Surveys in Geophysics*, *40*(6), 1603–1630. https://doi.org/10.1007/s10712-019-09549-5

IFRC. (2017). *Annual report 2017*. IFRC. Retrieved from https://www.ifrc.org/document/annual-report-2017

Intui, S., Inazumi, S., & Soralump, S. (2022). Sustainability of soil/ground environment under changes in groundwater level in Bangkok Plain, Thailand. *Sustainability*, *14*(17), 10908. https://doi.org/10.3390/su141710908

IPCC. (2019). In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, et al. (Eds.), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*.

Ishitsuka, K., Fukushima, Y., Tsuji, T., Yamada, Y., Matsuoka, T., & Giao, P. H. (2014). Natural surface rebound of the Bangkok plain and aquifer characterization by persistent scatterer interferometry. *Geochemistry, Geophysics, Geosystems*, *15*(4), 965–974. https://doi.org/10.1002/2013GC005154

Isikdogan, F., Bovik, A., & Passalacqua, P. (2015). Automatic channel network extraction from remotely sensed images by singularity analysis. *IEEE Geoscience and Remote Sensing Letters*, *12*(11), 2218–2221. https://doi.org/10.1109/LGRS.2015.2458898

Isikdogan, F., Bovik, A., & Passalacqua, P. (2017). RivaMap: An automated river analysis and mapping engine. *Remote Sensing of Environment*, *202*, 88–97. https://doi.org/10.1016/j.rse.2017.03.044

Ivins, E. R., Dokka, R. K., & Blom, R. G. (2007). Post-glacial sediment load and subsidence in coastal Louisiana. *Geophysical Research Letters*, *34*(16). https://doi.org/10.1029/2007GL030003

Jafarzadegan, K., Moradkhani, H., Pappenberger, F., Moftakhari, H., Bates, P., Abbaszadeh, P., et al. (2023). Recent advances and new Frontiers in riverine and coastal flood modeling. *Reviews of Geophysics*, *61*(2), e2022RG000788. https://doi.org/10.1029/2022RG000788

Jankowski, K. L., Törnqvist, T. E., & Fernandes, A. M. (2017). Vulnerability of Louisiana's coastal wetlands to present-day rates of relative sea-level rise. *Nature Communications*, *8*(1), 14792. https://doi.org/10.1038/ncomms14792

Jarriel, T., Isikdogan, L. F., Bovik, A., & Passalacqua, P. (2020). System wide channel network analysis reveals hotspots of morphological change in anthropogenically modified regions of the Ganges Delta. *Scientific Reports*, *10*(1), 12823. https://doi.org/10.1038/s41598-020-69688-3

Jarriel, T., Swartz, J., & Passalacqua, P. (2021). Global rates and patterns of channel migration in river deltas. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(46), e2103178118. https://doi.org/10.1073/pnas.2103178118

Jasechko, S., Seybold, H., Perrone, D., Fan, Y., Shamsudduha, M., Taylor, R. G., et al. (2024). Rapid groundwater decline and some cases of recovery in aquifers globally. *Nature*, *625*(7996), 715–721. https://doi.org/10.1038/s41586-023-06879-8

Jian, J., Webster, P. J., & Hoyos, C. D. (2009). Large-scale controls on Ganges and Brahmaputra river discharge on intraseasonal and seasonal time-scales. *Quarterly Journal of the Royal Meteorological Society*, *135*(639), 353–370. https://doi.org/10.1002/qj.384

Johnson, F., Hutton, C. W., Hornby, D., Lázár, A. N., & Mukhopadhyay, A. (2016). Is shrimp farming a successful adaptation to salinity intrusion? A geospatial associative analysis of poverty in the populous Ganges–Brahmaputra–Meghna Delta of Bangladesh. *Sustainability Science*, *11*(3), 423–439. https://doi.org/10.1007/s11625-016-0356-6

Kanan, A. H., Pirotti, F., Masiero, M., & Rahman, M. M. (2023). Mapping inundation from sea level rise and its interaction with land cover in the Sundarbans mangrove forest. *Climatic Change*, *176*(8), 104. https://doi.org/10.1007/s10584-023-03574-5

Karegar, M. A., Dixon, T. H., & Engelhart, S. E. (2016). Subsidence along the Atlantic Coast of North America: Insights from GPS and late Holocene relative sea level data. *Geophysical Research Letters*, *43*(7), 3126–3133. https://doi.org/10.1002/2016GL068015

Karegar, M. A., Dixon, T. H., & Malservisi, R. (2015). A three-dimensional surface velocity field for the Mississippi Delta: Implications for coastal restoration and flood potential. *Geology*, *43*(6), 519–522. https://doi.org/10.1130/G36598.1

Karegar, M. A., Kusche, J., Williams, S. D. P., Engelhart, S., & Nicholls, R. J. (2023). Insights into depth distribution of Holocene sediment compaction in global deltas—EP21B-01. In *Oral (Invited) presented at the AGU Fall Meeting, San Franciso, USA*. Retrieved from https://agu.confex.com/agu/fm23/meetingapp.cgi/Paper/1309811

Karegar, M. A., Larson, K. M., Kusche, J., & Dixon, T. H. (2020). Novel quantification of shallow sediment compaction by GPS interferometric reflectometry and implications for flood Susceptibility. *Geophysical Research Letters*, *47*(14), e2020GL087807. https://doi.org/10.1029/2020GL087807

Karlsrud, K., Vangelsten, B. V., & Frauenfelder, R. (2017). Subsidence and shoreline retreat in the Ca Mau Province–Vietnam. Causes, consequences and mitigation options. *Geotechnical Journal of the SEAGS & AGSSEA*, *48*(1), 26–32.

Karpytchev, M., Ballu, V., Krien, Y., Becker, M., Goodbred, S., Spada, G., et al. (2018). Contributions of a strengthened early holocene monsoon and sediment loading to present-day subsidence of the Ganges-Brahmaputra delta. *Geophysical Research Letters*, *45*(3), 1433–1442. https://doi.org/10.1002/2017GL076388

Kettner, A. J., Brakenridge, G. R., Schumann, G. J.-P., & Shen, X. (2021). Chapter 7—DFO—Flood observatory. In G. J.-P. Schumann (Ed.), *Earth observation for flood applications* (pp. 147–164). Elsevier. https://doi.org/10.1016/B978-0-12-819412-6.00007-9

Khan, M. J. U., Durand, F., Bertin, X., Testut, L., Krien, Y., Islam, A. K. M. S., et al. (2021). Towards an efficient storm surge and inundation forecasting system over the Bengal delta: Chasing the Supercyclone Amphan. *Natural Hazards and Earth System Sciences*, *21*(8), 2523–2541. https://doi.org/10.5194/nhess-21-2523-2021

Khan, M. J. U., Durand, F., Emanuel, K., Krien, Y., Testut, L., & Islam, A. K. M. S. (2022). Storm surge hazard over Bengal delta: A probabilistic–deterministic modelling approach. *Natural Hazards and Earth System Sciences*, *22*(7), 2359–2379. https://doi.org/10.5194/nhess-22-2359-2022

Khan, M. J. U., Durand, F., Testut, L., Krien, Y., & Islam, A. S. (2020). Sea level rise inducing tidal modulation along the coasts of Bengal delta. *Continental Shelf Research*, *211*, 104289. https://doi.org/10.1016/j.csr.2020.104289

Kim, D., Lee, H., Chang, C.-H., Bui, D. D., Jayasinghe, S., Basnayake, S., et al. (2019). Daily river discharge estimation using multi-mission radar altimetry data and ensemble learning regression in the lower Mekong River Basin. *Remote Sensing*, *11*(22), 2684. https://doi.org/10.3390/rs11222684

Kirezci, E., Young, I. R., Ranasinghe, R., Muis, S., Nicholls, R. J., Lincke, D., & Hinkel, J. (2020). Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. *Scientific Reports*, *10*(1), 11629. https://doi.org/10.1038/s41598-020-67736-6

Knapp, K. R., Diamond, H. J., Kossin, J. P., Kruk, M. C., & Schreck, C. J. (2018). International best track archive for climate Stewardship (IBTrACS) project, version 4 [Dataset]. *NOAA National Centers for Environmental Information*. https://doi.org/10.25921/82ty-9e16

Knapp, K. R., Kruk, M. C., Levinson, D. H., Diamond, H. J., & Neumann, C. J. (2010). The international best track archive for climate stewardship (IBTrACS): Unifying tropical cyclone data. *Bulletin of the American Meteorological Society*, *91*(3), 363–376. https://doi.org/10.1175/2009BAMS2755.1

Kondolf, G. M., Schmitt, R. J. P., Carling, P. A., Goichot, M., Keskinen, M., Arias, M. E., et al. (2022). Save the Mekong Delta from drowning. *Science*, *376*(6593), 583–585. https://doi.org/10.1126/science.abm5176

Kotera, A., Nagano, T., Hanittinan, P., & Koontanakulvong, S. (2016). Assessing the degree of flood damage to rice crops in the Chao Phraya delta, Thailand, using MODIS satellite imaging. *Paddy and Water Environment*, *14*(1), 271–280. https://doi.org/10.1007/s10333-015-0496-9

Krien, Y., Karpytchev, M., Ballu, V., Becker, M., Grall, C., Goodbred, S., et al. (2019). Present-day subsidence in the Ganges-Brahmaputra-Meghna Delta: Eastern amplification of the Holocene sediment loading contribution. *Geophysical Research Letters*, *46*(19), 10764–10772. https://doi.org/10.1029/2019gl083601

Krien, Y., Mayet, C., Testut, L., Durand, F., Tazkia, A. R., Islam, A., et al. (2016). Improved bathymetric dataset and tidal model for the northern Bay of Bengal. *Marine Geodesy*, *39*(6), 422–438. https://doi.org/10.1080/01490419.2016.1227405

Krien, Y., Testut, L., Islam, A., Bertin, X., Durand, F., Mayet, C., et al. (2017). Towards improved storm surge models in the northern Bay of Bengal. *Continental Shelf Research*, *135*, 58–73. https://doi.org/10.1016/j.csr.2017.01.014

Kuehl, S. A., Williams, J., Liu, J. P., Harris, C., Aung, D. W., Tarpley, D., et al. (2019). Sediment dispersal and accumulation off the Ayeyarwady delta—Tectonic and oceanographic controls. *Marine Geology*, *417*, 106000. https://doi.org/10.1016/j.margeo.2019.106000

Kuenzer, C., Guo, H., Huth, J., Leinenkugel, P., Li, X., & Dech, S. (2013). Flood mapping and flood dynamics of the Mekong Delta: ENVISAT-ASAR-WSM based time series analyses. *Remote Sensing*, *5*(2), 687–715. https://doi.org/10.3390/rs5020687

Kuenzer, C., Klein, I., Ullmann, T., Georgiou, E. F., Baumhauer, R., & Dech, S. (2015). Remote sensing of river delta inundation: Exploiting the potential of coarse spatial resolution, temporally-dense MODIS time series. *Remote Sensing*, *7*(7), 8516–8542. https://doi.org/10.3390/rs70708516

Kulp, S. A., & Strauss, B. H. (2019). New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications*, *10*(1), 4844. https://doi.org/10.1038/s41467-019-12808-z

Kulp, S. A., & Strauss, B. H. (2021). CoastalDEM v2. 1: A high-accuracy and high-resolution global coastal elevation model trained on ICESat-2 satellite lidar. In *Climate Central Scientific Report* (p. 17).

Kumar, V., Sharma, K. V., Caloiero, T., Mehta, D. J., & Singh, K. (2023). Comprehensive overview of flood modeling approaches: A review of recent advances. *Hydrology*, *10*(7), 141. https://doi.org/10.3390/hydrology10070141

Kummu, M., Lu, X. X., Rasphone, A., Sarkkula, J., & Koponen, J. (2008). Riverbank changes along the Mekong River: Remote sensing detection in the Vientiane–Nong Khai area. *Quaternary International*, *186*(1), 100–112. https://doi.org/10.1016/j.quaint.2007.10.015

Lagomasino, D., Fatoyinbo, T., Lee, S., Feliciano, E., Trettin, C., Shapiro, A., & Mangora, M. M. (2019). Measuring mangrove carbon loss and gain in deltas. *Environmental Research Letters*, *14*(2), 025002. https://doi.org/10.1088/1748-9326/aaf0de

Laignel, B., Vignudelli, S., Almar, R., Becker, M., Bentamy, A., Benveniste, J., et al. (2023). Observation of the coastal areas, estuaries and deltas from space. *Surveys in Geophysics*, *44*(5), 1309–1356. https://doi.org/10.1007/s10712-022-09757-6

Lambeck, K., Purcell, A., & Zhao, S. (2017). The North American Late Wisconsin ice sheet and mantle viscosity from glacial rebound analyses. *Quaternary Science Reviews*, *158*, 172–210. https://doi.org/10.1016/j.quascirev.2016.11.033

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., & Sambridge, M. (2014). Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(43), 15296–15303. https://doi.org/10.1073/pnas.1411762111

Lam-Dao, N., Pham-Bach, V., Nguyen-Thanh, M., Pham-Thi, M.-T., & Hoang-Phi, P. (2011). Change detection of land use and riverbank in Mekong Delta, Vietnam using time series remotely sensed data. *Journal of Resources and Ecology*, *2*(4), 370–374. https://doi.org/10.3969/j.issn.1674-764x.2011.04.011

Lan, N. T. P. (2013). Social and ecological challenges of market-oriented shrimp farming in Vietnam. *SpringerPlus*, *2*(1), 675. https://doi.org/10.1186/2193-1801-2-675

Latrubesse, E. M., Park, E., & Kästner, K. (2021). The Ayeyarwady River (Myanmar): Washload transport and its global role among rivers in the Anthropocene. *PLoS One*, *16*(5), e0251156. https://doi.org/10.1371/journal.pone.0251156

Lázár, A. N., Nicholls, R. J., Hall, J. W., Barbour, E. J., & Haque, A. (2020). Contrasting development trajectories for coastal Bangladesh to the end of century. *Regional Environmental Change*, *20*(3), 93. https://doi.org/10.1007/s10113-020-01681-y

Lazarus, K. M., Cardinale, P., Corbett, M., Lin, N. S., & Noeske, T. K. H. (2019). Strategic environmental assessment of the hydropower sector in Myanmar. In *Baseline assessment report: Social and livelihoods* (Vol. 7). Retrieved from http://documents.worldbank.org/curated/en/857971548867615099/Baseline-Assessment-Report-Hydropower

Li, X., Liu, J. P., Saito, Y., & Nguyen, V. L. (2017). Recent evolution of the Mekong Delta and the impacts of dams. *Earth-Science Reviews*, *175*, 1–17. https://doi.org/10.1016/j.earscirev.2017.10.008

Liew, S. C., Gupta, A., Chia, A. S., & Ang, W. C. (2016). The flood of 2011 in the lower Chao Phraya valley, Thailand: Study of a long-duration flood through satellite images. *Geomorphology*, *262*, 112–122. https://doi.org/10.1016/j.geomorph.2016.03.022

Likitswat, F., & Sahavacharin, A. (2023). Landscape change analysis: Ecosystem services in the peri-urban agriculture of Bangkok. *Journal of Architectural/Planning Research and Studies (JARS)*, *20*(2), 25–38. https://doi.org/10.56261/jars.v20i2.249694

Lin, L., Di, L., Yu, E. G., Kang, L., Shrestha, R., Rahman, M. S., et al. (2016). A review of remote sensing in flood assessment. In *2016 Fifth International Conference on Agro-Geoinformatics (Agro-Geoinformatics)* (pp. 1–4). https://doi.org/10.1109/Agro-Geoinformatics.2016.7577655

Long, C., Dai, Z., Zhou, X., Mei, X., & Mai Van, C. (2021). Mapping mangrove forests in the Red River Delta, Vietnam. *Forest Ecology and Management*, *483*, 118910. https://doi.org/10.1016/j.foreco.2020.118910

Lorphensri, O., Ladawadee, A., & Dhammasarn, S. (2011). Review of groundwater management and land subsidence in Bangkok, Thailand. In M. Taniguchi (Ed.), *Groundwater and subsurface environments: Human impacts in Asian coastal cities* (pp. 127–142). Springer Japan. https://doi.org/10.1007/978-4-431-53904-9_7

Loucks, D. P. (2019). Developed river deltas: Are they sustainable? *Environmental Research Letters*, *14*(11), 113004. https://doi.org/10.1088/1748-9326/ab4165

Lovelock, C. E., Cahoon, D. R., Friess, D. A., Guntenspergen, G. R., Krauss, K. W., Reef, R., et al. (2015). The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nature*, *526*(7574), 559–563. https://doi.org/10.1038/nature15538

Lu, X., Wrathall, D. J., Sundsøy, P. R., Nadiruzzaman, M., Wetter, E., Iqbal, A., et al. (2016). Unveiling hidden migration and mobility patterns in climate stressed regions: A longitudinal study of six million anonymous mobile phone users in Bangladesh. *Global Environmental Change*, *38*, 1–7. https://doi.org/10.1016/j.gloenvcha.2016.02.002

Lumbroso, D. M., Suckall, N. R., Nicholls, R. J., & White, K. D. (2017). Enhancing resilience to coastal flooding from severe storms in the USA: International lessons. *Natural Hazards and Earth System Sciences*, *17*(8), 1357–1373. https://doi.org/10.5194/nhess-17-1357-2017

Lupker, M., France-Lanord, C., Lavé, J., Bouchez, J., Galy, V., Métivier, F., et al. (2011). A Rouse-based method to integrate the chemical composition of river sediments: Application to the Ganga basin. *Journal of Geophysical Research*, *116*(F4), F04012. https://doi.org/10.1029/2010JF001947

Luu, T. N. M., Garnier, J., Billen, G., Orange, D., Némery, J., Le, T. P. Q., et al. (2010). Hydrological regime and water budget of the Red River Delta (Northern Vietnam). *Journal of Asian Earth Sciences*, *37*(3), 219–228. https://doi.org/10.1016/j.jseaes.2009.08.004

Lyard, F. H., Allain, D. J., Cancet, M., Carrère, L., & Picot, N. (2021). FES2014 global ocean tide atlas: Design and performance. *Ocean Science*, *17*(3), 615–649. https://doi.org/10.5194/os-17-615-2021

Mai, C. V., Stive, M. J. F., & Van Gelder, P. H. A. J. M. (2009). Coastal protection strategies for the Red River Delta. *Journal of Coastal Research*, *25*(1), 105–116. https://doi.org/10.2112/07-0888.1

Mallick, P. (2022). Transboundary River Cooperation in Mekong Basin: A sub-regional perspective. *Journal of Asian Security and International Affairs*, *9*(1), 50–71. https://doi.org/10.1177/23477970221076746

Maranzoni, A., D'Oria, M., & Rizzo, C. (2023). Quantitative flood hazard assessment methods: A review. *Journal of Flood Risk Management*, *16*(1), e12855. https://doi.org/10.1111/jfr3.12855

Marchesiello, P., Nguyen, N. M., Gratiot, N., Loisel, H., Anthony, E. J., Dinh, C. S., et al. (2019). Erosion of the coastal Mekong delta: Assessing natural against man induced processes. *Continental Shelf Research*, *181*, 72–89. https://doi.org/10.1016/j.csr.2019.05.004

Marcos, M., Marzeion, B., Dangendorf, S., Slangen, A. B. A., Palanisamy, H., & Fenoglio-Marc, L. (2017). Internal variability versus anthropogenic forcing on sea level and its Components. In A. Cazenave, N. Champollion, F. Paul, & J. Benveniste (Eds.), *Integrative study of the mean sea level and its components* (pp. 337–356). Springer International Publishing. https://doi.org/10.1007/978-3-319-56490-6_15

Mård, J., Di Baldassarre, G., & Mazzoleni, M. (2018). Nighttime light data reveal how flood protection shapes human proximity to rivers. *Science Advances*, *4*(8), eaar5779. https://doi.org/10.1126/sciadv.aar5779

McCormack, T., Campanyà, J., & Naughton, O. (2022). A methodology for mapping annual flood extent using multi-temporal Sentinel-1 imagery. *Remote Sensing of Environment*, *282*, 113273. https://doi.org/10.1016/j.rse.2022.113273

McGranahan, G., Balk, D., Colenbrander, S., Engin, H., & MacManus, K. (2023). Is rapid urbanization of low-elevation deltas undermining adaptation to climate change? A global review. *Environment and Urbanization*, *35*(2), 527–559. https://doi.org/10.1177/09562478231192176

McMillan, H., Krueger, T., & Freer, J. (2012). Benchmarking observational uncertainties for hydrology: Rainfall, river discharge and water quality. *Hydrological Processes*, *26*(26), 4078–4111. https://doi.org/10.1002/hyp.9384

Mekong River Commission. (2010). State of the basin report 2010.

Mekong River Commission. (2019). State of the basin report 2018. Retrieved from https://www.mrcmekong.org/assets/Publications/SOBR-v8_Final-for-web.pdf,2024-04-15

Merkens, J.-L., Lincke, D., Hinkel, J., Brown, S., & Vafeidis, A. T. (2018). Regionalisation of population growth projections in coastal exposure analysis. *Climatic Change*, *151*(3), 413–426. https://doi.org/10.1007/s10584-018-2334-8

Milliman, J. D., & Haq, B. U. (1996). In *Sea-level rise and coastal subsidence: Causes, consequences, and strategies* (Vol. 2). Springer Science & Business Media. Retrieved from https://books.google.com/books?hl=fr&lr=&id=oXrPSnlFswQC&oi=fnd&pg=PA1&dq=milliman+1999+%22sea+level+rise+and+coastal+subsidence%22&ots=rCqLsNJftM&sig=DM8bXfQ06aD3GFL3nSQXcSyeRT8

Milliman, J. D., & Syvitski, J. P. M. (1992). Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers. *The Journal of Geology*, *100*(5), 525–544. https://doi.org/10.1086/629606

Minderhoud, P. S. J., Coumou, L., Erban, L. E., Middelkoop, H., Stouthamer, E., & Addink, E. A. (2018). The relation between land use and subsidence in the Vietnamese Mekong delta. *Science of the Total Environment*, *634*, 715–726. https://doi.org/10.1016/j.scitotenv.2018.03.372

Minderhoud, P. S. J., Coumou, L., Erkens, G., Middelkoop, H., & Stouthamer, E. (2019). Mekong delta much lower than previously assumed in sea-level rise impact assessments. *Nature Communications*, *10*(1), 3847. https://doi.org/10.1038/s41467-019-11602-1

Minderhoud, P. S. J., Erkens, G., Pham, V. H., Bui, V. T., Erban, L., Kooi, H., & Stouthamer, E. (2017). Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam. *Environmental Research Letters*, *12*(6), 064006. https://doi.org/10.1088/1748-9326/aa7146

Minderhoud, P. S. J., Hlavacova, I., Kolomaznik, J., & Neussner, O. (2020). Towards unraveling total subsidence of a mega-delta—The potential of new PS InSAR data for the Mekong delta. In *Proceedings of the International Association of Hydrological Sciences, Proceedings of IAHS* (Vol. 382, pp. 327–332). Copernicus GmbH. https://doi.org/10.5194/piahs-382-327-2020

Minderhoud, P. S. J., Middelkoop, H., Erkens, G., & Stouthamer, E. (2020). Groundwater extraction may drown mega-delta: Projections of extraction-induced subsidence and elevation of the Mekong delta for the 21st century. *Environmental Research Communications*, *2*(1), 011005. https://doi.org/10.1088/2515-7620/ab5e21

Mirza, M. Q. (2003). Three recent extreme floods in Bangladesh: A hydro-meteorological analysis. *Natural Hazards*, *28*(1), 35–64. https://doi.org/10.1023/A:1021169731325

Mitchell, D., Hawker, L., Savage, J., Bingham, R., Lord, N. S., Khan, M. J. U., et al. (2022). Increased population exposure to Amphan-scale cyclones under future climates. *Climate Resilience and Sustainability*, *1*(2), e36. https://doi.org/10.1002/cli2.36

Mitra, B., Rahman, S. M., Uddin, M. S., Mahmud, K., Islam, M. K., Arifuzzaman, M., et al. (2023). Assessing demographic and economic vulnerabilities to sea level rise in Bangladesh via a nighttime light-based cellular automata model. *Scientific Reports*, *13*(1), 13351. https://doi.org/10.1038/s41598-023-40329-9

Moore, G. T., & Asquith, D. O. (1971). Delta: Term and concept. *GSA Bulletin*, *82*(9), 2563–2568. https://doi.org/10.1130/0016-7606(1971)82[2563:DTAC]2.0.CO;2

Moragoda, N., Cohen, S., Gardner, J., Muñoz, D., Narayanan, A., Moftakhari, H., & Pavelsky, T. M. (2023). Modeling and analysis of sediment trapping efficiency of large dams using remote sensing. *Water Resources Research*, *59*(6), e2022WR033296. https://doi.org/10.1029/2022WR033296

Morita, A. (2016). Infrastructuring amphibious space: The interplay of aquatic and terrestrial infrastructures in the Chao Phraya Delta in Thailand. *Science as Culture*, *25*(1), 117–140. https://doi.org/10.1080/09505431.2015.1081502

Mosavi, A., Ozturk, P., & Chau, K. (2018). Flood prediction using machine learning models: Literature review. *Water*, *10*(11), 1536. https://doi.org/10.3390/w10111536

Muis, S., Verlaan, M., Winsemius, H. C., Aerts, J. C. J. H., & Ward, P. J. (2016). A global reanalysis of storm surges and extreme sea levels. *Nature Communications*, *7*(1), 11969. https://doi.org/10.1038/ncomms11969

Munawar, H. S., Hammad, A. W. A., & Waller, S. T. (2022). Remote sensing methods for flood prediction: A review. *Sensors*, *22*(3), 960. https://doi.org/10.3390/s22030960

Myanmar Information Management Unit. (2015). Floods 2015 for Ayeyarwady. Retrieved from https://www.themimu.info/emergencies/floods-2015-ayeyarwady

Neal, J., Hawker, L., Savage, J., Durand, M., Bates, P., & Sampson, C. (2021). Estimating river channel bathymetry in large scale flood inundation models. *Water Resources Research*, *57*(5), e2020WR028301. https://doi.org/10.1029/2020WR028301

Nghia, B. P. Q., Pal, I., Chollacoop, N., & Mukhopadhyay, A. (2022). Applying Google earth engine for flood mapping and monitoring in the downstream provinces of Mekong River. *Progress in Disaster Science*, *14*, 100235. https://doi.org/10.1016/j.pdisas.2022.100235

Nguyen, G. S., Xu, C., & Buckley, B. M. (2022). Droughts, pluvials, and wet season timing across the Chao Phraya River Basin: A 254-year monthly reconstruction from tree ring widths and δ^{18}O. *Geophysical Research Letters*, *49*(17), e2022GL100442. https://doi.org/10.1029/2022GL100442

Nguyen, M. T., Renaud, F. G., & Sebesvari, Z. (2019). Drivers of change and adaptation pathways of agricultural systems facing increased salinity intrusion in coastal areas of the Mekong and Red River deltas in Vietnam. *Environmental Science & Policy*, *92*, 331–348. https://doi.org/10.1016/j.envsci.2018.10.016

Nguyen, T. C., Schwarzer, K., & Ricklefs, K. (2023). Water-level changes and subsidence rates along the Saigon-Dong Nai River Estuary and the East Sea coastline of the Mekong Delta. *Estuarine, Coastal and Shelf Science*, *283*, 108259. https://doi.org/10.1016/j.ecss.2023.108259

Nicholls, R. J., Adger, W. N., Hutton, C. W., & Hanson, S. E. (2020). *Deltas in the Anthropocene*. Springer Nature.

Nicholls, R. J., Hutton, C. W., Adger, W. N., Hanson, S. E., Rahman, M. M., & Salehin, M. (2018). *Ecosystem services for well-being in deltas: Integrated assessment for policy analysis*. Springer Nature. Retrieved from https://library.oapen.org/bitstream/handle/20.500.12657/27910/1/1002089.pdf

Nicholls, R. J., Hutton, C. W., Lázár, A. N., Allan, A., Adger, W. N., Adams, H., et al. (2016). Integrated assessment of social and environmental sustainability dynamics in the Ganges-Brahmaputra-Meghna delta, Bangladesh. *Estuarine, Coastal and Shelf Science*, *183*, 370–381. https://doi.org/10.1016/j.ecss.2016.08.017

Nicholls, R. J., Lincke, D., Hinkel, J., Brown, S., Vafeidis, A. T., Meyssignac, B., et al. (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

Nienhuis, J. H., & van de Wal, R. S. W. (2021). Projections of global delta land loss from sea-level rise in the 21st century. *Geophysical Research Letters*, *48*(14), e2021GL093368. https://doi.org/10.1029/2021GL093368

Oelsmann, J., Marcos, M., Passaro, M., Sanchez, L., Dettmering, D., Dangendorf, S., & Seitz, F. (2024). Regional variations in relative sea-level changes influenced by nonlinear vertical land motion. *Nature Geoscience*, *17*(2), 137–144. https://doi.org/10.1038/s41561-023-01357-2

Omori, K., Sakai, T., Miyamoto, J., Itou, A., Oo, A. N., & Hirano, A. (2021). Assessment of paddy fields' damage caused by Cyclone Nargis using MODIS time-series images (2004–2013). *Paddy and Water Environment*, *19*(2), 271–281. https://doi.org/10.1007/s10333-020-00829-0

Papa, F., Bala, S. K., Pandey, R. K., Durand, F., Gopalakrishna, V. V., Rahman, A., & Rossow, W. B. (2012). Ganga-Brahmaputra river discharge from Jason-2 radar altimetry: An update to the long-term satellite-derived estimates of continental freshwater forcing flux into the Bay of Bengal. *Journal of Geophysical Research*, *117*(C11), C11021. https://doi.org/10.1029/2012JC008158

Papa, F., Durand, F., Rossow, W. B., Rahman, A., & Bala, S. K. (2010). Satellite altimeter-derived monthly discharge of the Ganga-Brahmaputra River and its seasonal to interannual variations from 1993 to 2008. *Journal of Geophysical Research*, *115*(C12). https://doi.org/10.1029/2009JC006075

Park, E. (2024). Sand mining in the Mekong Delta: Extent and compounded impacts. *Science of the Total Environment*, *924*, 171620. https://doi.org/10.1016/j.scitotenv.2024.171620

Park, E., Lim, J., Ho, H. L., Herrin, J., & Chitwatkulsiri, D. (2021). Source-to-sink sediment fluxes and budget in the Chao Phraya River, Thailand: A multi-scale analysis based on the national dataset. *Journal of Hydrology*, *594*, 125643. https://doi.org/10.1016/j.jhydrol.2020.125643

Passalacqua, P., Lanzoni, S., Paola, C., & Rinaldo, A. (2013). Geomorphic signatures of deltaic processes and vegetation: The Ganges-Brahmaputra-Jamuna case study. *Journal of Geophysical Research: Earth Surface*, *118*(3), 1838–1849. https://doi.org/10.1002/jgrf.20128

Paszkowski, A., Goodbred, S., Borgomeo, E., Khan, M. S. A., & Hall, J. W. (2021). Geomorphic change in the Ganges–Brahmaputra–Meghna delta. *Nature Reviews Earth & Environment*, *2*(11), 763–780. https://doi.org/10.1038/s43017-021-00213-4

Paszkowski, A., Laurien, F., Mechler, R., & Hall, J. (2024). Quantifying community resilience to riverine hazards in Bangladesh. *Global Environmental Change*, *84*, 102778. https://doi.org/10.1016/j.gloenvcha.2023.102778

Pekel, J.-F., Cottam, A., Gorelick, N., & Belward, A. S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature*, *540*(7633), 418–422. https://doi.org/10.1038/nature20584

Pelling, M., & Dill, K. (2010). Disaster politics: Tipping points for change in the adaptation of sociopolitical regimes. *Progress in Human Geography*, *34*(1), 21–37. https://doi.org/10.1177/0309132509105004

Peltier, W. R., Argus, D. F., & Drummond, R. (2015). Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model. *Journal of Geophysical Research: Solid Earth*, *120*(1), 450–487. https://doi.org/10.1002/2014jb011176

Pham, D. T., Llovel, W., Nguyen, T. M., Le, H. Q., Le, M. N., & Ha, H. T. (2024). Sea-level trends and variability along the coast of Vietnam over 2002–2018: Insights from the X-TRACK/ALES altimetry dataset and coastal tide gauges. *Advances in Space Research*, *73*(3), 1630–1645. https://doi.org/10.1016/j.asr.2023.10.041

Pham-Duc, B., & Nguyen, H. (2022). A bibliometric analysis on the visibility of the Sentinel-1 mission in the scientific literature. *Arabian Journal of Geosciences*, *15*(9), 829. https://doi.org/10.1007/s12517-022-10089-3

Pham-Duc, B., Prigent, C., & Aires, F. (2017). Surface water monitoring within Cambodia and the Vietnamese Mekong Delta over a year, with Sentinel-1 SAR observations. *Water*, *9*(6), 366. https://doi.org/10.3390/w9060366

Phan, M. H., & Stive, M. J. F. (2022). Managing mangroves and coastal land cover in the Mekong Delta. *Ocean & Coastal Management*, *219*, 106013. https://doi.org/10.1016/j.ocecoaman.2021.106013

Phan, N., Ha, D., D. Man, C. T., Nguyen, T. Q., Bui, H., & Nguyen, T. N. (2019). Rapid assessment of flood inundation and damaged rice area in Red River delta from Sentinel 1A imagery. *Remote Sensing*, *11*(17), 2034. https://doi.org/10.3390/rs11172034

Phien-wej, N., Giao, P. H., & Nutalaya, P. (2006). Land subsidence in Bangkok, Thailand. *Engineering Geology*, *82*(4), 187–201. https://doi.org/10.1016/j.enggeo.2005.10.004

Phienwej, N., & Nutalaya, P. (2005). Subsidence and flooding in Bangkok. In A. Gupta (Ed.), *The Physical Geography of Southeast Asia* (p. 0). Oxford University Press. https://doi.org/10.1093/oso/9780199248025.003.0033

Piecuch, C. G., Huybers, P., Hay, C. C., Kemp, A. C., Little, C. M., Mitrovica, J. X., et al. (2018). Origin of spatial variation in US East Coast sea-level trends during 1900–2017. *Nature*, *564*(7736), 400–404. https://doi.org/10.1038/s41586-018-0787-6

Piégay, H., Arnaud, F., Belletti, B., Bertrand, M., Bizzi, S., Carbonneau, P., et al. (2020). Remotely sensed rivers in the Anthropocene: State of the art and prospects. *Earth Surface Processes and Landforms*, *45*(1), 157–188. https://doi.org/10.1002/esp.4787

Post-Nargis Joint Assessment. (2008). Myanmar—Government Association of South East Asian Nations United Nations—Headquarters Global Facility for Disaster Reduction and Recovery, the (GFDRR). Retrieved from https://www.preventionweb.net/media/75376/download

Pronk, M., Hooijer, A., Eilander, D., Haag, A., de Jong, T., Vousdoukas, M., et al. (2024). DeltaDTM: A global coastal digital terrain model. *Scientific Data*, *11*(1), 273. https://doi.org/10.1038/s41597-024-03091-9

Pumpuang, A., & Aobpaet, A. (2020). The comparison of land subsidence between east and west side of Bangkok, Thailand. *Built Environment Journal (BEJ)*, *17*(3), 1–9. https://doi.org/10.24191/bej.v17isi.11740

Punwong, P., Promplin, S., Lomchantrasilp, C., Soonthornampaipong, P., Englong, A., Marchant, R., et al. (2023). Documenting a thousand years of environmental and anthropogenic changes on mangroves on the Bangkok coast, the upper Gulf of Thailand. *Vegetation History and Archaeobotany*, *32*(1), 17–34. https://doi.org/10.1007/s00334-022-00876-z

Rabus, B., Eineder, M., Roth, A., & Bamler, R. (2003). The shuttle radar topography mission—A new class of digital elevation models acquired by spaceborne radar. *ISPRS Journal of Photogrammetry and Remote Sensing*, *57*(4), 241–262. https://doi.org/10.1016/S0924-2716(02)00124-7

Raff, J. L., Goodbred, S. L., Pickering, J. L., Sincavage, R. S., Ayers, J. C., Hossain, M. S., et al. (2023). Sediment delivery to sustain the Ganges-Brahmaputra delta under climate change and anthropogenic impacts. *Nature Communications*, *14*(1), 2429. https://doi.org/10.1038/s41467-023-38057-9

Rahman, M., Dustegir, M., Karim, R., Haque, A., Nicholls, R. J., Darby, S. E., et al. (2018). Recent sediment flux to the Ganges-Brahmaputra-Meghna delta system. *Science of the Total Environment*, *643*, 1054–1064. https://doi.org/10.1016/j.scitotenv.2018.06.147

Rahman, M. M., Haque, A., Nicholls, R. J., Darby, S. E., Urmi, M. T., Dustegir, M. M., et al. (2022). Sustainability of the coastal zone of the Ganges-Brahmaputra-Meghna delta under climatic and anthropogenic stresses. *Science of the Total Environment*, *829*, 154547. https://doi.org/10.1016/j.scitotenv.2022.154547

Rahman, M. M., Penny, G., Mondal, M. S., Zaman, M. H., Kryston, A., Salehin, M., et al. (2019). Salinization in large river deltas: Drivers, impacts and socio-hydrological feedbacks. *Water Security*, *6*, 100024. https://doi.org/10.1016/j.wasec.2019.100024

Rahman, R., & Salehin, M. (2013). Flood risks and reduction approaches in Bangladesh. In R. Shaw, F. Mallick, & A. Islam (Eds.), *Disaster risk reduction approaches in Bangladesh* (pp. 65–90). Springer Japan. https://doi.org/10.1007/978-4-431-54252-0_4

Ramirez, J. A., Lichter, M., Coulthard, T. J., & Skinner, C. (2016). Hyper-resolution mapping of regional storm surge and tide flooding: Comparison of static and dynamic models. *Natural Hazards*, *82*(1), 571–590. https://doi.org/10.1007/s11069-016-2198-z

Rao, M. P., Cook, E. R., Cook, B. I., D'Arrigo, R. D., Palmer, J. G., Lall, U., et al. (2020). Seven centuries of reconstructed Brahmaputra River discharge demonstrate underestimated high discharge and flood hazard frequency. *Nature Communications*, *11*(1), 6017. https://doi.org/10.1038/s41467-020-19795-6

Rao, P. S., Ramaswamy, V., & Thwin, S. (2005). Sediment texture, distribution and transport on the Ayeyarwady continental shelf, Andaman Sea. *Marine Geology*, *216*(4), 239–247. https://doi.org/10.1016/j.margeo.2005.02.016

Räsänen, A., Juhola, S., Nygren, A., Käkönen, M., Kallio, M., Monge, A. M., & Kanninen, M. (2016). Climate change, multiple stressors and human vulnerability: A systematic review. *Regional Environmental Change*, *16*(8), 2291–2302. https://doi.org/10.1007/s10113-016-0974-7

Reimann, L., Vafeidis, A. T., & Honsel, L. E. (2023). Population development as a driver of coastal risk: Current trends and future pathways. *Cambridge Prisms: Coastal Futures*, *1*, e14. https://doi.org/10.1017/cft.2023.3

Renaud, F. G., Syvitski, J. P., Sebesvari, Z., Werners, S. E., Kremer, H., Kuenzer, C., et al. (2013). Tipping from the Holocene to the Anthropocene: How threatened are major world deltas? *Current Opinion in Environmental Sustainability*, *5*(6), 644–654. https://doi.org/10.1016/j.cosust.2013.11.007

Riggs, R. M., Allen, G. H., Wang, J., Pavelsky, T. M., Gleason, C. J., David, C. H., & Durand, M. (2023). Extending global river gauge records using satellite observations. *Environmental Research Letters*, *18*(6), 064027. https://doi.org/10.1088/1748-9326/acd407

Robinson, R. A. J., Bird, M. I., Oo, N. W., Hoey, T. B., Aye, M. M., Higgitt, D. L., et al. (2007). The Irrawaddy River sediment flux to the Indian Ocean: The original nineteenth-century data revisited. *The Journal of Geology*, *115*(6), 629–640. https://doi.org/10.1086/521607

Rodell, M., Famiglietti, J. S., Wiese, D. N., Reager, J. T., Beaudoing, H. K., Landerer, F. W., & Lo, M.-H. (2018). Emerging trends in global freshwater availability. *Nature*, *557*(7707), 651–659. https://doi.org/10.1038/s41586-018-0123-1

Rodell, M., & Reager, J. T. (2023). Water cycle science enabled by the GRACE and GRACE-FO satellite missions. *Nature Water*, *1*(1), 47–59. https://doi.org/10.1038/s44221-022-00005-0

Rodrigues do Amaral, F., Gratiot, N., Pellarin, T., & Tu, T. A. (2023). Assessing typhoon-induced compound flood drivers: A case study in Ho Chi Minh City, Vietnam. *Natural Hazards and Earth System Sciences*, *23*(11), 3379–3405. https://doi.org/10.5194/nhess-23-3379-2023

Rose, L., & Bhaskaran, P. K. (2022). Tidal variations associated with sea level changes in the Northern Bay of Bengal. *Estuarine, Coastal and Shelf Science*, *272*, 107881. https://doi.org/10.1016/j.ecss.2022.107881

Rose, L., B, R., & Bhaskaran, P. K. (2022). Amplification of regional tides in response to sea level. *Ocean Engineering*, *266*, 112691. https://doi.org/10.1016/j.oceaneng.2022.112691

Sagawa, T., Yamashita, Y., Okumura, T., & Yamanokuchi, T. (2019). Satellite derived bathymetry using machine learning and multi-temporal satellite images. *Remote Sensing*, *11*(10), 1155. https://doi.org/10.3390/rs11101155

Saito, Y., Chaimanee, N., Jarupongsakul, T., & Syvitski, J. P. (2007). Shrinking megadeltas in Asia: Sea-level rise and sediment reduction impacts from case study of the Chao Phraya Delta. In *Inprint Newsletter of the IGBP/IHDP Land Ocean Interaction in the Coastal Zone* (Vol. 2, p. 2007).

Santos, M. J., & Dekker, S. C. (2020). Locked-in and living delta pathways in the Anthropocene. *Scientific Reports*, *10*(1), 19598. https://doi.org/10.1038/s41598-020-76304-x

Sayama, T., Tatebe, Y., Iwami, Y., & Tanaka, S. (2015). Hydrologic sensitivity of flood runoff and inundation: 2011 Thailand floods in the Chao Phraya River basin. *Natural Hazards and Earth System Sciences*, *15*(7), 1617–1630. https://doi.org/10.5194/nhess-15-1617-2015

Schneider, P., & Asch, F. (2020). Rice production and food security in Asian Mega deltas—A review on characteristics, vulnerabilities and agricultural adaptation options to cope with climate change. *Journal of Agronomy and Crop Science*, *206*(4), 491–503. https://doi.org/10.1111/jac.12415

Schumann, G. J.-P., & Bates, P. D. (2018). The need for a high-accuracy, open-access global DEM. *Frontiers in Earth Science*, *6*. https://doi.org/10.3389/feart.2018.00225

Scown, M. W., Dunn, F. E., Dekker, S. C., van Vuuren, D. P., Karabil, S., Sutanudjaja, E. H., et al. (2023). Global change scenarios in coastal river deltas and their sustainable development implications. *Global Environmental Change*, *82*, 102736. https://doi.org/10.1016/j.gloenvcha.2023.102736

Sebesvari, Z., Renaud, F. G., Haas, S., Tessler, Z., Hagenlocher, M., Kloos, J., et al. (2016). A review of vulnerability indicators for deltaic social–ecological systems. *Sustainability Science*, *11*(4), 575–590. https://doi.org/10.1007/s11625-016-0366-4

Seeger, K., Minderhoud, P. S. J., Peffeköver, A., Vogel, A., Brückner, H., Kraas, F., & Brill, D. (2023). Assessing land elevation in the Ayeyarwady Delta (Myanmar) and its relevance for studying sea level rise and delta flooding. *Hydrology and Earth System Sciences*, *27*(11), 2257–2281. https://doi.org/10.5194/hess-27-2257-2023

Seeger, K., Peffeköver, A., Minderhoud, P. S. J., Vogel, A., Brückner, H., Kraas, F., et al. (2024). Evaluating flood hazards in data-sparse coastal lowlands: Highlighting the Ayeyarwady Delta (Myanmar). *Environmental Research Letters*, *19*(8), 084007. https://doi.org/10.1088/1748-9326/ad5b07

Shaman, J., Cane, M., & Kaplan, A. (2005). The relationship between Tibetan snow depth, ENSO, river discharge and the monsoons of Bangladesh. *International Journal of Remote Sensing*, *26*(17), 3735–3748. https://doi.org/10.1080/01431160500185599

Shamsudduha, M., Chandler, R. E., Taylor, R. G., & Ahmed, K. M. (2009). Recent trends in groundwater levels in a highly seasonal hydrological system: The Ganges-Brahmaputra-Meghna Delta. *Hydrology and Earth System Sciences*, *13*(12), 2373–2385. https://doi.org/10.5194/hess-13-2373-2009

Shamsudduha, M., & Panda, D. K. (2019). Spatio-temporal changes in terrestrial water storage in the Himalayan river basins and risks to water security in the region: A review. *International Journal of Disaster Risk Reduction*, *35*, 101068. https://doi.org/10.1016/j.ijdrr.2019.101068

Shamsuzzoha, M., & Ahamed, T. (2023). Shoreline change assessment in the coastal region of Bangladesh delta using tasseled cap transformation from satellite remote sensing dataset. *Remote Sensing*, *15*(2), 295. https://doi.org/10.3390/rs15020295

Sherin, V. R., Durand, F., Papa, F., Islam, A. S., Gopalakrishna, V. V., Khaki, M., & Suneel, V. (2020). Recent salinity intrusion in the Bengal delta: Observations and possible causes. *Continental Shelf Research*, *202*, 104142. https://doi.org/10.1016/j.csr.2020.104142

Sherpa, S. F., Shirzaei, M., & Ojha, C. (2023). Disruptive role of vertical land motion in future assessments of climate change-driven sea-level rise and coastal flooding hazards in the Chesapeake Bay. *Journal of Geophysical Research: Solid Earth*, *128*(4), e2022JB025993. https://doi.org/10.1029/2022JB025993

Shirzaei, M., Freymueller, J., Törnqvist, T. E., Galloway, D. L., Dura, T., & Minderhoud, P. S. J. (2021). Measuring, modelling and projecting coastal land subsidence. *Nature Reviews Earth & Environment*, *2*(1), 40–58. https://doi.org/10.1038/s43017-020-00115-x

Sindhu, B., & Unnikrishnan, A. S. (2013). Characteristics of tides in the Bay of Bengal. *Marine Geodesy*, *36*(4), 377–407. https://doi.org/10.1080/01490419.2013.781088

Singha, M., Dong, J., Sarmah, S., You, N., Zhou, Y., Zhang, G., et al. (2020). Identifying floods and flood-affected paddy rice fields in Bangladesh based on Sentinel-1 imagery and Google Earth Engine. *ISPRS Journal of Photogrammetry and Remote Sensing*, *166*, 278–293. https://doi.org/10.1016/j.isprsjprs.2020.06.011

Sinsakul, S. (2000). Late quaternary geology of the lower central plain, Thailand. *Journal of Asian Earth Sciences*, *18*(4), 415–426. https://doi.org/10.1016/S1367-9120(99)00075-9

Small, C., & CIESIN. (2020). Center For International Earth Science Information Network-CIESIN-Columbia University: VIIRS Plus DMSP Change in Lights (VIIRS+DMSP dLIGHT) [Dataset]. [object Object]. https://doi.org/10.7927/9RYJ-6467

Small, C., Sousa, D., Yetman, G., Elvidge, C., & MacManus, K. (2018). Decades of urban growth and development on the Asian megadeltas. *Global and Planetary Change*, *165*, 62–89. https://doi.org/10.1016/j.gloplacha.2018.03.005

Son, N. T., Chen, C. F., Chen, C. R., & Chang, L. Y. (2013). Satellite-based investigation of flood-affected rice cultivation areas in Chao Phraya River Delta, Thailand. *ISPRS Journal of Photogrammetry and Remote Sensing*, *86*, 77–88. https://doi.org/10.1016/j.isprsjprs.2013.09.008

Steckler, M., Akhter, H. S., & Seeber, L. (2016). Bangladesh GPS Network—PUST-Patuakhali Science and Technology University P.S., The GAGE Facility operated by EarthScope Consortium [Dataset]. *GPS/GNSS Observations Dataset*. https://doi.org/10.7283/T5CR5S5G

Steckler, M., Oryan, B., Wilson, C. A., Grall, C., Nooner, S. L., Mondal, D. R., et al. (2022). Synthesis of the distribution of subsidence of the lower Ganges-Brahmaputra Delta, Bangladesh. *Earth-Science Reviews*, *224*, 103887. https://doi.org/10.1016/j.earscirev.2021.103887

Steckler, M., & Scott, N. (2020). Bangladesh GPS Network—KHL2-KHL2_Khu_BGD2014 P.S., The GAGE Facility operated by EarthScope Consortium [Dataset]. *GPS/GNSS Observations Dataset*. https://doi.org/10.7283/SKRK-3W80

Syvitski, J. (2008). Deltas at risk. *Sustainability Science*, *3*(1), 23–32. https://doi.org/10.1007/s11625-008-0043-3

Syvitski, J., Anthony, E., Saito, Y., Zăinescu, F., Day, J., Bhattacharya, J. P., & Giosan, L. (2022). Large deltas, small deltas: Toward a more rigorous understanding of coastal marine deltas. *Global and Planetary Change*, *218*, 103958. https://doi.org/10.1016/j.gloplacha.2022.103958

Syvitski, J., Kettner, A. J., Overeem, I., Hutton, E. W., Hannon, M. T., Brakenridge, G. R., et al. (2009). Sinking deltas due to human activities. *Nature Geoscience*, *2*(10), 681–686. https://doi.org/10.1038/ngeo629

Szuster, B. (2003). *Shrimp farming in Thailand's Chao Phraya river delta: Boom, bust and echo (Research Report)*. IWMI, Comprehensive Assessment of Water Management in Agriculture. Retrieved from http://www.iwmi.cgiar.org/assessment/files/pdf/publications/draftpapers/szuster.pdf

Tadono, T., Nagai, H., Ishida, H., Oda, F., Naito, S., Minakawa, K., & Iwamoto, H. (2016). Generation of the 30 M-MESH global digital surface model by ALOS PRISM. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLI-B4* (pp. 157–162). https://doi.org/10.5194/isprs-archives-XLI-B4-157-2016

Tamisiea, M. E., & Mitrovica, J. X. (2011). The moving boundaries of sea level change: Understanding the origins of geographic variability. *Oceanography*, *24*(2), 24–39. https://doi.org/10.5670/oceanog.2011.25

Tang, J. C. S., Vongvisessomjai, S., & Sahasakmontri, K. (1992). Estimation of flood damage cost for Bangkok. *Water Resources Management*, *6*(1), 47–56. https://doi.org/10.1007/BF00872187

Tarpanelli, A., Brocca, L., Lacava, T., Melone, F., Moramarco, T., Faruolo, M., et al. (2013). Toward the estimation of river discharge variations using MODIS data in ungauged basins. *Remote Sensing of Environment*, *136*, 47–55. https://doi.org/10.1016/j.rse.2013.04.010

Tarpanelli, A., Santi, E., Tourian, M. J., Filippucci, P., Amarnath, G., & Brocca, L. (2019). Daily River discharge estimates by merging satellite optical sensors and radar altimetry through artificial neural network. *IEEE Transactions on Geoscience and Remote Sensing*, *57*(1), 329–341. https://doi.org/10.1109/TGRS.2018.2854625

Tasnim, K. M., Shibayama, T., Esteban, M., Takagi, H., Ohira, K., & Nakamura, R. (2015). Field observation and numerical simulation of past and future storm surges in the Bay of Bengal: Case study of cyclone Nargis. *Natural Hazards*, *75*(2), 1619–1647. https://doi.org/10.1007/s11069-014-1387-x

Tay, C., Lindsey, E. O., Chin, S. T., McCaughey, J. W., Bekaert, D., Nguyen, M., et al. (2022). Sea-level rise from land subsidence in major coastal cities. *Nature Sustainability*, *5*(12), 1049–1057. https://doi.org/10.1038/s41893-022-00947-z

Tazkia, A. R., Krien, Y., Durand, F., Testut, L., Islam, A. S., Papa, F., & Bertin, X. (2017). Seasonal modulation of M2 tide in the Northern Bay of Bengal. *Continental Shelf Research*, *137*, 154–162. https://doi.org/10.1016/j.csr.2016.12.008

Teatini, P., Tosi, L., & Strozzi, T. (2011). Quantitative evidence that compaction of Holocene sediments drives the present land subsidence of the Po Delta, Italy. *Journal of Geophysical Research*, *116*(B8), 1978–2012. https://doi.org/10.1029/2010jb008122

Tellman, B., Sullivan, J. A., Kuhn, C., Kettner, A. J., Doyle, C. S., Brakenridge, G. R., et al. (2021). Satellite imaging reveals increased proportion of population exposed to floods. *Nature*, *596*(7870), 80–86. https://doi.org/10.1038/s41586-021-03695-w

Terry, J. P., Winspear, N., & Goff, J. (2021). Is Bangkok at risk of marine flooding? Evidence relating to the historical floods of AD 1785 and 1983. *Natural Hazards*, *105*(1), 1013–1030. https://doi.org/10.1007/s11069-020-04347-4

Tessler, Z. D., Vörösmarty, C. J., Grossberg, M., Gladkova, I., Aizenman, H., Syvitski, J. P. M., & 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

Tessler, Z. D., Vörösmarty, C. J., Overeem, I., & Syvitski, J. P. (2018). A model of water and sediment balance as determinants of relative sea level rise in contemporary and future deltas. *Geomorphology*, *305*, 209–220. https://doi.org/10.1016/j.geomorph.2017.09.040

Thi, M. M., Gunawardhana, L. N., & Kazama, S. (2012). A comparison of historical land-use change patterns and recommendations for flood plain developments in three delta regions in Southeast Asia. *Water International*, *37*(3), 218–235. https://doi.org/10.1080/02508060.2012.687511

Thien, B. B., Phuong, V. T., & Huong, D. T. V. (2023). Detection and assessment of the spatio-temporal land use/cover change in the Thai Binh province of Vietnam's Red River delta using remote sensing and GIS. *Modeling Earth Systems and Environment*, *9*(2), 2711–2722. https://doi.org/10.1007/s40808-022-01636-8

Thi Ha, D., Ouillon, S., & Van Vinh, G. (2018). Water and suspended sediment budgets in the lower mekong from high-frequency measurements (2009–2016). *Water*, *10*(7), 846. https://doi.org/10.3390/w10070846

Thu Trang, N. T., & Loc, H. H. (2021). Livelihood sustainability of rural households in adapting to environmental changes: An empirical analysis of ecological shrimp aquaculture model in the Vietnamese Mekong Delta. *Environmental Development*, *39*, 100653. https://doi.org/10.1016/j.envdev.2021.100653

Torbick, N., Chowdhury, D., Salas, W., & Qi, J. (2017). Monitoring rice agriculture across Myanmar using time series Sentinel-1 assisted by Landsat-8 and PALSAR-2. *Remote Sensing*, *9*(2), 119. https://doi.org/10.3390/rs9020119

Törnqvist, T. E., & Blum, M. D. (2024). What is coastal subsidence? *Cambridge Prisms: Coastal Futures*, *2*, e2. https://doi.org/10.1017/cft.2024.1

Törnqvist, T. E., Wallace, D. J., Storms, J. E. A., Wallinga, J., van Dam, R. L., Blaauw, M., et al. (2008). Mississippi Delta subsidence primarily caused by compaction of Holocene strata. *Nature Geoscience*, *1*(3), 173–176. https://doi.org/10.1038/ngeo129

Tran Anh, D., Hoang, L. P., Bui, M. D., & Rutschmann, P. (2018). Simulating future flows and salinity intrusion using combined one- and two-dimensional hydrodynamic modelling—The case of Hau River, Vietnamese Mekong Delta. *Water*, *10*(7), 897. https://doi.org/10.3390/w10070897

Tuan, N. T. (2022). Urbanization and land use change: A study in Vietnam. *Environmental & Socio-Economic Studies*, *10*(2), 19–29. https://doi.org/10.2478/environ-2022-0008

Uddin, K., Matin, M. A., & Meyer, F. J. (2019). Operational flood mapping using multi-temporal Sentinel-1 SAR images: A case study from Bangladesh. *Remote Sensing*, *11*(13), 1581. https://doi.org/10.3390/rs11131581

Umarhadi, D. A., Avtar, R., Widyatmanti, W., Johnson, B. A., Yunus, A. P., Khedher, K. M., & Singh, G. (2021). Use of multifrequency (C-band and L-band) SAR data to monitor peat subsidence based on time-series SBAS InSAR technique. *Land Degradation & Development*, *32*(16), 4779–4794. https://doi.org/10.1002/ldr.4061

Upadhyay, S., Shrestha, S., Loc, H. H., Mohanasundaram, S., Dhungana, S., Lim, S., & Tangdamrongsub, N. (2024). Satellite-based estimates of declining groundwater storage in the transboundary Cambodia-Mekong River Delta Aquifer of the Lower Mekong region, Southeast Asia. *Hydrogeology Journal*, *32*(2), 601–619. https://doi.org/10.1007/s10040-023-02746-y

Vafeidis, A. T., Schuerch, M., Wolff, C., Spencer, T., Merkens, J. L., Hinkel, J., et al. (2019). Water-level attenuation in global-scale assessments of exposure to coastal flooding: A sensitivity analysis. *Natural Hazards and Earth System Sciences*, *19*(5), 973–984. https://doi.org/10.5194/nhess-19-973-2019

Van, C. T., Thuy, H. T. T., Viet, C. T., Anh, L. N., Van Anh, V. T., & Tran, D. D. (2024). Unveiling flood vulnerability in the Vietnamese Mekong Delta: A case study of an Giang province. *International Journal of Disaster Risk Reduction*, *106*, 104429. https://doi.org/10.1016/j.ijdrr.2024.104429

van der Horst, T., Rutten, M. M., van de Giesen, N. C., & Hanssen, R. F. (2018). Monitoring land subsidence in Yangon, Myanmar using Sentinel-1 persistent scatterer interferometry and assessment of driving mechanisms. *Remote Sensing of Environment*, *217*, 101–110. https://doi.org/10.1016/j.rse.2018.08.004

Van Kien, N., Han, N. H., & Cramb, R. (2020). Trends in rice-based farming systems in the Mekong Delta. In *White Gold: The commercialisation of rice farming in the lower Mekong Basin* (pp. 347–373).

van Maren, D. S., Beemster, J. G. W., Wang, Z. B., Khan, Z. H., Schrijvershof, R. A., & Hoitink, A. J. F. (2023). Tidal amplification and river capture in response to land reclamation in the Ganges-Brahmaputra delta. *Catena*, *220*, 106651. https://doi.org/10.1016/j.catena.2022.106651

Van Oldenborgh, G. J., Van Urk, A., & Allen, M. (2012). The absence of a role of climate change in the 2011 Thailand floods. *Bulletin America Meteorology Social*, *93*, 1047–1049.

Ve, N. D., Fan, D., Van Vuong, B., & Lan, T. D. (2021). Sediment budget and morphological change in the Red River Delta under increasing human interferences. *Marine Geology*, *431*, 106379. https://doi.org/10.1016/j.margeo.2020.106379

Vernimmen, R., & Hooijer, A. (2023). New LiDAR-based elevation model shows greatest increase in global coastal exposure to flooding to be caused by early-stage sea-level rise. *Earth's Future*, *11*(1), e2022EF002880. https://doi.org/10.1029/2022EF002880

Vernimmen, R., Hooijer, A., & Pronk, M. (2020). New ICESat-2 satellite LiDAR data allow first global lowland DTM suitable for accurate coastal flood risk assessment. *Remote Sensing*, *12*(17), 2827. https://doi.org/10.3390/rs12172827

Vinh, V. D., Ouillon, S., Thanh, T. D., & Chu, L. V. (2014). Impact of the Hoa Binh dam (Vietnam) on water and sediment budgets in the Red River basin and delta. *Hydrology and Earth System Sciences*, *18*(10), 3987–4005. https://doi.org/10.5194/hess-18-3987-2014

Viossanges, M., Johnston, R., & Drury, L. (2017). *Groundwater resources of the Ayeyarwady Basin, Ayeyarwady state of the basin assessment (SOBA) report 2a* (p. 168). National Water Resources Committee (NWRC). Retrieved from http://themimu.info/sites/themimu.info/files/assessment_file_attachments/SOBA2a_Groundwater_Resources_ARB.pdf

Vogel, A., Seeger, K., Brill, D., Brückner, H., Kyaw, A., Myint, Z. N., & Kraas, F. (2024). Towards integrated flood management: Vulnerability and flood risk in the Ayeyarwady Delta of Myanmar. *International Journal of Disaster Risk Reduction*, *114*, 104723. https://doi.org/10.1016/j.ijdrr.2024.104723

Vogel, A., Seeger, K., Brill, D., Brückner, H., Soe, K. K., Win Oo, N., et al. (2022). Identifying land-use related potential disaster risk drivers in the Ayeyarwady Delta (Myanmar) during the last 50 Years (1974–2021) using a hybrid ensemble learning model. *Remote Sensing*, *14*(15), 3568. https://doi.org/10.3390/rs14153568

Vousdoukas, M. I., Voukouvalas, E., Mentaschi, L., Dottori, F., Giardino, A., Bouziotas, D., et al. (2016). Developments in large-scale coastal flood hazard mapping. *Natural Hazards and Earth System Sciences*, *16*(8), 1841–1853. https://doi.org/10.5194/nhess-16-1841-2016

Vu, H. T. D., Tran, D. D., Schenk, A., Nguyen, C. P., Vu, H. L., Oberle, P., et al. (2022). Land use change in the Vietnamese Mekong Delta: New evidence from remote sensing. *Science of the Total Environment*, *813*, 151918. https://doi.org/10.1016/j.scitotenv.2021.151918

Walling, D. E. (2009). *The impact of global change on erosion and sediment transport by rivers: Current progress and future challenges*. UNESCO.

Webb, E. L., Friess, D. A., Krauss, K. W., Cahoon, D. R., Guntenspergen, G. R., & Phelps, J. (2013). A global standard for monitoring coastal wetland vulnerability to accelerated sea-level rise. *Nature Climate Change*, *3*(5), 458–465. https://doi.org/10.1038/nclimate1756

Webster, P. J. (2008). Myanmar's deadly daffodil. *Nature Geoscience*, *1*(8), 488–490. https://doi.org/10.1038/ngeo257

Wilson, C., Akter, S., Rana, M., Steckler, M., & Oryan, B. (2021). Impacts of poldering: Elevation change, sediment dynamics, and subsidence in the natural and human-altered Ganges Brahmaputra tidal deltaplain, EGU21-13928. In *Presented at the EGU General Assembly Conference Abstracts*. https://doi.org/10.5194/egusphere-egu21-13928

Winterwerp, J. C., Borst, W. G., & de Vries, M. B. (2005). Pilot study on the erosion and rehabilitation of a mangrove mud coast. *Journal of Coastal Research*, *21*(2), 223–230. https://doi.org/10.2112/03-832A.1

Wood, M., Haigh, I. D., Le, Q. Q., Nguyen, H. N., Tran, H. B., Darby, S. E., et al. (2023). Climate-induced storminess forces major increases in future storm surge hazard in the South China Sea region. *Natural Hazards and Earth System Sciences*, *23*(7), 2475–2504. https://doi.org/10.5194/nhess-23-2475-2023

Woodroffe, C. D., Nicholls, R. J., Saito, Y., Chen, Z., & Goodbred, S. L. (2006). Landscape variability and the response of Asian megadeltas to environmental change. In N. Harvey (Ed.), *Global change and integrated coastal management* (Vol. 10, pp. 277–314). Springer Netherlands. https://doi.org/10.1007/1-4020-3628-0_10

World Bank. (2009). *Climate change impact and adaptation study for Bangkok metropolitan region: Final report (English)*. World Bank Group. (Text/HTML). Retrieved from https://documents.worldbank.org/en/publication/documents-reports/documentdetail/834261468025503285/Climate-change-impact-and-adaptation-study-for-Bangkok-metropolitan-region-final-report

World Bank. (2015). Social protection for disaster risk management: Opportunities for Myanmar. Retrieved from http://documents.worldbank.org/curated/en/961751468189538832/Social-protection-for-disaster-risk-management-Opportunities-for-Myanmar

WorldPop. (2018). (www.worldpop.org—School of Geographie, Universite de Namur) and Center for International Earth Science Information Network (CIESIN), Columbia University (2018). Global High Resolution Population Denominators Project - Funded by The Bill and Melinda Gates Foundation (OPP1134076)) [Dataset]. Retrieved from https://hub.worldpop.org/

World Population Review. (2023). Largest cities by population 2023. Retrieved from https://worldpopulationreview.com/world-cities

Wu, P.-C., Wei, M., & D'Hondt, S. (2022). Subsidence in coastal cities throughout the world observed by InSAR. *Geophysical Research Letters*, *49*(7), e2022GL098477. https://doi.org/10.1029/2022GL098477

WWF. (2018). The Ayeyarwady River and the economy of Myanmar report.

Yamazaki, D., Sato, T., Kanae, S., Hirabayashi, Y., & Bates, P. D. (2014). Regional flood dynamics in a bifurcating mega delta simulated in a global river model. *Geophysical Research Letters*, *41*(9), 3127–3135. https://doi.org/10.1002/2014GL059744

Yuen, K. W., Park, E., Tran, D. D., Loc, H. H., Feng, L., Wang, J., et al. (2024). Extent of illegal sand mining in the Mekong Delta. *Communications Earth & Environment*, *5*(1), 1–13. https://doi.org/10.1038/s43247-023-01161-1

Zanobetti, D., Lorgeré, H., Preissmann, A., & Cunge, J. (1970). Mékong delta Mathematical model program construction. *Journal of the Waterways, Harbors and Coastal Engineering Division*, *96*(2), 181–199. https://doi.org/10.1061/awhcar.0000013

Zhang, S., Gao, H., & Naz, B. S. (2014). Monitoring reservoir storage in South Asia from multisatellite remote sensing. *Water Resources Research*, *50*(11), 8927–8943. https://doi.org/10.1002/2014WR015829

Zoccarato, C., Minderhoud, P. S. J., & Teatini, P. (2018). The role of sedimentation and natural compaction in a prograding delta: Insights from the mega Mekong delta, Vietnam. *Scientific Reports*, *8*(1), 11437. https://doi.org/10.1038/s41598-018-29734-7

References From the Supporting Information

Austermann, J., Hoggard, M. J., Latychev, K., Richards, F. D., & Mitrovica, J. X. (2021). The effect of lateral variations in Earth structure on Last Interglacial sea level. *Geophysical Journal International*, *227*(3), 1938–1960. https://doi.org/10.1093/gji/ggab289

Gehrels, W. R. (1994). Determining relative sea-level change from salt-marsh foraminifera and plant zones on the coast of Maine, USA. *Journal of Coastal Research*, 990–1009.

Goodbred, S. L., Jr., & Kuehl, S. A. (2000). Enormous Ganges-Brahmaputra sediment discharge during strengthened early Holocene monsoon. *Geology*, *28*(12), 1083–1086. https://doi.org/10.1130/0091-7613(2000)28<1083:EGSDDS>2.0.CO;2

Kuchar, J., Milne, G., & Latychev, K. (2019). The importance of lateral Earth structure for North American glacial isostatic adjustment. *Earth and Planetary Science Letters*, *512*, 236–245. https://doi.org/10.1016/j.epsl.2019.01.046

Lambeck, K., Smither, C., & Johnston, P. (1998). Sea-level change, glacial rebound and mantle viscosity for northern Europe. *Geophysical Journal International*, *134*(1), 102–144. https://doi.org/10.1046/j.1365-246x.1998.00541.x

Lambeck, K., Purcell, A., Funder, S., KJæR, K. H., Larsen, E., & Moller, P. (2006). Constraints on the Late Saalian to early Middle Weichselian ice sheet of Eurasia from field data and rebound modelling. *Boreas*, *35*(3), 539–575. https://doi.org/10.1080/03009480600781875

Lambeck, K., Purcell, A., Zhao, J., & Svensson, N.-O. (2010). The Scandinavian ice sheet: From MIS 4 to the end of the last glacial maximum. *Boreas*, *39*(2), 410–435. https://doi.org/10.1111/j.1502-3885.2010.00140.x

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., & Sambridge, M. (2014). Sea level and global ice volumes from the last glacial maximum to the Holocene. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(43), 15296–15303. https://doi.org/10.1073/pnas.1411762111

Pan, L., Milne, G. A., Latychev, K., Goldberg, S. L., Austermann, J., Hoggard, M. J., & Mitrovica, J. X. (2022). The influence of lateral Earth structure on inferences of global ice volume during the Last Glacial Maximum. *Quaternary Science Reviews*, *290*, 107644. https://doi.org/10.1016/j.quascirev.2022.107644

Peltier, W. R. (2004). Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) model and GRACE. *Annual Review of Earth and Planetary Sciences*, *32*(1), 111–149. https://doi.org/10.1146/annurev.earth.32.082503.144359

Schmitt, R. J. P. (2022). Socio-economic development of global river deltas from gridded data [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.7483942

Schmitt, R. J. P., & Minderhoud, P. S. J. (2023). Data, knowledge, and modeling challenges for science-informed management of river deltas. *One Earth*, *6*(3), 216–235. https://doi.org/10.1016/j.oneear.2023.02.010

UN-DESA. (2019). *World urbanization prospects: The 2018 revision*. United Nations. https://doi.org/10.18356/b9e995fe-en

Woodroffe, S. A., & Horton, B. P. (2005). Holocene sea-level changes in the Indo-Pacific. *Journal of Asian Earth Sciences*, *25*(1), 29–43. https://doi.org/10.1016/j.jseaes.2004.01.009