Section 4

Subchapter 5F

Estuaries and deltas

Writing team: Feng Zhou (coordinating author), Pablo Muniz Maciel, Qicheng Meng, Ricardo J. Torres, Juying Wang (co-lead member), Wenxia Zhang and Tymon Zielinski (lead member).

Key points

- Intensified human activities, combined with stronger winds and increasingly frequent extreme events associated with climate warming, have caused complex changes in estuaries and deltas (Venturini and others, 2024).
- Coastal sediment suspension and river plumes increasingly reflect global trends; nevertheless, these changes are highly region-diverse (Laignel and others, 2023).
- Changing estuarine and deltaic environments have significantly altered sediment dynamics (Sengupta and others, 2023), water quality and ecosystem structures (De Souza and others, 2024), exacerbating ecological risks, such as hypoxia and acidification, as well as socioeconomic losses (Zhou and others, 2017; Meng and others, 2022; Ma and others, 2024).
- Governance efforts in estuaries and deltas have resulted in some progress. Local improvements include reduced hypoxia in the Black Sea and Long Island Sound and less eutrophication in the Yangtze River estuary. Ecosystem responses remain slow compared with management intensity, however, reflecting the complexity of multifactorial risks and delays in restoration (Uber and others, 2022; Pein and others, 2023).
- Ongoing efforts are essential for the sustainability of estuarine and deltaic ecosystems. Such efforts should emphasize monitoring, risk forecasting and integrated socioeconomic assessments.

1. Introduction

Estuaries and deltas are highly complex ecosystems, with diverse hydrodynamic and biogeomorphological profiles, facing considerable ecological and socioeconomic challenges (Laignel and others, 2023). These ecosystems provide numerous significant ecological functions and are particularly biologically productive. Coastal wetlands and other ecosystems offer vital ecosystem services, such as safeguarding coastal populations and infrastructure from erosion, flooding and storms, filtering pollutants and toxins from coastal waters, and supporting fisheries by serving as significant spawning grounds. These systems are among the most affected by human activities, such as land reclamation (Sengupta and others, 2023), eutrophication, invasive species (De Souza and others, 2024) and climate change, the impacts of which include sea level rise, storm surges, delta subsidence, waves and river flooding (Xuan and others, 2021; Ma and others, 2022).

In addition, such processes as storm surges, waves, high tides, coastal river inundation, groundwater inundation and sea level rise can lead to significant disasters when several processes occur simultaneously. Many of the world’s coastlines are eroding and therefore retreating. The marine ecosystem in estuaries and deltas is also affected significantly by compound weather and climate extremes, which can lead to severe ecological disasters, such as enhanced summertime hypoxia due to heavy precipitation in the Changjiang watershed (Meng and others, 2022; Ma and others, 2024; Zhang and others, 2025).

The present subchapter provides an update to the second *World Ocean Assessment* and serves to highlight the significant challenges faced by estuaries and deltas due to both human activities and weather and climate extremes. Such ecosystems are affected by multiscale oceanic and atmospheric processes in addition to human disturbances, which make their governance more challenging than before.

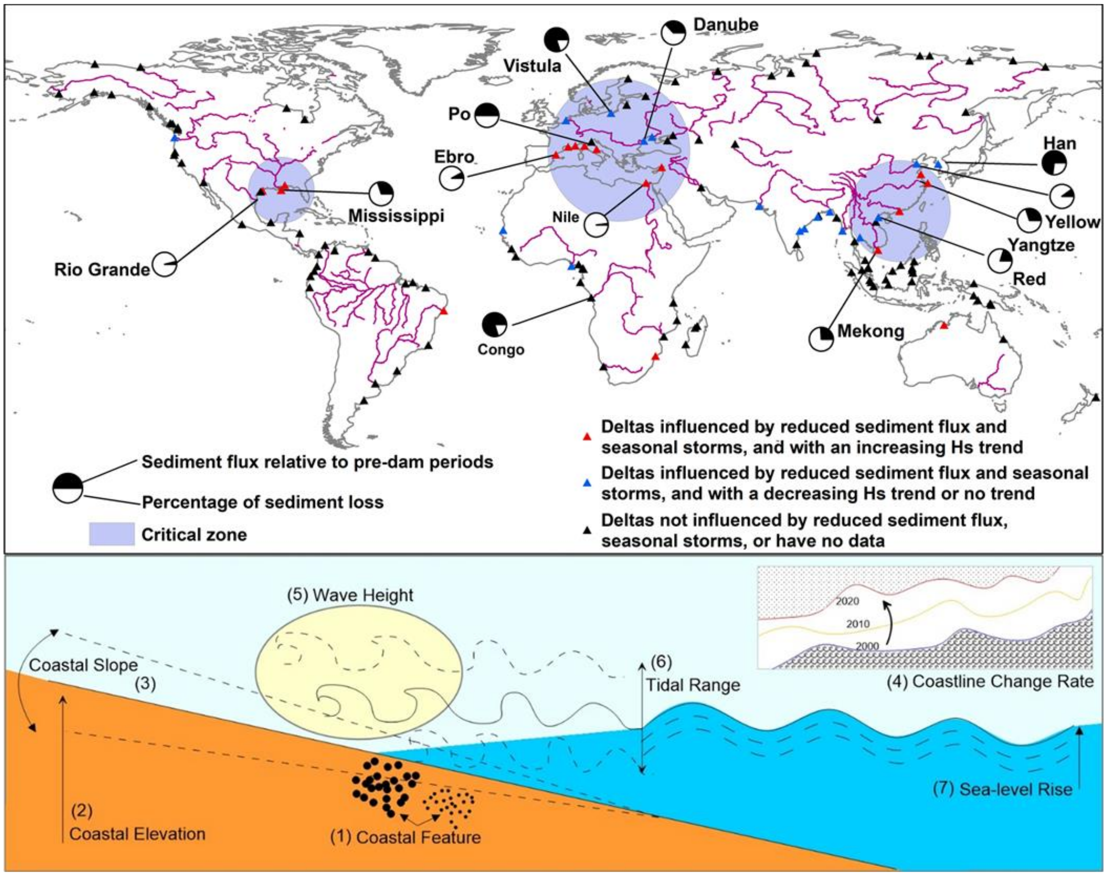
2. Environmental changes since the second *World Ocean Assessment*

Since the previous assessment, estuaries and deltas worldwide have undergone significant shifts in both physical and ecological states. Anthropogenic impacts on river run-off and suspended sediment flux exhibit strong spatial heterogeneity. In the Northern Hemisphere, extensive dam construction has reduced riverine sediment loads to about 49% of pre-dam levels, whereas in the Southern Hemisphere, intensified land-use changes have boosted suspended sediment concentrations by 41 ± 7% compared with the 1980s average (Dethier and others, 2022). As a result, the global riverine sediment supply to the ocean is being rapidly restructured, with the primary source shifting from Asia to South America.

Declining sediment supply poses a serious challenge to many deltas that rely on continuous accretion to offset relative sea level rise and subsidence (see figure I). Widespread groundwater abstraction, urban development and natural compaction are exacerbating these pressures, accelerating subsidence in large river deltas (Harris and others, 2020; Karlsrud and others, 2020). Where geological instability intersects with ongoing sea level rise, the net effect often leads to heightened flood risk and coastal retreat (Zhu and others, 2019). In parallel, anthropogenic changes to river discharge – both reductions and occasional increases – can alter estuarine and deltaic circulation patterns, modifying nutrient delivery and affecting biological productivity in nearshore waters.

Figure I

Global distribution of deltas influenced by both reduced sediment flux and seasonal storms and seven factors affecting coastal vulnerability



Source: Zhu and others, 2024; Pang and others, 2023.

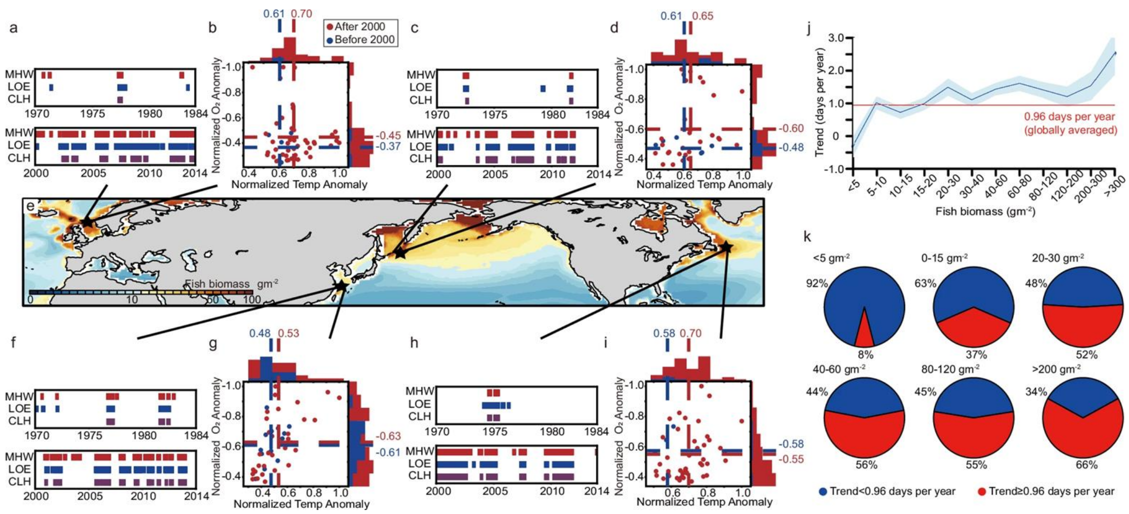
Climate change adds further stress by intensifying extreme weather and climate events, such as heavy precipitation, droughts, marine heatwaves and tropical cyclones (Iles and others, 2024; Studholme and others, 2022; Li and others, 2024b; Zhao and others, 2024). These events disrupt salinity regimes, shift sediment transport pathways and exacerbate erosion, undermining the stability of deltaic shorelines. There is growing evidence linking climate change to an upsurge in infectious diseases (Tsui and others, 2024) and to shifts in marine species distribution (Duffy and others, 2022; Hutchins and Capone, 2022). Ocean warming, marine heatwaves, eutrophication, acidification and low-oxygen extremes continue to pose significant threats to estuarine and deltaic ecosystems (Guo and others, 2022; Johnson and Lyman, 2020; Li and others, 2024a; Sampaio and others, 2021). In some estuarian areas, severe hypoxia episodes have led to ecological disasters that affect fisheries, benthic habitats and broader food webs (Ma and others, 2024). To mitigate these impacts, local stakeholders are endeavouring to alleviate ecological stresses through engineering interventions and management measures (Meng and others, 2024).

Estuaries across the globe have experienced nutrient loading from urban, agricultural and aquaculture sources, prompting eutrophication, harmful algal blooms (Brown and others, 2020) and bottom-water hypoxia (Chen and others, 2020; He and others, 2022; Ke and others, 2022; Zamora-López and others, 2023; Sudradjat and others, 2024; Zhou and others, 2020). While improved wastewater treatment has mitigated problems in some developed regions (Lenstra and others, 2020), the situation in many populous coastal zones continues to deteriorate. Coordinated nutrient management and integrated coastal planning remain key to long-term eutrophication control.

Invasive species represent another serious concern for estuarine and deltaic environments (Hensel, 2021; Ren and others, 2021). Maritime traffic and trade facilitate introductions, while warming waters expand the suitable habitat range for non-native organisms (Norton and Norton, 2021). Effective control hinges on targeted removal strategies and understanding complex ecological interactions (Creed and others, 2021; Liu and others, 2023).

Figure II

Compound low-oxygen extreme and heatwave events in relation to marine fish biomass



Source: Li and others, 2024a.

In addition to ecological shifts, geomorphological and hydrological changes require high-resolution monitoring. Accurate bathymetric and shoreline data are vital for understanding erosion, deposition and coastal flooding patterns, yet an estimated 70–80% of the global coastal zone lacks reliable bathymetric coverage (McCarthy and others, 2022). This gap impedes the ability to develop marine planning strategies, forecast coastal hazards, manage navigation channels and design adaptive measures for aquaculture or infrastructure protection (Han and Zhou, 2025). In locations with pronounced sediment deficits, even small errors in bathymetric data can lead to the underestimation of erosion rates and thus exacerbate vulnerabilities to storm surges or sea level rise.

Overall, the global picture since the second *World Ocean Assessment* is one of mounting pressures on estuaries and deltas from multiple sources. Anthropogenic activities (including dam construction, intensive groundwater pumping, sediment extraction and land-use changes) have reshaped sediment fluxes and accelerated subsidence in many heavily populated deltas. Pollution problems are prevalent in those systems with high population density. Inadequate investment in pollution control exacerbates these issues, particularly in underdeveloped areas. These problems often coexist, demonstrating the interconnectedness of hydrogeomorphic processes, ecological processes and economic development.

Concurrently, a warming climate has amplified extreme events, contributing to erosion, salinity regime alterations and more frequent low-oxygen conditions and marine heatwaves. Meanwhile, emerging challenges, such as invasive species, underscore the delicate balance of these interconnected ecosystems. As these trends intensify, the combination of physical alterations, biogeochemical perturbations and shifting species distributions will continue to transform estuarine and deltaic environments worldwide.

3. Region-specific changes

Arctic Ocean

Over 387 deltas, including the Lena Delta in the Russian Federation and the Mackenzie Delta in Canada, filter sediment and carbon fluxes from the Arctic landscape to the ocean (Mann and others, 2022). Compared with lower-latitude deltas, Arctic deltas have subdued morphodynamics due to ice cover. The warming climate has led to an expansion of the open-water season in Arctic deltas, however, which has caused increased wave influence and unknown changes in sediment transport and carbon cycling (Overeem and others, 2022). Nevertheless, Greenlandic deltas experience weak wave impacts because of the enclosed topography of their locations. The elongated open-water season is potentially inducing increased sediment loading (Bendixen and others, 2019), leading to a mean progradation rate of 0.011 km^2/year for the 75 Greenlandic deltas (Overeem and others, 2022).

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

Several deltas are experiencing significant changes due to subsidence, erosion and human interventions. Subsidence rates have reached 16 mm/year in the Mississippi Delta (Harris and others, 2020) and 12–20 mm/year in the Nile Delta (Rateb and Abotalib, 2020). Erosion is worsened by extreme weather, especially in the Mississippi and Elbe Deltas (Zhu and others, 2024; Uber and others, 2022). Dam construction and river modifications have reduced sediment delivery, slowing delta growth in the Rhône and Danube Deltas (Mikhailova and Isupova, 2006; Constantinescu and others, 2023). Saltwater intrusion affects the Rhône and Nile Deltas, while ecological degradation is evident in the Dnieper Delta (Minaieva and Korzhov, 2024). Effective management is critical for restoration (Uber and others, 2022; Pein and others, 2023).

South Atlantic Ocean and wider Caribbean

The ecosystem of the Amazon Delta is largely intact, supporting diverse species and transporting between 2.3 billion and 3.1 billion tons of sediment annually, aiding coastline growth without significant subsidence. It should be noted, however, that population growth and sea level rise will require improved management (Anthony and others, 2021).

The River Plate estuary, one of the largest estuarine systems in South America, is experiencing continuous but moderate sea level rise and has suffered an extraordinary increase in the flow of the main tributaries since the early 1970s. The frequency of extreme events, mainly wind-induced storm surges, has risen over the past three decades. At present, anthropogenic eutrophication (caused by nutrient inputs linked to human activities) is one of the most important environmental impacts on the ecosystem’s health and services. Massive cyanobacteria blooms promoted by nutrient enrichment associated with hydrological, oceanographic and meteorological factors have been reported more frequently in recent years, generating a loss of water quality, cultural ecosystem services and tourism revenues (Venturini and others, 2024).

The Niger Delta has seen significant coastline retreat, in particular during the periods 1950–1987 and 2007–2012, linked to run-off changes and human activities (Dada and others, 2018). The Congo River basin faces future drought and food scarcity risks, necessitating adaptive measures (Karam and others, 2023).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

The Ganges-Brahmaputra-Meghna Delta faces risks from climate change, extreme hazards and human activities, including a subsidence rate of 5.6 mm/year. Riverbank erosion displaces 300,000 people annually, damaging land and infrastructure (Paszkowski and others, 2021). While sediment supply generally offsets sea level rise, dams and water diversions threaten this balance, making upstream sediment management crucial (Raff and others, 2023). The Indus Delta has seen a decline in organic carbon fluxes due to damming and reduced river discharge, worsened by coastal erosion and changing monsoon patterns (Ahmed and others, 2021). Human activities, such as sediment mining, have caused erosion in the west and accretion in the east (Chen and others, 2020). The Ganges-Brahmaputra-Meghna Delta also faces severe subsidence (20 ± 10 mm/year), increasing the risk of sea level rise (Steckler and others, 2024).

North Pacific Ocean

Dams and sediment mining have reduced suspended sediment in Asian estuaries, worsening coastal ecosystem degradation (Yunus and others, 2022). The Mekong Delta faces subsidence (17–44 mm/year) due to over 130 dams and groundwater extraction (Hecht and others, 2019). The expanding coastline of the Yangtze Delta shows declining sediment concentrations and worsening hypoxia (Ma and others, 2024). The Pearl River estuary suffers severe subsidence (~87.3 mm/year, Liu and others, 2023), while the Yellow River Delta faces erosion from reduced sediment supply (Zhu and others, 2024). In Osaka Bay, warming has caused a shift in fish distributions. Overall, human activities, such as dams, sediment extraction and land reclamation, are key drivers of these environmental changes.

South Pacific Ocean

Sediment transport from the deltas to the ocean has generally increased in the South Pacific Ocean, especially in Australia (Hou and others, 2024). For example, despite dam-building upstream of the Burdekin River, located in the dry tropics of north-east Australia, coarse sediments downstream of the dam have reached the river delta. The riverbed of the Burdekin River Delta has risen measurably in the past few decades, which has caused an increase in flood levels of approximately 1 m (Wolanski and Hopper, 2022). The trapping of sediment in the delta has induced erosion of the offshore Cape Bowling Green Peninsula, which has fundamental ecological impacts on the coastal ecosystem.

Southern Ocean

The surfaces of ice shelves in Antarctica melt during the austral summer; for instance, the meltwater volume reached as high as 0.83×10^9 m^3 in the summer of 2016/2017 on Amery Ice Shelf (Spergel and others, 2021). The meltwater forms surface lakes on the sea ice, which play essential roles in the surface energy balance of sea ice (Dell and others, 2024). Increased surface meltwater on ice shelves associated with climate warming may trigger the development of estuaries in Antarctica, which could lead to accelerated ice loss and sea level rise (Boghosian and others, 2021).

4. Key remaining knowledge and capacity gaps and new gaps

Intensified human activities, coupled with climate change, have exposed estuaries and deltas to severe hydrological and ecological threats. Human activities (such as dam-building and groundwater extraction), natural subsidence of deltas and climate-associated sea level rise are gradually squeezing the inland space of coastal zones. Inland flooding, compounded by astronomical high tides, may cause substantial losses to coastal zones and surrounding megacities. In addition to inland flooding, extreme estuarine upstream droughts compounded by astronomical high tides cause serious saltwater intrusion that threatens drinking water safety by affecting the drinking water reservoirs of megacities in coastal zones. Global warming has caused extreme atmospheric and oceanic events to occur with higher frequency. Populations are increasingly concentrated in coastal areas, which may put stressed ecosystems and local environments at higher risk, entailing greater complexity and uncertainty.

Socioeconomic structures directly influence human activities, which have significant impacts on the sustainability and resilience of estuarine and deltaic systems. In return, estuarine and deltaic environments influence the societies and economies of coastal zones in multiple and complex ways, which could potentially require restructuring. It is difficult to project how societies and economies in coastal zones will change in the future. It would be even more difficult to forecast the effects of feedback from local marine ecosystems, as well as estuarine and deltaic environments, to coastal societies and economies. Integrated monitoring systems and scientific investigations can effectively advance a comprehensive understanding of inland areas and estuary or delta systems as a continuum. Science-based cooperation, planning and strategy are required to build sustainable and resilient estuarine and deltaic systems.

Both short- and long-term strategies are urgently needed for the sustainable development and use of both inland and coastal zones. Existing modelling cannot provide timely early warnings of extreme events or accurate long-term predictions of their occurrence in coastal zones. Although theories regarding two-way feedback between upstream activities and estuarine or deltaic environments are improving, integrated monitoring systems and engineered protections can also be beneficial, especially during short-term emergency response and mitigation. Integrated planning of emergency responses to extreme events by coastal megacities is required in order to reduce losses effectively. Public science education can help people to utilize resources sustainably and respond effectively to extreme events, such as storm surges and flooding. Long-term integrated investigations are crucial for sustaining estuarine and deltaic environments and the ecosystem services they provide for human well-being. A comprehensive database and improved modelling, offering reliable tools for short-term predictions and long-term projections, are essential for the sustainability and resilience of estuarine and deltaic services.

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