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Delta sustainability from the Holocene to the Anthropocene and envisioning the future

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River deltas offer numerous ecosystem services and host an estimated global population of 350 million to more than 500 million inhabitants in over 100 countries. To maintain their sustainability into the future, deltas need to withstand sea-level rise from global warming, but human pressures and diminishing sediment supplies are exacerbating their vulnerability. In this Review, we show how deltas have served as environmental incubators for societal development over the past 7,000 years, and how this tightly interlocked relationship now poses challenges to deltas globally. Without climate stabilization, the sustainability of populous low-to-mid-latitude deltas will be difficult to maintain, probably terminating the delta–human relationship that we know today.

Coastal river deltas (Fig. 1) offer numerous ecosystem services and resources and host growing populations in more than 100 countries, underscoring the need for a better understanding of how these landforms function. This has given rise to a remarkable corpus of studies, reports and knowledge-driven delta-resilience organizations across a spectrum of evolving geo-, climate, ecological and social sciences, and from the individual delta scale to the global scale. The human footprint spans up to 7,000 years of the 8,000-year-long evolution of modern deltas across the Holocene. Coastal space, flat topography, rich ecology and water and other resources have provided a favourable environment for human development, but human activities are leading to the global-scale vulnerability of deltas and the need for anticipation and planning[1–6].

One of the largest human migrations in history (in raw numbers) occurred during the twentieth century with the rapid growth of delta cities and megacities (where many now exceed 10 million inhabitants). In 1975, the 86 largest coastal river deltas were home to about 146 million people (Fig. 2), 3.5% of the total global population of 4 billion. In 2020, the global population had almost doubled to 7.8 billion, but the delta population had increased disproportionately to an estimated number between 350 million and 500 million people or more[4,7,8], outpacing the global population at ~4.5%. In 2020, this population was concentrated in ~730,000 km^2 of deltaic lands[9], yielding a density (in the range of 480–680 inhabitants per km^2) at over eight times that of Earth's habitable landmass. The global delta population

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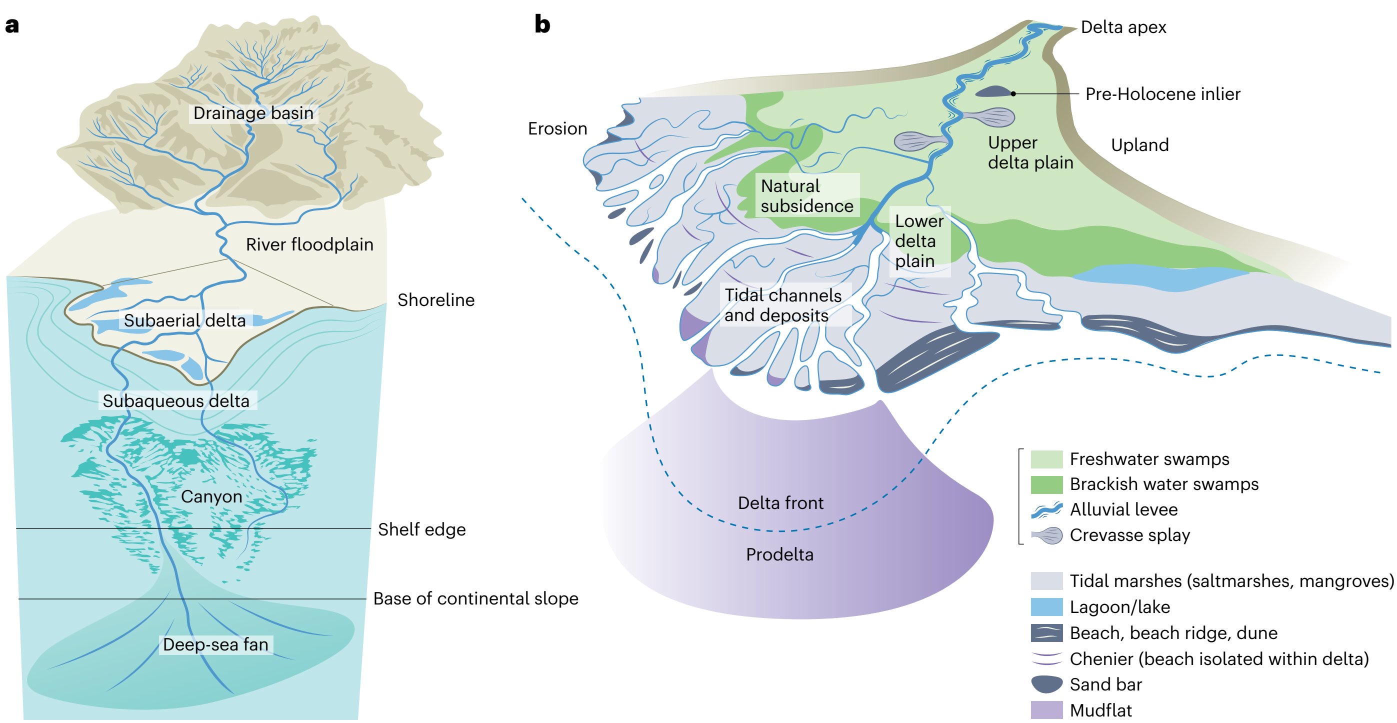

Fig. 1 | Simplified sketch of a river delta. a, Deltas result from a river feeding sediment into a standing body of water at a rate that exceeds dispersal processes, leading, especially in large deltas, to the accumulation of a considerable sediment mass both on land and in the subaqueous zone[9]. The largest deltas started to develop about 8,000 years ago (covering much of the Holocene, that is, the past 10,000 years of Earth's history). Delta existence has hinged on an abundant supply of sediment from river catchments. **b**, Idealized delta. Deltas expanded and built up and out from initial bayhead settings. Their growth was favoured by a relatively stable global sea level, and most of the world's deltas have a mean elevation less than 2 m above the present mean sea level[88], although precise elevation data are lacking. Deltas undergo natural subsidence (sinking) due to sediment, which includes organic matter, compacting under its own weight. Deltas are ecologically diverse with subtle variations in elevation, and are subject to floods, channel switches (avulsions) and meandering, marine incursions during storms, and localized erosion. In spite of these hazards, deltas have provided space and resources for the development and thriving of human society. During the past 7,000 years, humans have progressively adapted to deltas, building up a highly imbricated relationship but also generating profound biophysical modifications in these landforms. Low-to-mid-latitude deltas are increasingly subjected to sediment starvation from the development of river basin hydropower that involves dams and reservoirs, from aggregate mining and from aggravated subsidence caused by delta population growth and resource exploitation, all of which culminate in vulnerability to global sea-level rise.

is concentrated in Asia (~87%). Growth is driven by large cities acting as economic motors[10] across the largest 86 deltas (>1,000 km^2) that capture 84% of the global human delta population, but small deltas are also often completely urbanized[9]. This rapid urbanization is a product of the Anthropocene[11] (taken here as beginning in 1950 CE)[12]. Although the Anthropocene has now been formally rejected (perhaps only provisionally) by the International Union of Geological Sciences as a unit of geological time[13], we take the timely opportunity to refer to that decision and point out that the multifaceted Anthropocene as a concept is here to stay. It lends itself particularly well to describing delta social–ecological systems and gives us an opportunity to conceptualize delta sustainability in a time (if not an epoch) of human dominance of global environmental change. The massive urbanization of deltas that is a product of this human dominance poses challenges to climate change adaptation[4,7,8,10,14,15]. The human–delta association has become locked in a quasi-irreversible situation[16] for many deltas, at a time when the Anthropocene planetary transition from nature dominance to human dominance implies a sustainability in the balance for deltas[17] due to aggregated human impacts that include sea-level rise (SLR). It is hard enough to create delta megacities that can cope with the influx of people let alone deal with an environment that is rendered ephemeral by SLR and subject to sinking, a process that is intrinsic to deltas but which is now exacerbated by human activities[14,18]. There will be no easy fixing or undoing of this urbanization. We can re-nourish eroding beaches, but can we remove cities from sinking deltas, pour in the sediment and move the cities back? No, we cannot. Could the future simply consist of 'sustaining' deltas by manipulating sediment and water? Even doing that would not necessarily make deltas sustainable.

We review delta sustainability from historical through present to future perspectives, conceptualizing the human–environment relationship that started as the global sea level stabilized after the rapid postglacial rise, where the strengthening of which, over time, now challenges this sustainability. We show how changing delta environments in the low- to mid-latitudes served as incubators for the Earth's earliest political entities[19], sustaining transitions in human development. We chart delta resilience over the 7,000 year relationship with humans, to the current stage where humans are adversely altering the trajectory of many deltas towards perilous futures. We illustrate the future challenges of global environmental change for delta sustainability. Regarding these challenges, we draw attention to the specificity of deltas as coastal landforms, but also the distinctness of each delta, how we visualize sustainability and the obstacles to this, including what revolves around who 'owns' deltas, and governance and management, if they exist at all, and the role of planning. Inequalities in political–social actions around delta 'ownership', governance and management will influence resilience and adaptation, creating differences between the world's deltas. All deltas are already intrinsically different, even if humans had not colonized them. But human history and cultural heritage in particular create diversified delta landscapes and their capacity to cope with change. Accessing reliable data, improved modelling and anticipating sustainability hurdles and tipping points from intensive human occupation,

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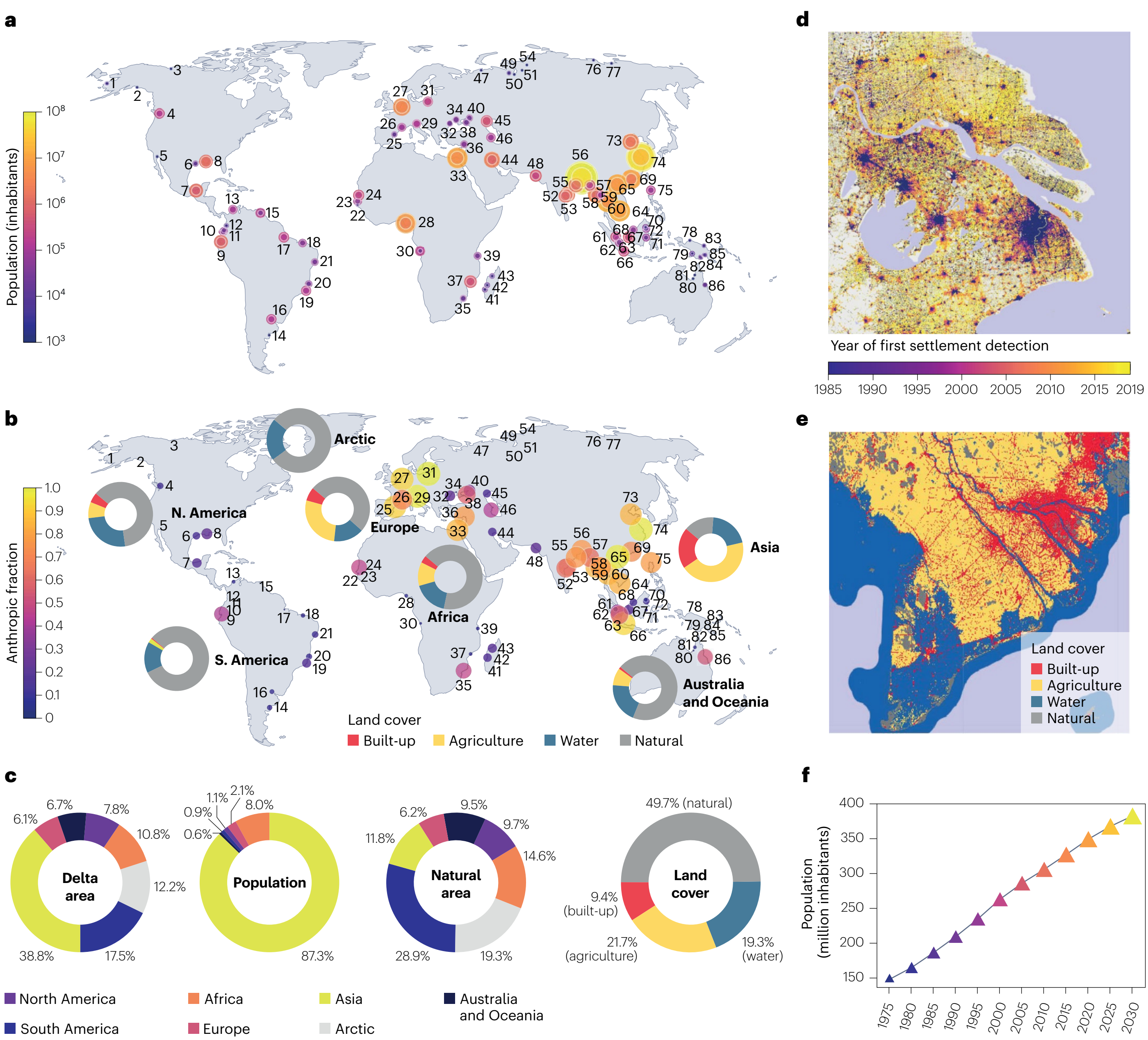

Fig. 2 | Anthropocene delta demography and land changes. a, Population data over a total area of approximately 730,000 km² that is covered by the largest 86 global deltas[9], with concentric circles representing values for 1975, 2020 and projected for 2030. **b**, Anthropogenic footprint: combined fractions of built-up and cropland areas within delta plains, with the juxtaposed regional averages. **c**, Breakdown of delta area, population and natural area by region, and global land cover emphasizing the disproportionate anthropogenic influences across the different regions. **d**, Urban development example of Shanghai (Yangtze Delta), one of the world's largest conurbations and cities with, respectively, 80 million and 22.3 million inhabitants in 2018. **e**, Land-use patterns in the Mekong Delta. **f**, Temporal trends illustrating the population growth dynamics within deltas over the decades, underscoring the increasing anthropogenic pressures. Population data in **a**, **c** and **f** are from the GHS-POP R2023A population grid multitemporal (1975–2030) of the European Commission available at http://data.europa.eu/89h/2ff68a52-5b5b-4a22-8f40-c41da8332cfe (ref. 100); land cover data in **b**, **c** and **e** are from the ESRI 2020 Land Cover dataset[101] with the original ten classes simplified into four classes: cropland, settlement, water and natural; and settlement area data in **d** are from the World Settlement Footprint: 1985–2015 and 2019[102] and from the samapriya-awesome-gee community-dataset hosted at https://doi.org/10.5281/zenodo.8223455 (ref. 103) retrieved via Google Earth Engine. Google Earth Engine in place of Earth Engine.

the exploitation and alteration of deltas and from failing sediment supplies should help to inform delta management and adaptation regarding projected sinking/drowning due to exacerbated subsidence and climate-induced SLR. Our Review briefly frames three Holocene phases of the delta–human association (that is, the inception, expansion and upbuilding–outbuilding of deltas), hinged on a historical stable sea level with changes limited to around ±2 m, followed by the Anthropocene overprint (delta vulnerability). We then chart pathways of management, planning and anticipation that we confront with an outlook on the sustainability and future of deltas.

Delta inception and human encroachment

About 8,000 years ago, as postglacial SLR decelerated[20], accommodation space in the vicinity of some large river mouths was filled more completely, stopping their landward retreat and initiating delta formation. Accommodation space is the vertical and lateral space that

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is available for clastic sediment filling, the accumulation of organic matter and freshwater bodies that counterbalance rising seas[21]. A delta plain traversed by distributary channels gradually develops behind changing beach coastlines up to an inland apex where it grades into the lower river valley (Fig. 1). As deltas started to develop, they provided space and resources for humans[19,22]. The oldest human settlements on these early marshy and swampy delta plains and their coasts date to 5000–4000 BCE, from radiocarbon dating and archaeological artefacts in the Danube, Rhine, Rhone, Nile, Tigris-Euphrates, Yangtze[22] and Grijalva[23] Deltas. The early human incursions into developing deltas were motivated by the availability of favourable lands and coastal-zone resources[19], notably from harvesting lagoons and salt pans, but were also conditioned by each delta's geomorphology and sediment-dispersive dynamics, which involved risks but also possibilities for resilience to river floods and marine forces. We briefly describe in the succeeding sections a number of spikes that were to mark this relationship during the course of the 7,000 years that followed the earliest human incursions into deltas (Fig. 3).

Deltas become incubators of human progress

Delta environments and Neolithic occupation

The start of Neolithic encroachment (Fig. 3) and the shift to sedentary occupation occurred as deltas expanded, providing wetlands for agriculture, thus favouring settlements, sedentary continuity and food security that had not been experienced before by Mesolithic fishers[24]. Agricultural subsistence spread from terrestrial uplands to delta wetlands, providing aquatic diets supplemented by wetland plants and fauna. As the deltas became populous and lower river valleys infilled with sediment, hunter–gatherer subsistence was replaced by grains and fibre crops[25] supplemented by fish, enabling power-centre cities to form, with the Tigris-Euphrates having a head start[19]. Within a millennium of sea-level stabilization, the Nile's originally marine flood-prone initial bayhead delta had grown large and protected enough from waves to be exploited by herding communities around 5000 BCE and agri-cultivated by predynastic Egyptians from around 4700 BCE[26]. This time frame is similar to that from archaeological records in the Yangtze and Yellow (Huang He) Deltas[27,28] where rice farming and the exploitation of coastal resources were fostered by a wet monsoon climate[29], and in the Grijalva Delta where farmers domesticated maize and possibly manioc[23]. Neolithic expansion in the Rhine delta began about 4300 BCE[30] in the wake of the cultivation of valley and delta-apex floodplains and loess hillslopes upstream (5500–4500 BCE: Linear Pottery culture). A subneolithic culture practised farming (crops and cattle) along river channels (5300–3400 BCE: Swifterbant culture) and beach-ridge complexes (after 3500 BCE: Vlaardingen culture).

A protein-rich diet of fatty acids and staple foods fostered increasing population densities within a few hundred years after sea-level stabilization, contributing to the emergence of complex societies with increased social ranking and the construction of monumental architecture[19]. In the Nile Delta, farming and animal husbandry played a fundamental role in establishing a robust and sustainable food system that supported the construction of the pyramid chain[31] along a now abandoned river branch[32,33]. Delta avulsions (a mechanism by which new river branches and delta lobes are created progressively or suddenly, leading to the abandonment of older ones) closely conditioned settlement location choices as early as 4000–3300 BCE in the Tigris-Euphrates[34]. Avulsions were particularly important for the perennity of settlements in the large Pacific and Indian Ocean deltas of East and Southeast Asia, enabling the occupation of abandoned lobes[27]. In the Indus floodplain and delta, avulsions commonly left settlements and cities without water resources, leading to their abandonment[35]. As avulsion-exposed deltas became more populous in the Neolithic, population centres could be more easily moved to available arable lands in adjacent river valleys[19] with channels that were less subject to avulsions.

Deltas foster the emergence of state societies

States originated primarily in fluvial and expanding deltaic settings in areas that are currently arid[36], where agricultural communities supported cities that served as precursors for statehood (Fig. 3): Tigris-Euphrates, 4000–3100 BCE[37]; Nile, 3800–3100 BCE[38]; and Indus, 3300–2800 BCE[39,40]. In Asia, various archaeological cultures in the middle to lower valleys and deltas of the Yellow and Yangtze rivers developed circa 4000–3000 BCE, but whether these late Neolithic polities are early states remains controversial[41].

Delta expansion was favoured by high sediment influx from river basins that were increasingly affected by human activities, alongside climate fluctuations[42]. Good evidence for these allocyclic (external) controls was provided by climate proxies, notably the so-called '4.2 ka event' (2150 BCE), which was essentially an Indian Ocean monsoonal event. This has been identified as the cause of the decline of societies in some Asian deltas by affecting rice cultivation[29]. In the Indus Valley, the 4.2 ka event overlapped with flourishing Harappan urbanism: between 2500 and 1900 BCE, aridification may have diminished the intensity of floods, thus allowing inundation agriculture to develop across the region[40]. The swings in the Harappan Civilization (3200–1000 BCE), from urban to rural settlements, along with the abandonment of a large number of sites, occurred between 1900 and 1000 BCE as adjustments to climate variations and water availability associated with the Monsoon[43].

Delta modifications in the Bronze and Iron Ages

The Bronze Age witnessed an upsurge in the human occupation of deltas, notably in the Mediterranean, marked by the establishment of trading harbours in numerous deltas[44]. The hold on deltas, which were rich in water and food resources in times of changing climate regimes that affected societies, especially in the Mediterranean, was consolidated by waterway engineering transformations to enhance agriculture and mitigate risks in the Iron Age. In the Arno and Serchio Deltas in Italy, meandering in expanding swamps strongly influenced early Etruscan (700–500 BCE) settlement patterns, culture and society, whereas the Roman age (from 100 BCE onwards) saw the ascendancy of human influence with wetland drainage as the modern delta plains prograded[45]. In the Rhine Delta, clusters of farms practising trade and exchanging ceremonial goods over long distances are identified from middle Bronze Age sites (1500–800 BCE)[46], as a mature delta plain developed. Rhine Delta farm clusters persisted during the Iron Age (800–1 BCE).

Humans reinforce their control over deltas

Delta vicissitudes in Europe

The first half of the Common Era witnessed increasing delta instability that was generated by human activities. The most noteworthy aspect of the early Common Era on Mediterranean and Black Sea deltas was the impact of the Roman Empire, through the direct engineering of deltas, but also through this empire's influence on the supply of river sediment through deforestation for agriculture, roads and water harnessing. The postulate of an overarching upstream anthropogenic influence on deltas via fluvial sediment loads is embodied here in the concept of 'man made' deltas[47]. For small deltas, it may be postulated that hinterland deforestation by the Romans led, within a century or so, to a progradational response, whereas the fall of the Roman Empire and the Dark Ages that followed, or the massive population decline caused by the Black Death[48], all resulted in agricultural regression with forests regaining area, contributing to soil stabilization in catchments and diminished delta growth[49]. For large European deltas (Danube, Rhine, Rhone, Po, Ebro), growth more probably reflected a longer cumulative impact spanning the expansion and upbuilding–outbuilding phases of delta development (Bronze Age, Iron Age).

Engineering reinforces the delta–human nexus

Historical records from courts and monastic/ecclesiastical accounts show, during the course of the Early Middle Ages in Europe, a strategy

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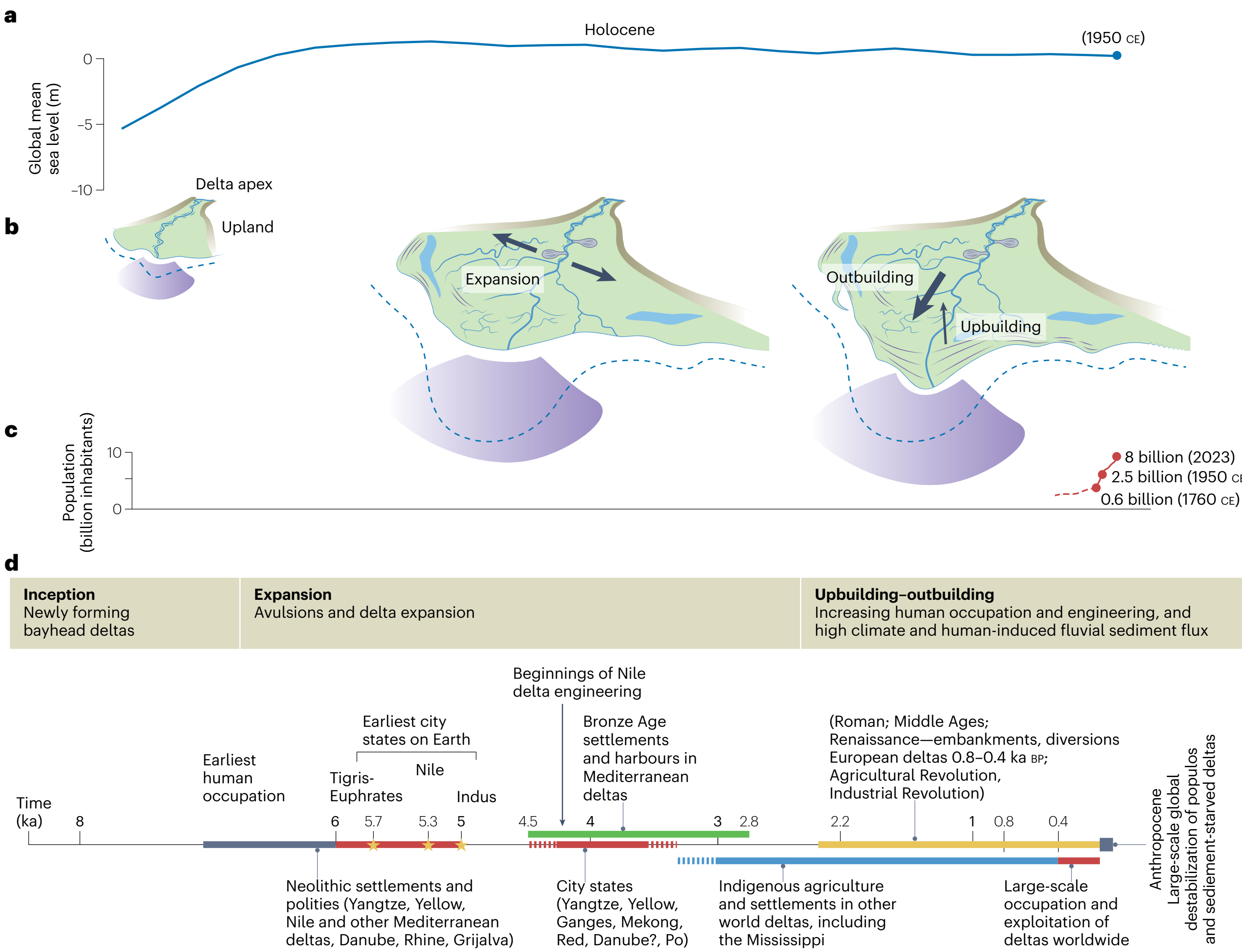

Fig. 3 | Human intersection with delta geomorphological development over the past 7,000 years in the wake of stabilization of the postglacial SLR. **a**, Smoothed global mean sea level over the past 8,000 years[20]. The strong association between sea level and deltas has been reviewed recently[75]. **b**, Idealized geomorphic phases of Holocene delta development: inception (left) following sea-level stabilization; expansion (middle) over much of the Neolithic and the Bronze Age, notably through active avulsions, resulting in the broad fan shape of modern deltas downstream of the apex (Fig. 1); and upbuilding–outbuilding (right), especially during the Common Era that has, over the past 3,000 years, led to the burial of anthropogenic artefacts along nameless (and no doubt numerous) former delta river branches, long abandoned during classic to modern times. **c**, Global population in billion inhabitants (sources are provided in ref. 12) since 1670 CE (taken as the start of the informal pre-industrial period), showing the Anthropocene spike that also saw the creation of numerous delta cities and megacities. **d**, Timeline showing important phases and spikes in the 7,000-year-long delta–human relationship from the earliest human occupation, through the Neolithic and formation of the world's first city states and important expansion of settlements in the Bronze Age, followed by increasing human engineering and transformation during the Common Era, accompanied by strong human influence on river catchment sediment supply. This culminated in the globalization of human occupation of deltas during the industrial era that has resulted in many deltas being locked into anthropogenic transformations that have become irreversible during the Anthropocene[16]. Yellow stars refer to city state inceptions, respectively, in the Tigris-Euphrates (5.7), Nile (5.3) and Indus (5) deltas. ka BP, thousand years ago before present.

of delta conquest that was both religious and political, especially in the Rhine[50], where Roman-age settlement shows relative continuity (despite population and power shifts during the Dark Ages), with new towns and churches built along newly avulsed channels. Dyke systems along all active distributaries emerged between 1050 and 1300 CE, as bishoprics and counties implemented land reclamation campaigns to secure food production for the growing town and city populations. In the central and lower delta, and especially the northern and southern distal coastal-plain sectors, embankments and the drainage of areas with organic topsoils and subsoils (peat) caused problems with land-use sustainability that were generated by human-induced subsidence[51]. In the Danube catchment, important sediment release from major land-use changes caused several avulsions in the delta that resulted in the development of a southern distributary—the St George—and the incorporation of the Greek colony of Histria, a former open-coast city, into the delta plain[52]. The northern Chilia branch, the formation of which began during the Greek Antiquity, progressively became the largest Danube distributary, attracting new settlements along its course during the Middle Ages[53].

In Asia, human impacts on channels and dyke-building efforts have been summarized for the Yellow Delta[54], a spectacular example that illustrates the impact of humans on delta growth. Between 1580 and 1849, human-accelerated erosion of the Loess Plateau led to a super-elevated lower Yellow River channel bed that facilitated frequent breaching (up to 280 times) of the artificial river bank levees, and sediment storage, to the tune of ~312 Gt, on the river's floodplain outside

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these levees[55]. Ninety per cent of the modern delta (that is, since 1855 CE) is due to farming and gullying of the Loess Plateau.

By 1670 CE, and the start of the informal pre-industrial period, the global population was about 600 million, and 50–70% of gross domestic product was still devoted to basic energy resources (human food, fodder for animals and wood fuel)[12]. By 1850 CE and the start of the global industrial interval (100 years earlier in Europe), the population reached 1.25 billion (a growth of 0.8% per year), powered by excess energy from the combustion of fossil fuels (coal, oil) and from hydroelectric plants, enabling societies to mechanize[12]. These changes brought increasing human pressure to bear on deltas and prompted various technological developments, including hydraulic engineering in the Po[56], and the management of embanked fields (polders), wind mills and pumping stations in the Rhine[57].

Globalization of the delta–human nexus

The industrial/colonial interval (1850–1950 CE) captures the global change in human–nature interactions and the widespread occupation and transformation of deltas in North America and South America, and less than 100 years ago in Africa, the Subarctic and Arctic environments, although the human footprint is, in all likelihood, as ancient in African deltas as in New World deltas[23,58]. The millennial-scale pressures on deltas did not initiate vulnerability as deltas generally benefited from sustained fluvial sediment supplies due to catchment deforestation by growing upland populations. Under these conditions, the relatively stable Holocene sea level (Fig. 3) constituted an important background template for delta sustainability. In Europe, deforestation and soil-erosion impacts on deltas are well documented[49]. In the Danube, rapidly prograding lobes formed after 1800 CE[53], which led to around 2.5-fold higher rates of area increase compared with rates during the Middle Ages[59]. Channel instability and avulsions caused by a high supply of river sediment during the Little Ice Age in the Rhone Delta were countered by engineering modifications in the late eighteenth century that were a prelude to massive river-damming after the 1950s[60]. A similar scenario played out in many river systems and their deltas worldwide during the nineteenth century and the first half of the twentieth century.

The Anthropocene global pressure on deltas

More populous and sediment-starved deltas

The previous sections have shown how deltas progressively served, during the course of their growth, as incubators of human development. As humans consolidated their hold on deltas, they undertook landscape and hydraulic engineering modifications that enabled better harnessing of resources and protection against floods, erosion and avulsions, encouraging further widespread urbanization, agriculture and engineering. These developments reinforced the 'locked in' human–delta relationship[16]. The already impressive human footprint of the industrial/colonial interval is dwarfed, however, by that of the Anthropocene. Pressure on low-to-mid-latitude deltas has occurred through exponential population growth (Fig. 2), bringing with it dramatic changes that strain the sustainability of deltas, whatever the breadth of their Holocene relationship with humans. A now widespread and shared global pattern of delta vulnerability prevails.

Humans now dominate the sediment cycle, the nitrogen cycle, the terrestrial hydrological cycle, the geochemical cycles (particularly the chalcophile elements, which have an affinity for sulfide and, more recently, the platinum group elements), the planet's forest covers, ocean fish stocks, atmospheric greenhouse gases (H_2O, CO_2, N_2O and CH_4) and plant and animal density and diversity. The global warming impact of burning fossil fuels results in 20 times more heat being retained by our planet than from the original energy produced during combustion[12]. As a result, humans have overwhelmed the planetary forcings from orbital variations in insolation, warmed the planet by >1.2 °C, initiated ocean acidification and reduced the sea ice volume, glacial ice mass and permafrost, and global SLR is now at ~4 mm yr^{-1}. Regarding the shared socio-economic pathways (SSPs), a high-end SSP 5-8.5 scenario forecasts a median global mean SLR of nearly 1.4 m by 2150[61], setting a template for increasing delta vulnerability. Beyond 2150, sea levels will keep rising for centuries even if we do stabilize climate[62].

Population growth (Fig. 2), sediment starvation and human exploitation of deltas are leading to broad trends of vulnerability that involve shoreline erosion and land loss[63,64], elevation loss[18,65,66] and a growing dependence on engineered flood defences and 'lock in' as defined earlier[16]. Humans currently depend so much on long-established uses and infrastructure that it becomes extremely difficult or costly to reverse the situation, weakening resilience and creating conditions of vulnerability. A synthesis of 48 deltas revealed that 46% have a lock-in relationship with humans, especially in Europe and Asia, but also in the New World[16]. While the Earth's sediment production (supply) from anthropogenic soil erosion, construction activities, mineral mining, aggregate mining and sand and gravel mining increased by about 467% between 1950 and 2010, sediment transport from land to the coastal ocean (the fluvial part of which underpinned 8,000 years of delta growth) has decreased by 23%, largely due to sediment trapping behind dams that is associated with global hydropower development[67], notably in the Asia–Pacific, South America and Africa[68]. Other human activities, such as subsurface resource overexploitation (notably water and hydrocarbons) but also surface extractions of aggregates and clay, increasingly cause subsidence, which affects delta megacities in particular[14,18,51,69]. This subsidence is no longer balanced by sedimentation[3,14,18], leading to the transformation of permanent or seasonal delta drylands into permanent wetlands and to shoreline retreat[63,64]. Many deltas are no doubt overloaded with nutrients and, increasingly, microplastics (for example, ref. 70), leading to the rapid deterioration of delta ecology and ecosystem services[71]. Channel deepening caused by sediment mining and fluvial sediment starvation (for example, ref. 72) exacerbates salt intrusion in many deltas[73,74]. Although deltas have always been subjected to fluctuations in sediment supply that have guided, in part, patterns of human occupation, the current massive diminutions in catchment sediment supply, combined with increased human-driven environmental changes, are rendering many deltas being ranked as 'in peril'[18] or 'highly vulnerable'[64]. SLR, under these conditions, poses a sustainability issue and ultimately an existential threat to deltas[18,75]. Similar sustainability issues face the world's estuaries[76].

Delta futures in question

Humans are now masters (wittingly or unwittingly) of the flow of water (when, where and how much), nutrients, sediment supply and redistribution, land cover and land use, urban and non-urban areas, coastal structures and protection, and energy. Humans caused the SLR, the land subsidence and the loss of wetlands in deltas. Hence, maintaining future delta sustainability will depend on how humans, as masters of the environment, can efficiently manage, if at all, the complex blend of evolving geological–climate–ecological–social science relationships that has driven the delta–human relationship over the past 7,000 years, and rebuild resilience, while scaling all of this down locally to individual delta social–ecological systems, each of which is distinct. A relatively stable sea level formed the background for this long relationship that now unfurls in a context of global SLR at rates into the future that are uncertain, and in a time of diminishing sediment supply. Maintaining delta sustainability raises challenging questions around the relationship of river basin–delta governance, delta ownership and management, long-term planning (preferably knowledge- and data-driven and -sharing), delta distinctness and strategies or imposed approaches into the future (Fig. 4). River basin management is key to understanding the link between climate change, local precipitation, sediment supply to deltas and delta governance.

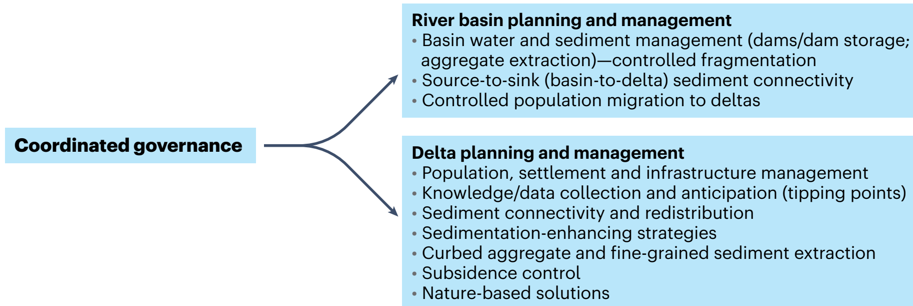

Fig. 4 | Coordinated river and delta planning and management strategies to reduce vulnerability and maintain delta sustainability. Thriving deltas in the past have done so within the framework of a complex balanced geological–climate–ecological–social science relationship. Revolving around this blend, the coordinated planning and management of river basins and deltas should be at the forefront of future delta sustainability as they will be determinant in assuring, or not, vulnerability reductions and in maintaining delta sustainability at low-end near-future SLR scenarios (SSP 1-1.9/1-2.6). River basins are fundamental to the link between climate change, local precipitation and sediment supply to deltas. Important areas for the management of river basins are water and sediment fluxes, to minimize river fragmentation and delta subsidence and to assure connectivity—notably through the rethinking of alternative solutions to hydropower and irrigation dams where feasible, and where dams are inevitable, via their optimal design and operation to minimize sediment trapping by enabling sediment routing through reservoirs via sluices, sediment-drawdown gates, bypass tunnels, dredging and the downstream relocation of dredged sediment. Other aspects include controlled aggregate mining and population mobility from upland basin areas to deltas. Hence the importance of considering knowledge- and data-backed aspects that revolve around what is implied by delta ownership, and how governance, management and adaptation are deployed. Anticipation is of equal importance at a time when most deltas have no known management structure. Differences in the extent to which these actions are taken, or not, will generate inequalities among deltas and their vulnerability to global/regional SLR. Both the river basin and delta spheres face social–ecological, political and funding challenges that will generate variability among deltas in the capacity to act. Sustainability will decline for all deltas under high-SLR scenarios, underlining the overarching condition of urgent climate stabilization.

Challenges of delta ownership and management

The issue of delta ownership and the embedded questions, both now and into the future, about who manages/governs a delta's health, how it is done and with what resources, are fundamental when considering delta sustainability. Ownership is generally defined as 'the fact of owning something'. There is an explicit link between 'owning' a delta and being in a position to determine how it evolves, through some form of management (including anticipation and planning) or through no management at all. Most deltas have little or no management structure. Some deltas are managed where political systems recognize them as such, but this varies extensively, with engineers, elected government representatives, wildlife/nature interests and so on having strong roles in different deltas and sometimes exerting little management at all. When considering the river basin, delta management always involves upstream cross-border planning and management, be they national or federal (internal) boundaries. How are management decisions made? How inclusive is the decision process? How is management funded? We raise questions that merit pondering if society is ready to examine the inequalities in, and realities and challenges of, delta sustainability into the future. Unfortunately, however, we believe that society is clearly not yet ready to do so.

Towards knowledge-driven long-term planning

Delta planning should be integrated through a systems approach[3], (re)connecting river basins to deltas and rivers to floodplains, and include the management of (re)sedimention and the control of human-accelerated subsidence (Fig. 4), something that is being attempted in only a few deltas[77,78]. The feasibility and implications of re-establishing delta-plain connectivity following, for instance, the strategic deployment of sedimentation-enhancing strategies[79,80] and nature-based solutions[81]—involving dialogue and knowledge-sharing[5] from biophysics through to legislation—should be at the forefront of interdisciplinary studies[82] aimed at supporting planning (Fig. 4). But even here, we should refrain from over-optimism. In the Mekong Delta, for instance, sedimentation-enhancing strategies could be effective against SLR but are limited by the sediment-starved situation of the delta[83]. Current sedimentation-enhancing strategies collectively comprise only 0.1% of the global delta area[79]. Unlocking the full adaptation potential of nature-based, sedimentation-enhancing strategies will require a fundamental paradigm shift in delta management if the biophysical and societal barriers that currently impede their widespread deployability are to be surpassed[80].

Subsisting dataset and knowledge challenges

Insight from big data now permeates delta studies globally. Remote sensing and modelling, in particular, confronted with the global/regional issues of climate change and regional/local anthropogenic pressures, should help us to investigate the challenges and solutions to delta sustainability. Lines of progress include the accurate quantification and projection of sediment fluxes to provide a scientific basis for basin-wide management directives and planning (for example, ref. 84), estimates of sediment connectivity and (re)distribution processes within deltas[81] and natural and human-induced subsidence[69]. There are, however, several areas in delta research where our knowledge remains patchy and datasets too sketchy or challenging to obtain, which impact the possibility of reliable modelling and forecasting. There is a plethora of land-cover remote-sensing datasets that are used, for instance, to identify anthropogenic delta transformations and human occupation of subaerial delta area (Fig. 2), including megacities, agriculture, aquaculture, infrastructure, land reclamation and polders (all increasingly detrimental to mangroves and marshes), engineered distributary channels, engineered coastal barriers and the impacts of subsidence. These datasets are useful, but we still need to make progress on resolution and exert caution in data analysis and interpretation[85]. The standardization of datasets should also be a future goal, which is especially relevant in the identification of the areal limits of deltas and the distinction of delta subenvironments. Accurate delta-plain elevations and reliable projections of subsidence are also crucial for the quantitative assessment of future delta elevation changes under SLR. High-resolution data on the elevation of most of the world's deltas, including the 86 largest deltas (Fig. 2), are currently lacking. Recent attempts to tackle this problem have shown that high-resolution mean delta elevations are lower than estimated using lower-resolution data[86–88]. The example of the Mekong Delta (with a mean elevation of ~0.8 m above sea level, which is dramatically lower than the earlier erroneously assumed value of ~2.6 m) also underscores the fact that

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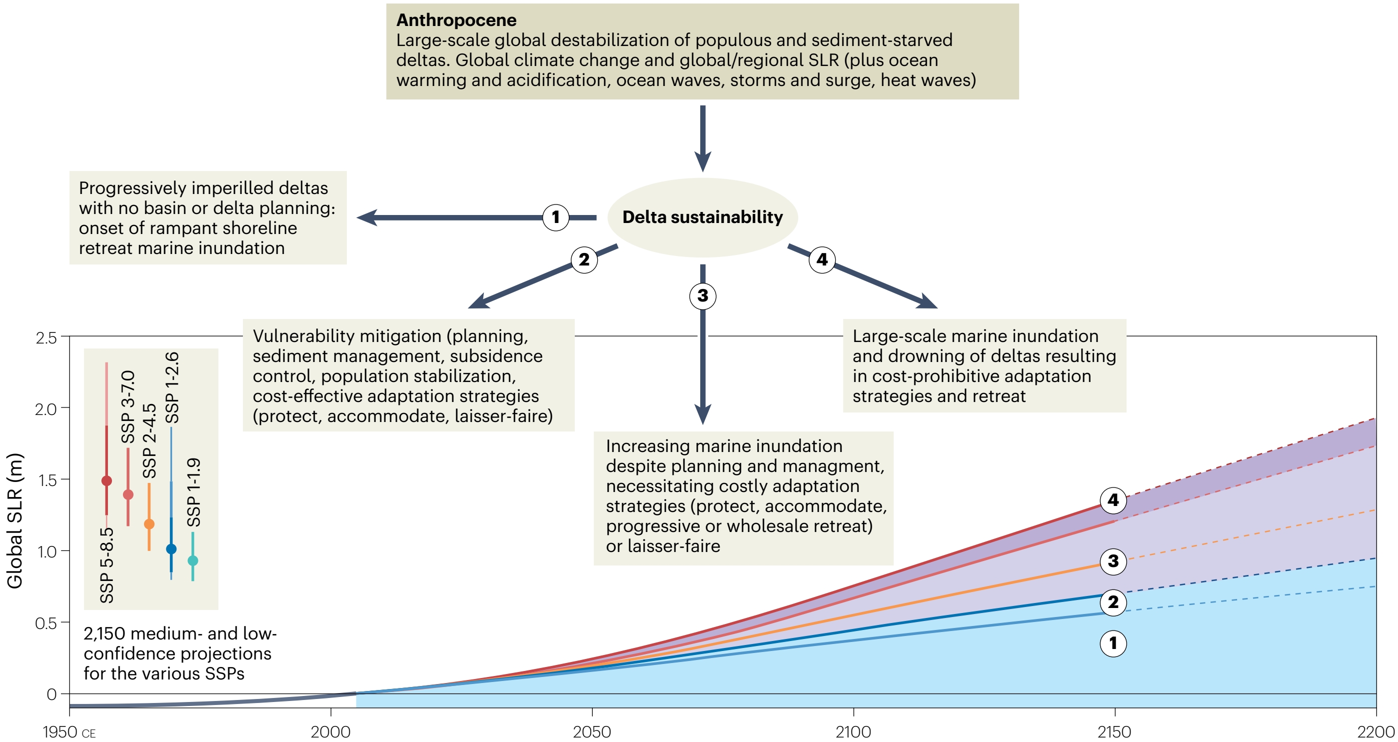

Fig. 5 | SLR and delta sustainability. Sustainability is scaled against projected likely ranges of global SLR under different SSP scenarios from ref. 61, assuming mean delta-plain elevations less than 2 m above the present mean sea level[86,88]: (1) progressively imperilled, notably sediment-starved deltas, with no river basin–delta management or planning, even under a near-future low-end scenario (SSP 1-1.9); (2) deltas with good adaptation through basin–delta planning and management and sustainable at low-end (SSP 1-1.9) and moderately low (SSP 1-2.6) scenarios; (3) increasing marine inundation and costlier and unsustainable adaptation at a moderately high scenario (SSP 2-4.5) that is likely to affect most world deltas; and (4) large-scale inundation and drowning of world deltas at high-end scenarios (SSP 3-7.0 and SSP 5-8.5) of 1–1.4 m above the present mean sea level. Action perspectives will strongly diverge between deltas, and whereas stronger economic means and governance may provide larger space for solution, adaptation will (rapidly) decline for all deltas under high-SLR scenarios. Projection uncertainties constitute a challenge for investment planning in Protect and Accommodate strategies (Box 1). In the Netherlands, at the forefront in battling SLR[57], a rise of 1 m is factored into defences up to 2100, following the Delta Commission Plan, and defences will continue to be raised to withstand another rise of 1 m by 2200. Residual risks such as storm surges and unforeseeable extremely rapid SLR, however, cause concern and raise questions about which strategy to adopt. Retreat could be selective, letting, for instance, Friesland become flooded but protecting the Rhine Delta provinces that host the most people and economic activities. Note that subsidence is as important as global SLR in any individual delta.

the quality of global coastal elevation data is inadequate, and the crucial need for converting to the local tidal datum is often neglected[86].

Another challenge consists of addressing the delta volume change[9] that is caused by miscellaneous human actions such as organic matter production through rewilding, mangrove replanting or reforestation, oxidation through soil drainage, empoldering and engineering, groundwater mining, peat mining, sand and gravel mining, clay extraction, deforestation and anthropogenic infrastructure. Some cause surface deformation, resulting in land subsidence in growing delta megacities that can be further exacerbated by earthquake deformation, monsoon flood weight or drought-driven shrink–swell dynamics. We also need to improve our knowledge of the delta subaqueous domain, which can store large amounts of sediment[9]. Deltas are substantial Earth sediment sinks. Beyond the need for the integration of subaqueous delta erosion into sustainability evaluations, especially under the stormier conditions that accompany climate change[89], fundamental questions concern the effects of changes in the delta sediment load on continental margin geological (for example, volcanic activity) and sea-level feedbacks, hence providing a link between local (river basin–delta) processes and global regulation. The geoengineering of individual deltas has been ongoing for at least 5,000 years. The current global situation suggests that regulating industrial waste outputs is a necessary step in mitigating environmental damage. Managing deltas is an obvious component of such mitigation, at least as a source of data but also as a means of managing inputs and thresholds in the Earth system.

Sustainability uncertainties into the future

Innovative knowledge-driven delta management and planning strategies, in addition to data acquisition and modelling[3,4], are in their infancy but, where feasible, now and into the future could provide sustainable options for deltas against near-future projected SLR (low-end SSP), including low rates of land subsidence (Fig. 5). There are, however, other potential obstacles here, in addition to those related to datasets and knowledge acquisition. Individual deltas are distinct entities, each with unique boundary conditions and a unique history of human change and impacts. Large deltas may in fact display physical, cultural and human history diversity even within their individual boundary conditions. This complicates the deployment of general 'models' of sustainability. Alongside this difficult outlook, management strategies are simply not feasible at present for most deltas, and reflect a lack of resources and planning and management capacity (Fig. 4). This raises the question of human capacity building about better knowledge of delta functioning and management[3], but also of harnessing better Indigenous knowledge[90] and its perspectives. Accessing reliable data remains a problem in many deltas due to geopolitical sensitivities, and yet is important not only for management, planning and anticipation but also for gauging tipping points in the delta–human relationship. The diversity of the Earth's deltas will require high-quality field observations to inform important and often costly environmental decisions, as well as community-level information with citizens who are conversant with the finer-scale changes that affect their daily livelihoods[6,9], especially

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in the populous deltas. Transferable lessons should also be identified, and, where possible, implemented to improve climate resilience[5]. These include: from the Ganges–Brahmaputra and Mekong Deltas, strategic plans to identify risk hotspots, guide decision-making and enhance grassroots resilience through community livelihood diversification in response to changing risks and land–water conditions; and from the Yangtze and Pearl Deltas, forecasting and sensing technologies that are developed to enable effective preparedness for, and response to, hazards[5].

However, climate control for mitigating SLR[62], sustained fluvial sediment supplies, control of human-induced land subsidence and the delta population, which is set to reach an averaged global density[4] of ~700 inhabitants per km^2 by 2050, are sources of future constraints. The sustainability of many low-to-mid-latitude deltas will be severely affected by relative SLR[3,4,7,8,10,14,75] in the absence of climate stabilization, in addition to being compounded by fluvial sediment starvation[91] and accelerated land subsidence[3,14]. The growing construction of hydropower dams in developing economies[68] will further negatively impact sediment supply to deltas in the future. Basin-wide planning of sediment releases from dams will need to be thoroughly gauged and calibrated, notably by resorting less to the widespread use of large dead storages (that is, the portion of the reservoirs that cannot be emptied) in dam designs and designing smaller dead storages that can ease sediment starvation in sinking deltas[92].

In spite of a high loss of fluvial connectivity due to dams and engineering, some deltas associated with Asia–Pacific rivers still continue to gain land[64], as dams are flushed of sediment to increase the calculated yield (for example, ref. 93). Rapid SLR will also outpace marsh and mangrove growth[21,94], which are important components of sedimentation in many deltas. Low-population Arctic deltas with increasing climate-change-induced sediment loads[95] may be a temporary exception regarding their sediment budgets but could also become increasingly exposed to anthropogenic pressures with climate warming. Sustainability will depend on our capacity to mitigate climate change and global SLR, whereas differences in current and future anthropogenic pressures on individual deltas as well as inequalities in political–social actions for addressing them will strongly influence the effectiveness of local mitigation and adaptation measures (Fig. 4). The recent United Nations Convention on Conserving River Deltas initiative proposed by engaged scientists at the COP28 meeting in 2023 is an important global endeavour that could consolidate our efforts, but properly enacting this convention could take, at best, several years. The International Panel on Deltas and Coastal Areas (http://www.deltasandcoasts.net), launched in 2023, could also promote sustainability efforts.

Expected outcomes without climate mitigation

In the crucial battle against inevitable SLR, three end-member strategies (for example, ref. 96), alongside an approach of 'laisser-faire' (a term borrowed from economists), are currently deployed and/or envisaged for coasts in general. However, we need to recognize the biophysical specificities of deltas (Box 1), which go beyond just the coastline fringe. These strategies/approaches are not mutually exclusive. The 'protect' and 'accommodate' strategies are costly and impact the delta biophysics, and larger and larger areas are threatened with deeper floods if protection fails, especially for the higher-emission scenarios of SSP 3-7.0 and SSP 5-8.5 (Box 1). Even for wealthy economies that are dedicated to containing the effects of SLR, such as the Netherlands with the Rhine Delta[97,98] or the United States with the Mississippi Delta[99], this outcome is undesirable (Fig. 5), and protection that works with delta processes is more desirable. Both absolute SLR and the annual rate of rise pose challenges, with the latter being susceptible to reducing, for instance, the lifetime of defence constructions when the rate of SLR rise increases beyond projected values[98]. Assuming no protection measures, deltas globally may lose 5% (35,000 km^2) of their area by 2100 and 50% by 2300 due to SLR under the high-emission scenarios[75]. Large-scale marine inundation, scaled against prohibitive adaptation costs[10,99], will impose generalized 'give up' and human retreat (Fig. 5). Drastic wholesale urban migrations and landward redeployments from sinking and marine-inundated deltas may become more frequent in

BOX 1

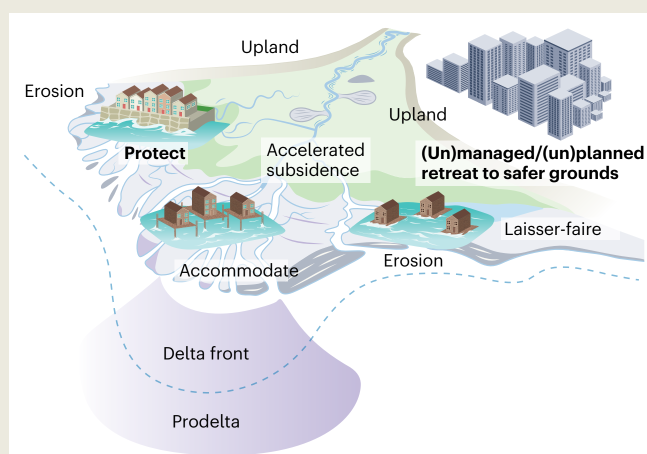
Adaptation strategies and approaches to SLR in deltas

Protect. Levees, dykes, seawalls and storm-surge barriers offer straightforward, but costly, protection in populous deltas, sometimes with land reclamation (termed 'advance'[97]). Addressing SLR necessitates a strong commitment, with mass construction and ongoing raising of dykes as in the Ganges–Brahmaputra Delta. As sea levels rise and land levels sink, the costs of holding the line and the consequences of failure (residual risk) increase, ultimately representing an existential disaster for delta inhabitants. Leveed deltas buy time but are probably not tenable in the long run[98].

Accommodate. This strategy integrates adaptive living solutions in wetlands and sedimentation-enhancing approaches. It appears to be sustainable in the face of SLR in the near future, aligns with historical human–delta coexistence and is favoured by some local communities[90]. It poses challenges in densely populated deltas, requiring alterations in planning and lifestyle.

Retreat. Either managed as realignment[96] (eventually orchestrated under delta governance) or unmanaged (spontaneous), this approach involves community relocation from high-risk zones to safer terrain, underscoring classic climate adaptation, but it is fraught with socio-cultural and economic considerations[10], particularly regarding community integrity, heritage loss and funding. It is an alternative to costlier Protect and Accommodate strategies in urbanized deltas and is suited to low-population deltas (Mississippi, Danube).

Laisser-faire. This give-up approach may be cost-effective but is only really workable where the population is low. It implies minimal human intervention and, whether adopted in resignation or deliberately, aligns with preserving natural delta processes and ecological integrity. It is currently implemented to varying degrees in the Mississippi, Danube and Rhone, and is pertinent to Arctic deltas.



the future: the population of New Orleans has not recovered since Hurricane Katrina. Djakarta, 40% of which is now below present sea level on the sinking Ciliwung–Citarum Delta, is fourth in the world conurbation population ranking (with 30 million inhabitants), and Bangkok, on the sediment-starved Chao Phraya Delta, ranks 13th (at 18 million inhabitants); each of these countries is considering moving its capital city rather than engaging in costly engineering for its survival. In some delta areas that are subject to extremely high subsidence rates (>10 cm yr^{-1}) that threaten their sustainability, for example, the Semarang–Demak region in northern Java or the Province of Pampanga in the Philippines, reports have shown that entire drowning villages can simply become abandoned in the space of five to ten years. Important movements of people away from deltas may be anticipated, with retreat managed in delta zones that are most exposed to SLR and/or subsidence.

The 7,000 year relationship between deltas and humans has fostered technological developments that are geared at water control and the fight against subsidence, erosion and the sea.

These developments, together with new technologies, strategies and data, will be instrumental in the battle of sustaining our deltas and maintaining sustainable, if not entirely habitable, deltas with SLR. Pathways of sustainability and survival in the populous low-to-mid-latitude deltas will need to be addressed using paradigms embodying tough challenges that revolve around dedicated and coordinated governance, management, planning (at both river basin and delta levels) and subsidence control that do not lose sight of either the distinctness of each delta or the diversity within some large deltas. Without climate control, an extreme SLR scenario (reaching 2 m or more) over the next two centuries will lead to progressive delta drowning, which will impose untenable conditions on human occupation from both environmental and economic standpoints, leading to global-scale human retreat from deltas. This will terminate the 7,000 year mutual relationship between humans and deltas that we know and experience today, and will establish a future of living with drowning and drowned deltas.

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Author contributions

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Competing interests

The authors declare no competing interests.

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