Data, knowledge and modeling challenges for science-informed management of river deltas

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1. Abstract

450 million people live on river deltas and thus on land that is precariously low above rising sea levels and sinking because of a complex interplay of human activities and natural processes. Yet, the understanding of drivers behind sinking deltas is often limited, as is our ability to model the biophysical response of deltas to anthropic drivers. This is a major limitation for developing portfolios of measures to address the many drivers of sinking deltas. Based on reviewing the state of science regarding dominant drivers behind sinking river deltas, we stake out a research agenda to inform the sustainable management of deltas. Our review reveals that the ability to model local, delta-scale processes (accelerated land subsidence, delta sediment dynamics and vegetation feedbacks) lacks behind the ability to model processes on larger, i.e., basin or global, scales (sea level rise and sediment supply). Models and data are no panacea, but we argue that four steps would be critical to identify avenues for sustainable, science-informed management of river deltas. Those steps are (1) progressing the capacity to model delta-scale processes, (2) developing modeling frameworks that integrate basin and delta processes, (3) bridging the major knowledge disparities between different river deltas, and (4) working on a better integration of deltas in assessments of global change and *vise-versa*.

2. Introduction

Global environmental change drastically alters human life and ecosystems in all their domains, but few environments embody consequences of human activities as drastically as river deltas. Many of those unique landforms could disappear below rising sea levels by the end of the century, drowning not only ecosystems but also critical areas for food supply [1,2] and human livelihoods [3–5]. The great risk faced by deltas is documented by increasingly urgent calls for action by the global scientific community [6–10] over the last few years.

Averting potentially disastrous environmental degradation in river deltas will require decisive action across scales and sectors. River deltas were created by the interplay of rising sea levels and fluvial sediment supply, but the processes that created deltas are heavily altered by human activities today (Figure 1 a). Rates of global sea levels rise are increasing [11], while the sediment load of many large rivers is reduced by artificial reservoirs [12–14] and sand mining [15]. The spreading of the remaining sediment supply across delta floodplains is hindered by dykes and levees [1,9,10,16,17]. Deltas are geologically young, depositional landforms that, by nature, experience land subsidence as their unconsolidated sediments compact over time [18]. Anthropic activities , e.g., the extraction of underground resources, drainage of shallow soils, and artificial loading further accelerate land subsidence [6,19,20]. Together, those drivers across scales lead to rapid rates of relative sea level rise (rSLR), which denotes a lowering of the land surface compared to rising sea levels [21] and thus a greater risk of land falling below the ocean surface than from either sea level rise or accelerated subsidence alone.

Sustainable management of river deltas requires considering connections and drivers across some critical sectors that are themselves interconnected (Figure 1 b). For instance, reducing rSLR and maintaining relative delta elevation will require reducing greenhouse gas emissions, limiting fossil fuel extraction, avoiding sediment trapping in dams and reservoirs [1,22–26], reducing surface drainage and groundwater overextraction for irrigation, domestic and industrial use [27,28], enhancing sedimentation [29], and conservation or restoration of coastal vegetation in the face of agricultural encroachment. Those exemplary measures concern all sectors of the water-energy-food nexus, and require thinking across global, regional, and local scales. Managing rSLR also links to global climate adaptation and mitigation across scales (Figure 1 c). On global scales, climate mitigation through reducing emissions and carbon removal will be critical to reduce sea level rise and the occurrence of hydro-climatic extremes. Climate adaptation is required to reduce vulnerability of people and ecosystems [11] in deltas. In a nested manner, climate adaptation for deltas requires to mitigate root causes of rSLR for a delta, e.g., by phasing out groundwater overuse and sand mining, as well as adaptation, e.g., through improved grey-green coastal protection, nature-based solutions, and diversified livelihoods [11].

In the face of complexities and interconnections, delta management needs to be informed by science. Curbing rSLR requires understandings current baselines and risks from continued "business as usual" as well as identifying effective adaptive and sustainable management strategies [16,30,31]. Those tasks need both reliable data as well as predictive capacities. There have been detailed reviews of global patterns [3,6,20,26,32–35], monitoring techniques [36], and numerical models [37–39] for specific drivers, and in-depth reviews of the multiple drivers behind rSLR in specific deltas [1,24,40–42]. Yet, what is missing is a global review to understand key knowledge gaps towards developing an integrated understanding of drivers behind rSLR across scales. Such an understanding will help to synthesize opportunities to transfer and upscale the knowledge and (numerical) approaches we have gained for some deltas to deltas across the world.

To close this knowledge gap, our paper does not attempt to provide an exhaustive review for the modeling of each driver of rSLR. Instead, we focus specifically on identifying which drivers create knowledge "bottlenecks" that limit the ability to study future adaptation/mitigation strategies across scales and domains, and we highlight which scientific efforts will be required to overcome those bottlenecks in the near future. Towards this objective, this paper firstly provides a brief overview about what is at risk in deltas globally, and thus what should motivate those scientific efforts. Secondly, we introduce key concepts and drivers behind land subsidence and relative sea level rise. Thirdly, we review what is known and how well we can model each driver. Fourthly, we review literature for a set of five large river deltas to further highlight management-relevant knowledge gaps across drivers and geographies. Filling those knowledge gaps will be critical to sustain the world's river deltas in a changing future.

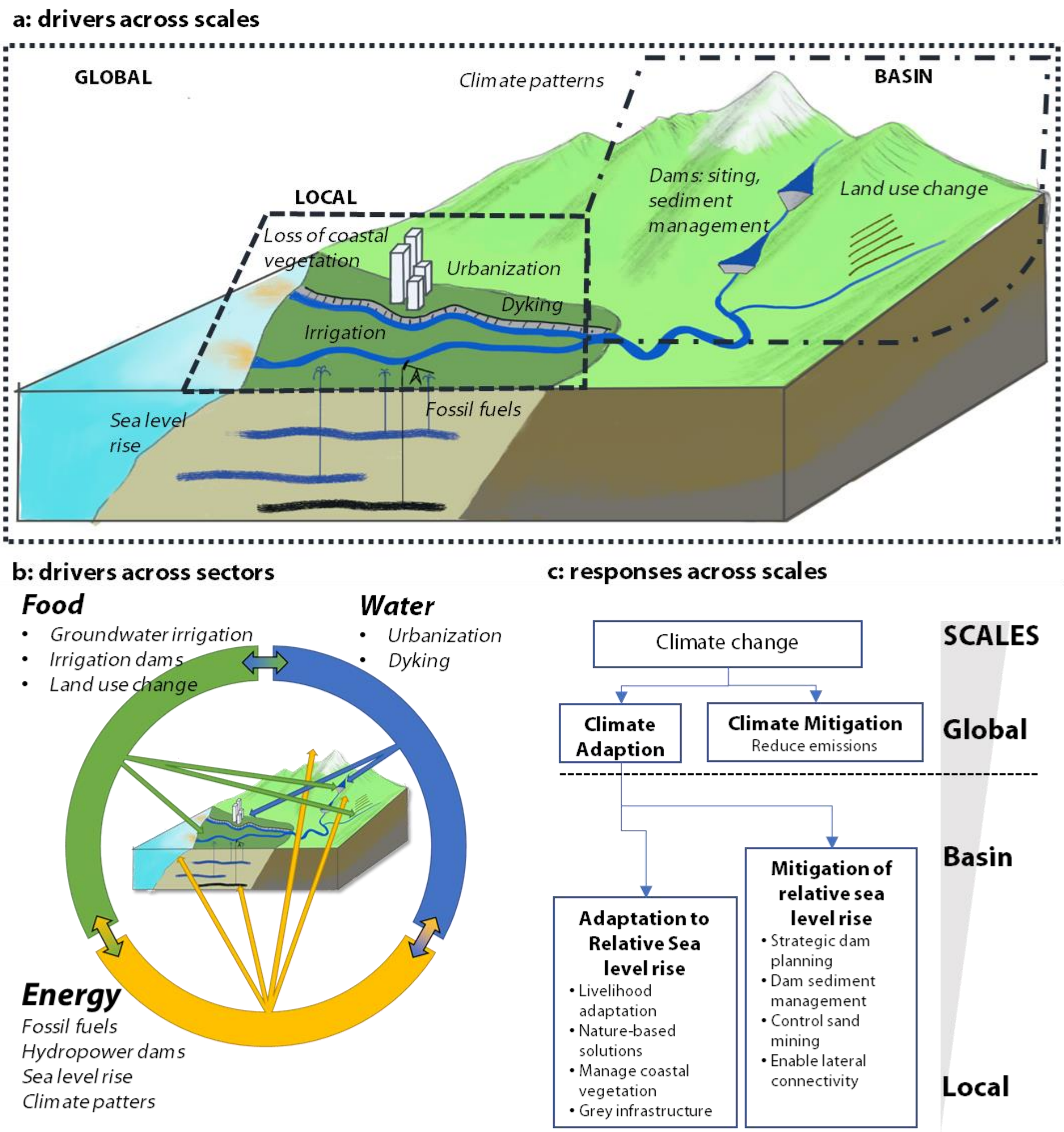

Figure 1: Natural and anthropic complexities for sustainable delta management across scales and domains. Deltas are created at the interface of coastal and basin processes, and their future is determined by actions across multiple scales (a). Sustainable management of deltas will require thinking across sectors (e.g., water energy food) while considering multiple scales for each sector (local-regional-global) and linkages between sectors (b). Additionally, sustainable delta management needs to be embedded in global actions for climate mitigation and adaptation, where basin and local scales offer an increasingly wider range in mitigation options (c).

3. Values at risk in global deltas

Deltas support important economic activities and ecosystem services. Estimates indicate that global deltas generate economic and ecosystem services in the order of hundreds of billions or even trillions of dollars per year [7,43]. This makes deltas an important part of the global economy and important contributors to global ecosystem services (in total valued between $125 - $145 trillions [44]).

The value of ecosystem services for individual deltas can be major and has been estimated to be $12 – 47 billion/year for the Mississippi Delta [45] and $10 to 27 billion/year for the Yangtze Delta [46,47]. In purely economic terms, the Mekong Delta covers only 10 % of Vietnam's land area, but studies suggest that the delta contributes around 25 % [48] of the country's GDP of $360 billion [49]. Based on global gridded GDP values [50], we estimate that the contribution of deltas to the global GDP is around 4.4 trillion dollars or 4.1 % of the global GDP (107 trillion in 2015), a notable increase from 2.6 % of the global GDP in 1990 (1.2 trillion of 47 trillion). These findings provide quantitative support for previous estimates [7] and highlight the growing importance of delta landforms for the global economy.

Deltas are created from recent deposits of sediments, thus offering fertile agricultural lands with easy access to freshwater resources [51]. As a result, deltas support significant agricultural production and thus contribute to food security for populations living on delta land and people receiving food grown on deltas. For instance, it has been estimated that up to 5 % of the global rice production takes place on the Mekong Delta in Vietnam [1]. Other deltas in Asia play similarly important roles, being typically the location of the region's most productive agricultural areas [2]. Based on global gridded data [52], we estimate that the value of agricultural production on delta land was around $40 billion in 2010, and thus around 3 % of the total global crop production of $1.25 trillion.

The fate of river deltas is also a key determinant for sustainable human development [53]. Currently, 5.6 % (450 million out of 8 billion) of the world's population live on river deltas. Deltaic populations make up the majority of population in a number of countries, notably 33 % of Nigeria's population live on the Niger Delta, and 10 % of Egypt's population live on the Nile Delta [51]. The number of people living on deltas or along low-lying coastlines is expected to reach up to a billion by 2100 [54]. Some deltas, mostly in Asia, stand out across indicators (GDP, agricultural production, population, see histograms in Figure 2). It is also notable that many deltas see rates of growth that outperform the growth in the country where the respective delta is located, highlighting that deltas have been global hotspots of socio-economic growth over the past few decades (see upward triangle markers in Figure 2).

Deltas also provide significant other benefits to global societies that are harder to quantify. In addition to crop production, deltas also contribute to food security through fishing [55,56], aquaculture [57–60], and livestock production [61]. Additional ecosystem services are provided through water quality regulation, flood protection, recreation [45], and habitat provision along the world's major flyways [62,63]. Some deltas are also important hotspots for extracting hydrocarbons [51,64,65] and other mineral resources such as sand [15]. Often those activities have negative impacts on ecosystems and people, e.g., impacting water quality and accelerating subsidence and coastal erosion. The fate of livelihoods and ecosystems is closely linked to sustainable human development. Examples range from food security (SDG 2), to sustainable and livable cities (SDG 11, some of the most dynamically growing cities are located on or close to deltas) to life on water and land (SDGs 14 and 15), and many other goals that can only be achieved if there is exposure to natural hazards and rising sea levels is low (e.g.: SDG 4: Good education, SDG 9: Industry, Innovation and Infrastructure).

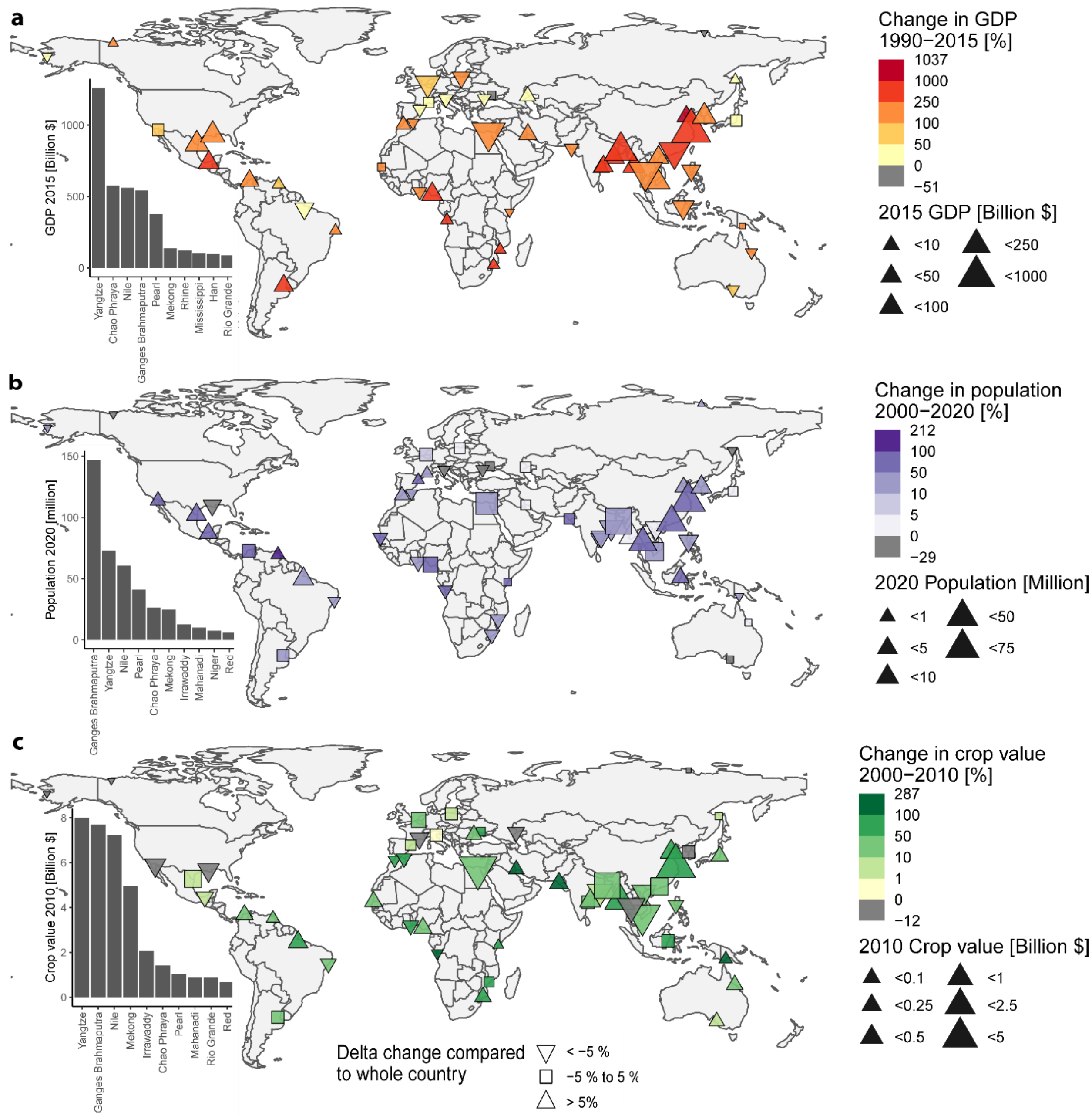

Figure 2: Global deltas are critical hotspots of economic activity, livelihoods, and food production [66]. Panels a, b, and c show these three indicators for 52 major river deltas. Marker sizes indicate the latest total value. Colors indicate the change over the past decades (1990-2015 for GDP [50], and 2000 – 2020 for population [67], 2000-2010 for food system values [52]). The orientation of markers shows how indicators performed compared to the country where the delta is located, e.g., an upward triangle indicates that an indicator grew at least five percent faster than the same indicator for the country where the delta is located. Bar charts show total values for the top-10 deltas for each indicator. Values are represented at the delta centroids, but values are extracted using the outlines of 52 major deltas [22].

4. Global trends and models for key drivers of relative sea level rise and land loss

The relevant linkages between altered delta processes and human livelihoods are manifest in recent research on global land subsidence, its drivers and magnitude [8,68] and its socio-economic consequences [69,70]. Relative sea level rise (rSLR) is the sum of vertical land motion (VLM), with negative motion meaning land subsidence, which is often but not always accelerated by human activities, and sea level rise (SLR) [21,71]. Rates of rSLR for a river delta can thus be expressed as

$$rSLR = -VLM + SLR$$

Vertical land movement is the cumulative result of many processes, for instance, (1) deep earth-crust dynamics like isostacy and tectonics [72], (2) shallow natural compaction and peat oxidation [18,73–75], (3) increased compaction from increased loading (e.g., buildings, linear infrastructure or drainage) [27,76,77], (4) extraction of underground resources like groundwater [28,78,79] or hydrocarbons [80–82]. The natural mechanism of deltas to cope with rSLR is to build elevation through sediment aggradation, both from fluvial and marine sediment deposition and organic accumulation [7,24,83,84].

Most of these processes are not isolated but interconnected across domains and scales. For instance, understanding the impact of dams on deltas requires to take a regional perspective on human needs for energy and food, a basin-scale perspective on sediment transport processes [22,85–87], and a local perspective on channel, floodplain and coastal processes in deltas [10,16]. Additionally understanding is required on deltaic surface-subsurface process as, for example, increased sediment deposition drives compaction of underlying sediments [88], in turn altering surface dynamics.

The most fundamental challenge for modeling rSLR is that accurate information on land surface elevation is hard to obtain for deltas. While global DEMs are now widely available, their remote-sensing derived elevation data are still prone to vertical errors in the order of several meters, significantly more than the average elevation of many deltas. For instance an analysis of ground elevation measurements for the Mekong delzta Minderhoud et al. (2019) [89] revealed that the average elevation of the delta is around 0.8 m above local sea level, significantly less than the 2.6 m average elevation apparent from widely used global DEMs. Such a difference has obviously major consequences when assessing what is at risk for different levels of rSLR. A recent study on the Ayeyarwady delta revealed similar large discrepancies between different global DEM and local control data [90]. On a global scale, attempts are being made to improve existing global DEMs for the coastal zones, for example using machine-learning [91,92] or interpolating space-borne LiDAR data (I.e. ICEsat 2) for the coastal zone [93]. Such products allow improved modeling of coastal and delta products than "raw" DEMs but they should be validated using local groundtruth data, as large discrepancies may still occur [89,90], and need to be updated periodically to reflect latest developments in land subsidence [28].

Discovering opportunities to curb rSLR will not only rely on better data, but also on new types of numerical modeling approaches. Numerical models are no panacea for solving complex real-world problems [94] but models, ideally informed by in-situ data [95], can be useful to study hazards, exposure, vulnerability, and thus risks [30] from continued "business as usual" (Figure 3 a, b). Models are also critical to explore future adaptation in a way that reduces risk for deltas and avoids exceeding societal and biophysical limits for adaptation. Another application is to use numerical models to solve trade-off problems, e.g., between hydropower development and sediment supply to deltas [86,87,96], or to optimize green-grey infrastructure portfolios [97]. Many challenges faced by deltas are typical “wicked” [94] problems without a single “win-win” solution. Thus, iterative and participatory [98] model-based explorations of the many dimensions of threats and management opportunities are essential to mitigated and adapt to climate risk [99].

In this review, we focus on some key drivers that have been identified as dominant forces behind anthropic rSLR and delta elevation change in many of the world’s largest deltas. Those drivers are (from larger to smaller scales): (1) global sea level rise [11,100], (2) changes in sediment supply from contribution basins [12,13,22,101,102], (3) accelerated land subsidence due to the extraction of underground resources such as groundwater and hydrocarbons [28,40,103], (4) altered sediment dynamics on the delta surface [29,104–106]. The following sections will discuss the current state of knowledge for those four drivers, with an additional section on socio-economic dynamics. Each section will provide a brief overview over what is known about each driver from empirical observations or modeling studies and then discuss our ability to model each drivers’ impact on rSLR in future management applications.

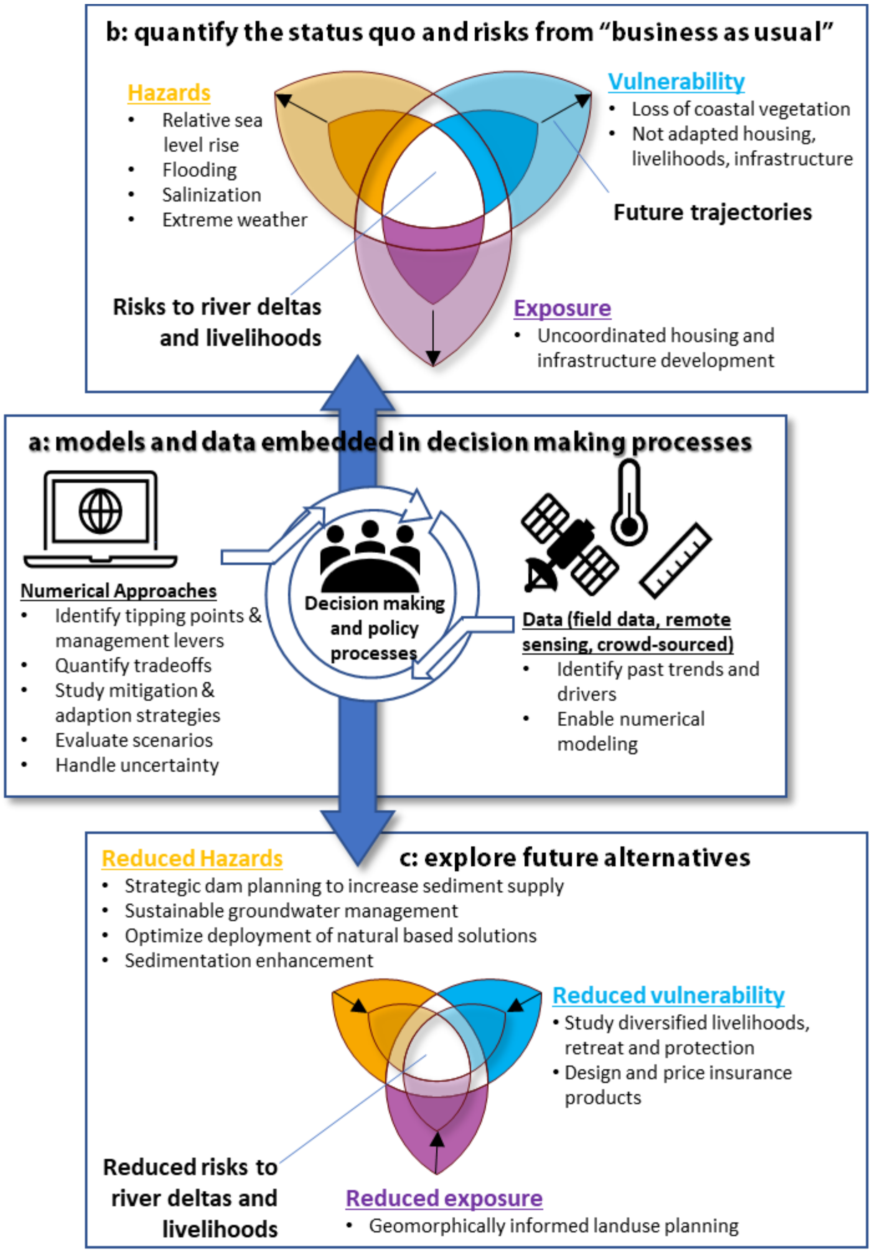

Figure 3: Numerical models can play a key role to reduce climate risk and inform climate adaptation in deltas. Embedded in decision making and policy processes (a), models can help to better understand driver of risks associated with the current status quo and following "business as usual" trajectories. Understanding what is at risk from "business as usual" can help to explore future pathways to reduce risks and increase adaptive capacity (c).

4.1. Global sea level rise

Global sea levels have risen by around 1.5 mm per year since 1900 [107,108] with a notable increase in rates post-2000. Total sea level rise is the compound effect of as a result of baristatic and thermosteric sea level rise. Baristatic sea level rise results from changes in ocean mass as the cumulative effect of decreasing water storage in glaciers and polar ice mass (and to a smaller degree from groundwater depletion), counteracted by increased storage of water in artificial reservoirs. Thermosteric sea level rise refers to the thermal expansion of oceans in a warming climate [109]. Of the total, Baristatic sea level rise has contributed most to observed sea level rise [107], with the exception of the mid-20th century when a rapid rise in dam storage counteracted losses in global ice mass [107].

Sea level rise is spatially heterogenous with variability within [110] and between the world's major oceans basins [107] and between coasts and offshore oceans [111]. This spatial heterogeneity is driven by gravitational differences, currents and spatially heterogenous thermal expansion. Notably, satellite observations seems to indicate that coastal sea-level rise is most quickly accelerating in South Asia [111] (comparing 1973-1982 and 1993-2000 periods) and thus in a location where many large deltas are located (Fig. 2), and more on the northern than in the southern hemisphere [112]. Model estimates for off-shore sea levels indicate greatest increases in the South Pacific, around the coasts of North America, Northern Europe and the poles [11]. In addition, asymmetric uncertainties in ice loss may exacerbate regional sea level rise in certain hotspots [113], notably also the east Pacific Ocean with large deltas like the Mekong, Red and Pearl River deltas. Past and future sea level rise contributes to rSLR in global deltas and expose populations and infrastructure to extreme events [7,43] such as hurricanes and typhoons. Obtaining realistic ranges of sea level rise is critical as a boundary condition for modeling any type of delta management.

By 2100, sea levels are expected to rise up to 0.84 m on global average compared to the year 2000 and even optimistic climate futures result in at least 0.43 m of sea level rise [11]. Those estimates are derived using global circulation models for different socio-economic pathways (SSPs) that cover relevant ocean and ice-sheet processes [11] (Figure 4). Additionally, different statistic and mechanistic approaches can be used to estimate combined effects of rising average sea levels and increasing extreme events such as storm surges and similar. Each of those processes adds considerable uncertainty [114]. IPCC's 2019 special report on Oceans and the Cryosphere thus indicates only medium confidence in sea level rise estimates, while solicitations of expert opinions indicate greater expected rates of SLR [115]. Projections of future sea level rise are freely available and can be used to constrain assessments for specific deltas (e.g., refs. [116,117]).

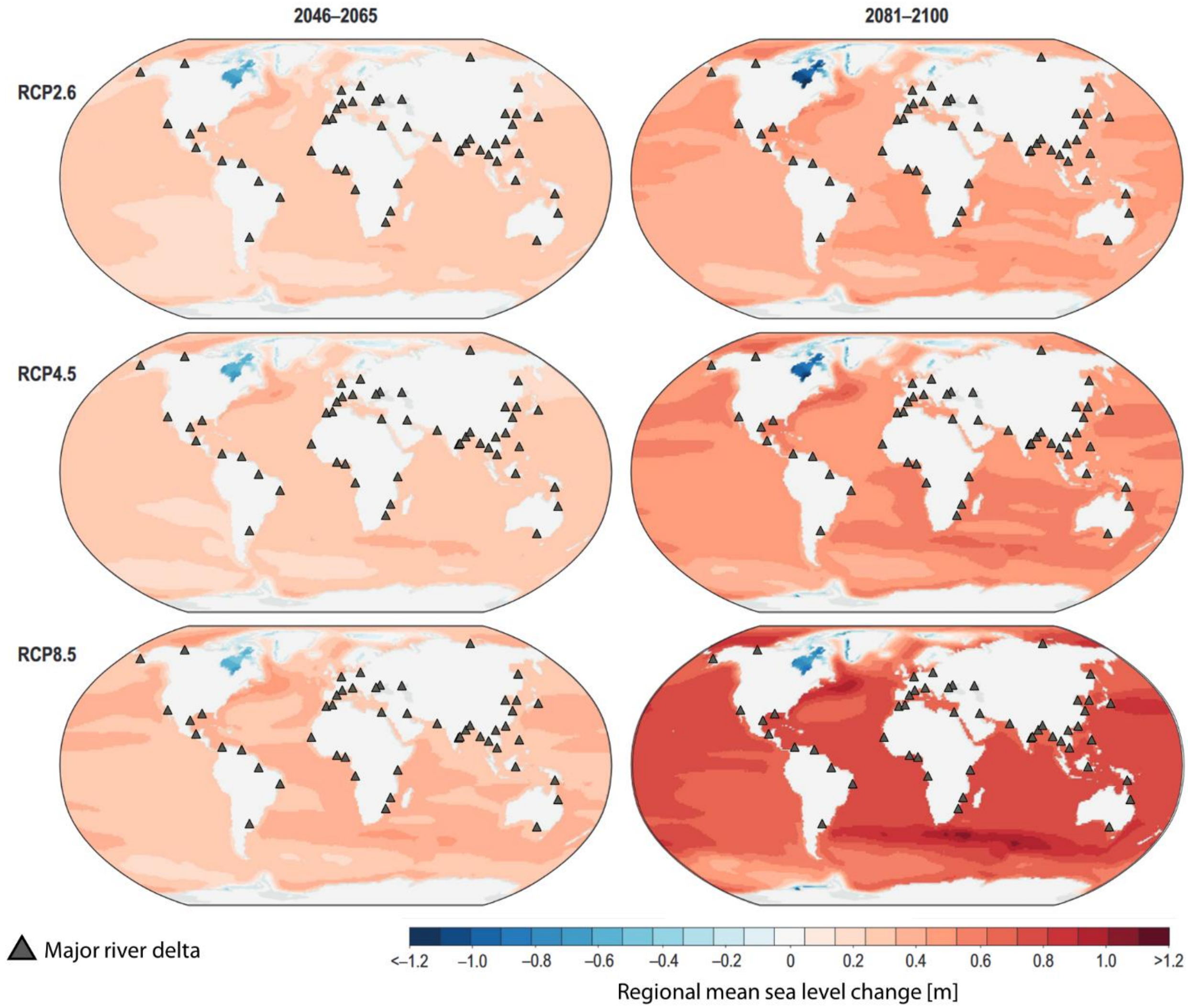

Figure 4: Global projections of sea level rise show positive trends as well as significant spatial heterogeneity. Based on a compilation of multiple studies, the IPCC's special report on "Oceans and the Cryosphere" indicates hotspots of sea level rise in the southern Pacific, and around North America, with greater increases in the farther future (right column) and for more extreme emission scenarios (bottom rows). Local and regional effects from storm surges, asymmetric ice sheet melting and other drivers could add additional variability. Figure from Oppenheimer et al. / IPCC (2019) [11], overlaid with centroids of the world's major river deltas [66].

4.2. Modeling changing sediment supply

Sediment supply from river basins to deltas is controlled (1) by how much sediment is supplied from hillslopes to rivers and (2) by the capacity of river networks to convey sediment to downstream deltas [118]. These two overarching processes are the result on many spatially heterogenous drivers that are altered by human activities in many ways. Land use and climate change can increase erosion rates and thus how much sediment is supplied to rivers, while dams and reservoirs trap sediment in their impoundment and reduce sediment conveyance in rivers [119] (Figure 1 a). Additionally, dams alter river discharges and thus the transport capacity of downstream rivers, i.e., how much of the remaining sediment can be transported downstream [120]. If the transport capacity after dam construction exceeds the remaining sediment supply, dammed rivers can erode sediment from riverbeds and banks, which increases sediment transport. Yet this effect is only temporary until sediment stores are depleted and results in significant negative impacts, e.g., on instream habitat and infrastructure

[121,122]. Mining of sand and other aggregates can lead to significant sediment starvation [123,124] particularly when rivers are both impacted by dams and mining activities. In downstream deltas this results in deepening of the channels, leading to tidal amplification and consequently increased flooding [125], salinity intrusion [126]) and coastal erosion [127].

Erosion from hillslopes and sediment supply to rivers can be modelled on basin scales with a variety of tools. Global studies have used regression models, such as the BQART model [13] to estimate sediment export based on a number of covariates aggregated on a basin-level (e.g., total glaciation, trapping efficiency of reservoirs and human footprints, for the entire contributing basin of a delta) [12–14,101]. While those models are easy to deploy, they are fitted to past observed sediment loads and might not hold in a future in which climate and landuse change pushes relevant covariates outside of ranges used for model training. Originally, models like BQART were used in a lumped manner, i.e., representing a whole river basin by a single set of parameters, and could thus only estimate sediment at the outlet of major river basins, but not where sediment originates in that catchment. Yet, more recent work has seen efforts to disaggregate BQART results to smaller scales, and then use the predicted outcomes as inputs into explicit schemes for sediment routing [128,129]. BQART was instrumental to understand dominant human controls on global sediment deliveries from continents to deltas and coastal oceans [12–14,101], and has been used to assess future human impacts on those deliveries [22].

While BQART and similar approaches are being downscaled to more local applications, the Universal Soil Loss Equation [130], USLE, and its various derivatives [37] were originally developed for single hillslopes [131], but are now used to model erosion from tributary basins to global scales. USLE is based on a number of process-related parameters (e.g., rainfall erosivity, erodibility of soils, contribution of vegetation to retain sediment), which can be derived from globally available datasets. Compared to BQART, USLE enables to represent some processes and management actions more explicitly, for instance the role of land use and management on local erosion. Also, USLE has some relevant limitations. Firstly, USLE has been developed and parameterized to represent sheet and rill erosion only and thus omitting processes such as gully erosion and mass movements and landslides. Secondly, USLE does not account for the fact that not all eroded material is reaching rivers but that part of the eroded material will deposit along its flow path. To overcome some of these limitations, USLE can be combined with conceptual sediment connectivity indices to allow for more realistic estimates of sediment supply from hillslopes [132–134].

Modeling more complex interactions between river processes, human disturbance, and sediment supply to deltas remains challenging. Firstly, estimating sediment supply as sum of upstream sediment erosion introduces a systematic bias. Natural processes, such as overbank flow, will typically lead to some deposition, so that the sediment load in any point in a river is typically less than the sum of erosion throughout the upstream contributing area [118]. This problem is somewhat mitigated by using empirical models trained on downstream observations [14]. However both process-related (like USLE) and empirical models rely heavily on sediment observations [135], which are sparse and heavily biased towards fine sediment fractions transported in suspension. Not considering for other fractions of sediment (e.g., sand or gravel) is a limitation as well, firstly because coarser sediment fractions might over-proportionately contribute to building stable coastlines and, secondly, because human interventions such as dams and sand mining will impact different sediment fractions to a different degree [136].

2D or 3D models for river morphodynamics are typically prohibitively data and resource intensive to be useful for studying how sediment is conveyed between upstream sources of erosion and downstream deltas. Data and computational demands are particularly prohibitive for use in large river basins or for water management applications that might require evaluating many different decision alternatives [37]. Thus, studies using morphodynamic models to evaluate and minimize impacts of dams on river sediment budgets are typically limited to small river sections and individual dams [137,138]. On larger scales, studies using water resources and distributed hydrologic models to optimize the passage of sediment through dams and towards deltas [139–141] rely on very simplified representations of sediment transport processes. Also approaches for optimizing the siting of dams often represent sediment transport to downstream deltas in a highly stylized manner [87,96,142,143]

To address this gap, new models are emerging that represent the transport of multiple grain sizes and their interactions (e.g., the presence of sand might impact the transport rates of gravel in a river [144]) for longer river reaches [145] or entire basins [146–152,87]. Those models are probably best described as "process related models" as they leverage approaches from graph theory [153], combined with empirical sediment transport equations, and a simplified handling of hydrology (and more recently, morphodynamics) to estimate the impacts of all sediment fractions on a network scale. Results can then be used to quantify impacts of sediment delivery to deltas and opportunities to mitigate those impacts [152].

4.3. Accelerated compaction and land subsidence

Most deltas will naturally subside because sediment compacts under its own weight [18,154] and because of downward tectonic and isostatic movements [155]. Yet the rates of subsidence are often significantly increased by human activities and unsustainable use of natural subsurface resources is a leading driver of rSLR in many large river deltas [28,78,79,156,157] . When fluids are extracted from porous subsurface layers compaction ensues as the overburden compresses lower sedimentary layers, resulting eventually in land subsidence [34,158]. Subsidence related to groundwater pumping can lead to subsidence rates which exceed rates for SLR by an order of magnitude [8,158,159]. Additional shallow subsidence can be triggered when drainage leads to lowering of the surface water table, triggering shallow compaction and volume loss following oxidation of soil organic material and peats [32,160,161].

Satellite-based estimates of subsidence in the Mekong Delta, where the phenomenon has been relatively well studied, range from 10 – 40 mm/yr between 2006-2010 [78] and up to 60 mm/yr between 2014-2019 [162] with contemporary rates associated to groundwater pumping alone modeled to be on average around 11 - 16 mm/yr [78,79], with continued acceleration into the future as groundwater extraction keeps increasing [28]. Also in other deltas, rates of subsidence in areas with known major groundwater extraction can reach similar rates, e.g., localized up to 18 mm/yr in the Ganges-Brahmaputra Delta [103], and up to 9.8 mm [163] over parts of the Nile Delta. Typically, rates are highest around cities [78,158,164], and particularly cities in Asia [68,165], which greatly increases potential socio-economic impacts of land subsidence. Where deltas hold reserves of hydrocarbon such as oil and gas, such as in the Niger [82,166] or Mississippi Delta [81,167], hydrocarbon extraction can further accelerate land subsidence.

Total land subsidence, especially in unconsolidated deltaic settings, is the cumulative result of various subsurface processes acting at different depths, time scales and spatial extents [6,168]. As a result, land subsidence can be highly spatio-temporally variable, which makes modeling and projecting it not straightforward and current models tend to focus on a single driver or process only. As human induced subsidence, predominantly the overextraction of groundwater [28,159], is responsible for the majority of subsidence in deltas, proper modeling and accurately predicting these anthropogenically driven processes is critical for delta management.

Modeling future overuse of groundwater and extraction-induced accelerated delta subsidence remains a major challenge. Firstly, contemporary data on groundwater extraction in deltas is sparse and when available comes with large uncertainties. Consequently, estimating rates of future groundwater extraction are even more challenging. Groundwater is primarily used for irrigated agriculture [33] and extraction rates depend on crop decisions and surface water availability, which could be derived from global crop models and climate change projections allow to estimate water demands [169]. The role of groundwater to meet this water demand could then be estimated based on the availability of surface and groundwater and country level statistics, similar to studies on past groundwater extraction [33,170]. Yet, such modeling studies are usually executed using medium resolution agrohydrologic models [169,170]. Current agrohydrologic models also operate on relatively coarse resolutions (typically 10 – 50 km at the equator), which would reduce even a large delta, such as the Mekong Delta to few pixels and hide fine-scale spatial patterns and dynamics [171]. Current extraction estimates from such global models are shown for several major deltas to be several factors off (up to 4 times higher or lower) compared to locally validated datasets [172]. A new generation of scalable hydrologic models might help overcome those limitations in the near future [173].

Models to translate groundwater depletion rates and other drivers into rates of subsidence vary widely in their complexity and their data demand, as well in how well they represent different processes (Figure 5). One extreme are complex 3D aquifer system models [20] which require a detailed understanding of sub-surface hydrogeological layering, hydromechanical properties and extraction rates (i.e. history, depth, amount). The required data will be challenging to obtain in many deltas, particularly in the global south. Some exceptions are, e.g., Ye et al. (2016) [174] and Minderhoud et al. (2017) [79]. Minderhoud et al. (2017), for instance, developed a 3D hydrogeological model with 17 distinct layers explicitly representing the multi aquifer-aquitard system for the Mekong Delta. This differs from most hydrogeological models, which typically focus on groundwater flow only and which do not represent aquifer compaction. Both studies relied on a significant amount of subsurface data from boreholes and geomechanical lab test to characterize the deltaic sediment body and ample measurements of hydraulic head and surface deformation as validation. The full potential of complex models is their ability to provide process-based, non-linear projections of future spatial patterns of land subsidence in response to resource extraction [28].

"Back of the envelope" calculations [24,178] represent the other extreme in terms of model complexity. Such approaches can yield results for accelerated subsidence and future elevation change in the right order-of-magnitude and will be feasible for most global deltas. However, such "back of the envelop" approaches omit the significant spatial and temporal heterogeneity in sub-subsurface processes that control subsidence, feedbacks with sedimentation, and resulting complex patterns of land subsidence and land loss [16]. This is particularly relevant because even small errors in projected rates of subsidence will result in major differences when projected until the mid or the end of the century. In a setting where land is often only few meters above the sea level, a cumulative error of 50 cm, or 0.5 cm/yr over 100 years, would lead to major differences in estimated land loss.

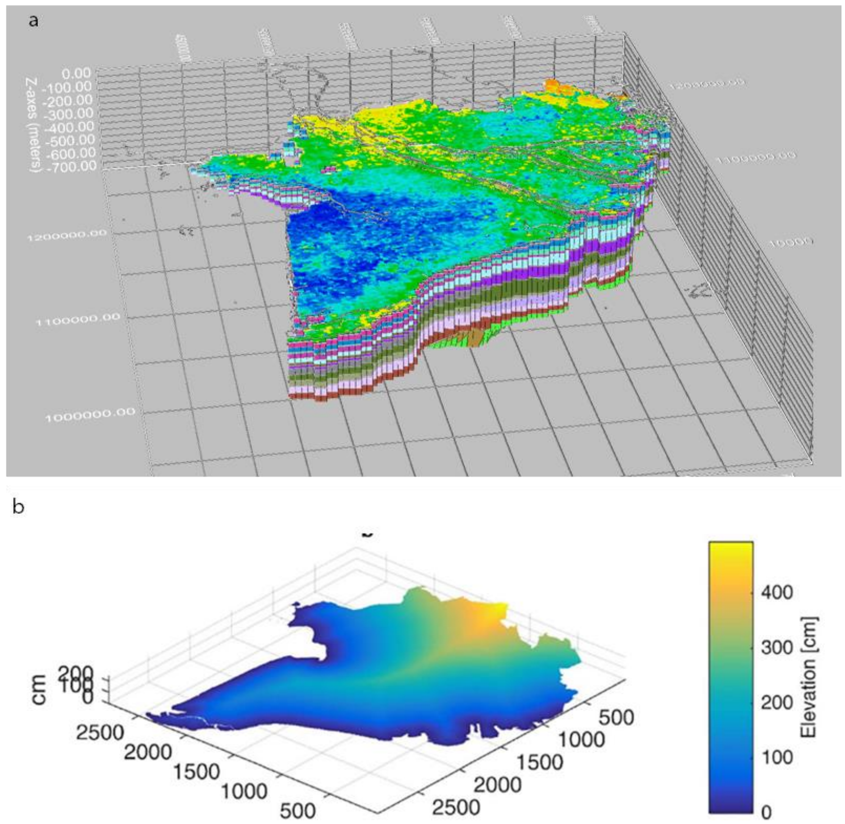

Figure 5: Different models for delta subsidence pose different opportunities and challenges, as exemplified for the Mekong Delta. High resolution 3D models of subsurface processes (a) enable detailed spatio-temporal estimates of land subsidence as a result of groundwater overuse[79] but require significant amounts of input and validation data, as well as expertise. . Simple "delta plain" models [24] (b) are a spatial expansions of delta sediment budgets [26,178]. Such models are useful to translate vertical rates of subsidence into spatial approximations of land loss without considering dynamic feedbacks between processes (panel a from Minderhoud et al. [79], panel b from Schmitt et al. [24]).

4.4. Delta-scale processes and nature-based solutions

Sediment deposition on deltas is not only reduced because of changes in sediment supply, but also because of modifications of lateral connectivity between river channels and delta floodplains. A natural delta is built by the gradual spreading of sediment on the delta surface by floods, and by avulsion events that drastically change patterns of sediment distribution [39]. Both floods and avulsions can have catastrophic impacts on human lives and livelihoods [10,39,179]. Hard engineering in the form of dykes and levees was therefore deployed in many deltas to reduce the impact of floods on agriculture, settlements and infrastructure; and river control structures were built to control avulsions [10,16,180]. Today, those infrastructures impede the natural flow of sediment across delta plains and thus the processes that would fuel natural aggradation [4,75,105,127,181–186]. Rethinking those linear infrastructures and allowing for natural sediment spills can contribute to maintaining and restoring delta land [17,29,187,188]. Modeling lateral connectivity becomes particularly relevant in sediment-limited conditions in which decision makers will need to decide where artificial splays of available sediment would lead to the greatest benefits in terms of land building [29].

Modeling delta evolution and feedbacks between sediment and accretion is common in landscape evolution studies but less for management applications. As reviewed in, e.g., Edmonds et al. and Liang et al. (ref. [38,189]), models for sediment distribution on delta surfaces range from full 3D models that explicitly describe the hydrodynamic processes behind the routing of water and sediment (e.g., Delft 3D), to reduced complexity models (RCMs) [189–191] in 2D, and simplified 1 D models of delta cross-sectional profiles [38]. Similar to what is described above for subsidence, even simple back-of-the-envelope calculations can yield some insights into how different levels of sediment splaying can contribute to aggregation [24,26,192]. One important process that all above mentioned models lack is post-depositional compaction of newly deposited sediments, a relevant [18] aspect which is only recently included in fully coupled 3D geo-mechanical models [193].

As discussed above for fluvial sediment transport, the accuracy of full-complexity, three-dimensional delta evolution models entails significant computational and data needs and specialized skills. Where data and resources are available, such models can yield detailed insights into interactions between surface water flows, sediment splays, and even groundwater dynamics [194]. Also RCMs can yield insights into relevant management questions, e.g., feedbacks between delta vegetation [195] and tectonics [196] with implications for delta management. Yet, reviewing citations for, e.g., ref [189], reveals that even simplified 2D models of sediment dynamics are still predominantly used for studies of landscape evolution, rather than for management applications.

Modeling and managing the lateral exchange of sediment between channels and delta floodplains is not only a modeling, but also a data challenge, particularly when it comes to water infrastructure. The question of sediment distribution on a delta surface will need to consider for infrastructure impacts in many ways. Yet, data on dykes and levee locations and the operation of associated floodgates are rare. Crowd-sourced data from, e.g., Open Street Maps, contain detailed maps of water infrastructure but lack information on their design and operation. The new OpenDELVE [197] aims to provide a platform for continued, community-driven mapping of such infrastructure, but still misses many smaller infrastructures that are crucial for spatio-temporal sediment dynamics (Figure 6).

Delta sediment dynamics are also critical deployment of nature-based solutions. Nature-based solutions in deltas and coastal zones, e.g., protection or restoration of Mangroves, dunes, and marshlands, have received considerable attention in recent years [11,198]. Indeed, the benefits are compelling. By maintaining a soft coastline with mangroves elevation may naturally grow with rising sea levels while providing a wide range of additional benefits for livelihoods and biodiversity. While more human-controlled interventions like sediment enhancing strategies can do the same in other parts of a delta (Dunn et al., 2023). Most nature-based solutions in deltas are dependent on trapping sediment and are thus unlikely to thrive and to provide desired benefits in erosional, sediment-starved environments [199,200]. These linkages between sediment supply, coastal sediment transport, and vegetation dynamics could be explored using hydrodynamic models [201]. So far, such approaches are not commonly used in delta modeling or management, risking to overlook potentials and risks for deploying nature-based solutions at scale.

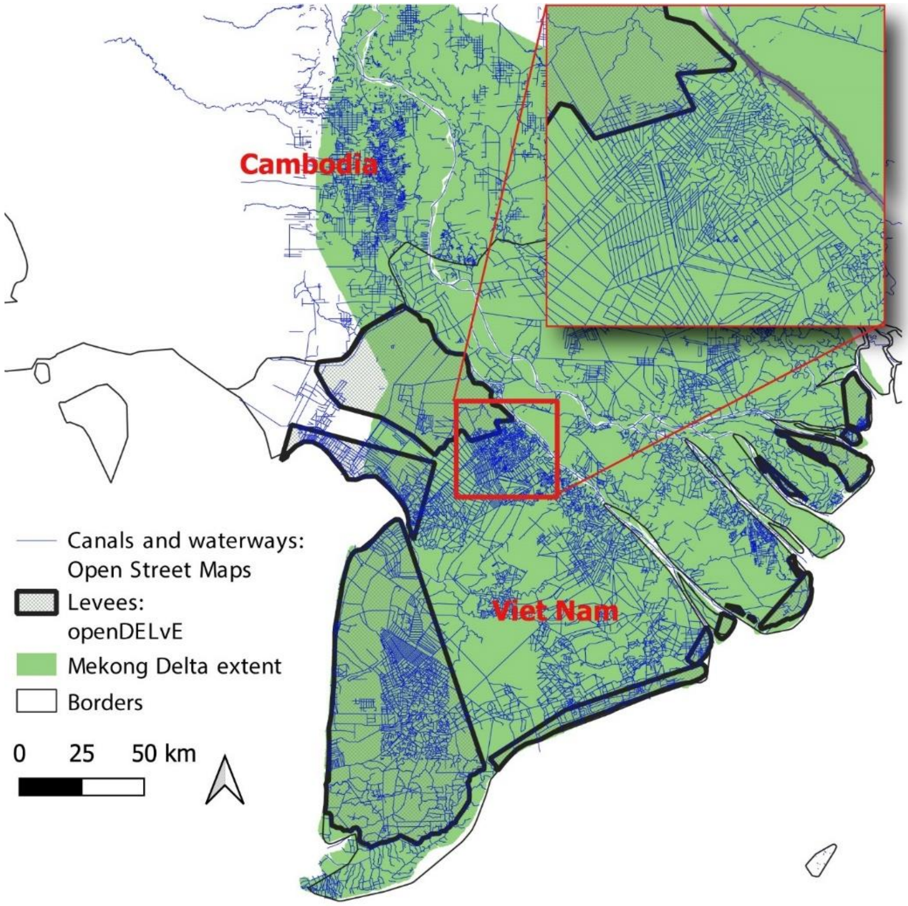

Figure 6: Modeling and managing human impacts on lateral sediment connectivity will require significant additional data. The openDELvE [197] data set is the first to globally map levees and polders. Yet, the example of the Mekong Delta highlights that there is significant additional water infrastructure, such as canals and floodgates (from Open Street Map), which has been crowd-mapped in great detail (see zoomed panel). Dykes and levees are present along many of those canals [105,185], yet this information is not commonly available.

4.5. Socio-economic dynamics and feedbacks across scales and domains

The future management of deltas and thus their resilience to change will depend on complex feedbacks across biophysical and socio-economic domains [202,203]. Questions like "where will people live?", "how will people make a living?" or "to how frequent and severe events will people be exposed?" are relevant question for managing sinking and shrinking deltas. Answering those questions, but also developing relevant plans for delta management, will require to understand how local livelihoods will respond to global pressures, and how those together will impact the biophysical resilience of a delta.

For instance, salinization of freshwater resources is driven by a multitude of drivers, from rising sea levels, to groundwater overuse, to unsustainable irrigation practices and modifications of distributary channels [35,125,126]. From that starting point, a number of adaptation scenarios are possible leading to considerably different delta futures. For instance, farmers might abandon land and migrate to cities (as already observed, e.g., in the Mekong and Ganges-Brahmaputra Delta), which would lead to a lower population density in rural parts of deltas. Such a population shift opens opportunities for soft path adaptation, like implementing sedimentation enhancing strategies [17,85], but increasing pressure on resources in urban centers. Increasing salinization of freshwater might also motivate construction of levees, increased pumping of deeper groundwater, or switching to less sustainable food systems (e.g., from rice to shrimp farming) and thus to practices with negative feedbacks on subsidence and land loss.

No single model can capture all those complexities or provide a one-fits-all solution for all deltas. Yet it is a major knowledge gap that global estimates of coastal population growth and future land use do not consider for the fact that even under a baseline of sea level rise (i.e., without accelerated subsidence) significant parts of global deltas might fall below sea level in this century. Even broad level information on such feedbacks between rSLR could be extremely useful to constrain future exposure and thus adaptation options (e.g., retreat, protect, accommodate, ecosystem-based adaptions [11]). Resolving those problems for coastal systems will required more attention for how global and local changes propagate across domains (water, energy, food climate).

5. The global state of deltas

There are major disparities in what is known and what is unknown with regard to drivers of rSLR across the world's major deltas, and across drivers. To illustrate this point, we reviewed papers that discuss major drivers of rSLR for several of the world's most productive deltas (Figure 2), selected to represent a wide range of geographies and states of knowledge (Mekong, Ganges-Brahmaputra, Mississippi, Nile, Niger). We focus on delta and basin specific drivers discussed above, namely sediment supply, accelerated subsidence related to groundwater overuse, lateral connectivity, and socio-economic dynamics. We do not include sea level rise in this delta-scale review because its magnitude and uncertainties are reviewed in detail elsewhere [11].

This in-depth review for selected deltas aims to shine light on knowledge gaps and areas where science is mostly in agreement when it comes to drivers of rSLR. For each delta, we review the peer-reviewed literature available for each driver (mostly post-2010) through a literature search on Web of Science. From our review, we determine if drivers are subject to an increasing trend (getting worse), a decreasing trend (getting better), or no trend (respectively no agreement between studies). We also reviewed the confidence in these trends, assigning a "high confidence" level when there were >5 studies, "medium confidence" when 3 or 4 studies, and low confidence if there was <3 studies. We also distinguish if the results are based on local data, on location specific models, or on global models and data (Figure 7).

From a perspective of drivers, sediment supply is best studied while sediment dynamics on deltas and socio-economic feedbacks are in general poorly understood. There is high confidence in trends for sediment supply for e.g., the Mekong and Mississippi, medium confidence for the Nile and Ganges Brahmaputra, and limited confidence for the Niger (based on global data [22]). There is high confidence in rates of accelerated subsidence for the Mekong and Mississippi, and some evidence for the Ganges Brahmaputra, Niger and Nile deltas. Only for the Mekong, Ganges Brahmaputra, and Mississippi deltas sediment dynamics are well enough studied to infer a trend with confidence. Studies on more complex feedbacks between socio-economic and biophysical factors are only available for the Mekong and Mississippi.

Concerningly, not only is evidence scarce but the available evidence points to worsening trends in nearly all drivers for nearly all considered deltas. This is notable for sediment supply, which is decreasing for all deltas, except for the Ganges-Brahmaputra where past trends seem decreasing [204], but future trends could be increasing or decreasing [22,205] as a function of scenarios of upstream dam construction. The only other example for a delta where we found some ambiguity was the Mississippi Delta, where many studies indicate worsening trends and lock ins into non-sustainable conditions [206] for people and some key sectors [207], while other sectors have some adaptation capacity [208], and opportunities for socio-economic adaptation are being studied [209,210].

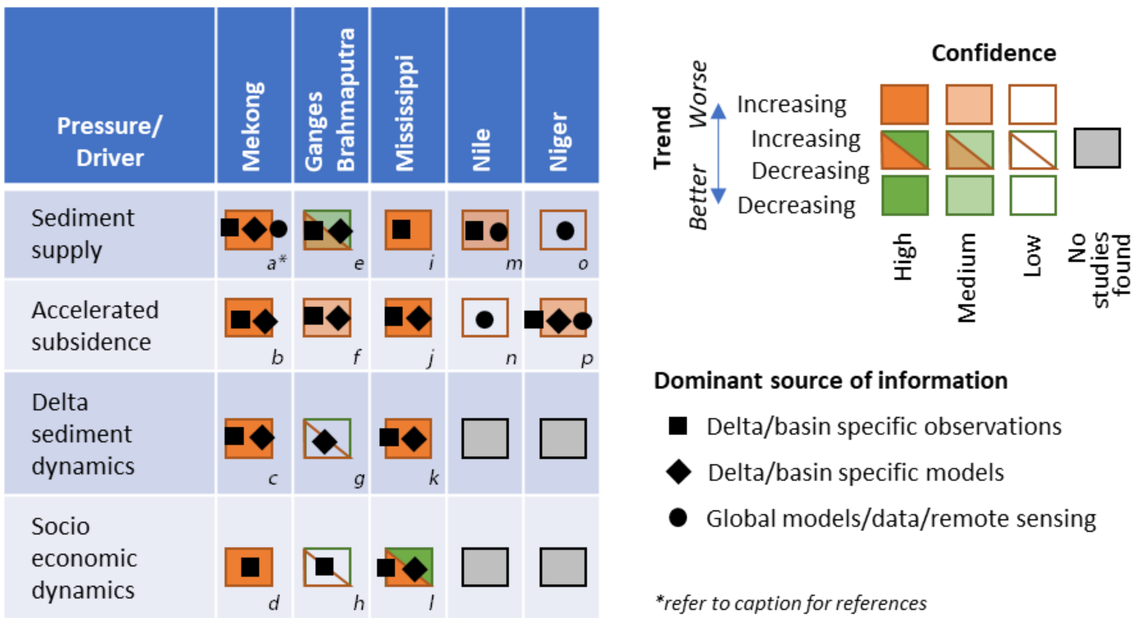

Figure 7: The state of knowledge about global drivers of VLM, rSLR and land loss varies widely across deltas and domains. This classification is based on Web of Knowledge searches using relevant key words since 2010. Confidence levels are defined as high confidence: >5 papers with similar conclusions; medium confidence: > 3 papers with similar conclusions; low confidence: at least one paper. Dominant sources of information are listed in order of specificity, from empirical local data for a specific delta, models for a specific delta, or global models. The highlighted deltas were selected to cover a wide range of geographies, scales, and levels of knowledge. Lower case letters indicate relevant references. a: refs. [23,86,151,211–215], b: refs. [28,29,78,79,162,216,217], c: refs. [105,185,218–221], d: refs. [57,59,222,222–224], e: refs. [22,204,205,225,226], f: refs. [40,103,226–228], g: refs. [228,229], h: ref. [230], i: refs. [192,231–235], j: refs. [236–240], k: refs. [17,241–245], l: refs. [206–210,246], m: refs. [247–250], n: refs. [163,247], o: ref. [22], p: refs. [82,251–254].

6. Conclusion: The state of delta modeling and priorities for the future

Global deltas are unique in terms of values and services that they provide to societies. River deltas are also uniquely endangered by drivers that are interconnected across sectors and spatio-temporal scales. From our review we identify four key shortcomings in terms of models and data and thus priorities for future research and model development. Those priorities are (1) modeling of delta-scale processes and the integrating models across scales and domains, (2) coupling of such integrated models with state-of-the-art frameworks for decision analysis, (3) closing major knowledge disparities between deltas, and (4) consolidation of existing knowledge about global deltas and integrating the fate of deltas in global assessments.

Numerical models are critical for quantifying complex and interrelated processes, for identifying challenges and management opportunities, for resolving conflicts between sectors, and for identifying pathways for sustainable delta management. We thus reviewed the current state of modeling with regard to four key drivers of subsidence, relative sea level rise, and land loss.

We find that regional sea level rise in response to global warming can be relatively well modeled and is included in well-tested earth systems models, with some of the greatest uncertainties associated to certain tipping points, such as the melting of major ice shields.

Sediment supply from upstream contributing basins is an area that has seen many innovations over the past decade. Today, several process-related frameworks are freely available that are applicable on systems scales. Suspended load of rivers can now be monitored using remote sensing and sediment transport models now commonly integrate some key human drivers, e.g., landuse change and the location and operation of dams. Some of the greatest uncertainties related to sediment transport concern the transport of bed load, sand mining rates and impacts [255–257], and in general the poor availability of sediment data, which hinders effective model calibration and determining a reliable baseline.

The capacity to model accelerated subsidence is, with few exceptions, very limited. However, rates of subsidence can be tracked with very high spatial resolution using the latest generation of space-born radar sensors. Moving from remote sensed observations towards process-based modelling of land subsidence is crucial to 1) disentangle the subsidence signal into different drivers and processes, and 2) properly simulate the spatio-temporal heterogeneity of deltaic subsidence, enabling highly relevant non-linear scenario projections. However, this is hindered by the need for subsurface data that can only be obtained *in-situ* and the simultaneous need for understanding socio-economic drivers such as groundwater use.

Lateral connectivity and sediment dynamics on delta floodplains also remain understudied. While there are some examples of detailed models of channel-floodplain sediment exchange and its links to infrastructure operations [218–220,258], those models remain a notable exception and data on infrastructure location and operation are absent for most river deltas. Yet, remote sensing can be used to monitor channel-floodplain sediment exchanges and could be leveraged more widely for model building an calibration [259,260]. Only very recently a new generation of numerical models is being developed that can account for post-depositional sediment compaction and consequent delta elevation change. Future efforts needed to link these to morphodynamic sedimentation models to resolve process feedbacks and connect deltaic surface to subsurface processes.

Thus, modeling abilities are most limited when it comes to processes on a delta scale, namely accelerated subsidence and sedimentation dynamics. There are successful examples for how those processes can be modelled for management or research applications [28,193], but efforts are needed to develop modeling frameworks that are generalizable and modular to account for delta-specific differences in data and resource availability.

Secondly, new models that integrate biotic and abiotic delta and basin processes are needed to represent the fate of deltas in decision making frameworks and for sensitivity analyses. Delta management would be an ideal use case for approaches for robust and adaptive decision making [30,261], e.g. to design effective portfolios of grey-green infrastructure interventions and associated policies [186] across delta and basin scales. Yet, there are only few examples that integrate rSLR as objective in basin-scale planning, and those examples are based on simplifying and implicit representations of sedimentation and accelerated subsidence [86]. In turn, there are only few studies that consider basin management in the evaluation of local mitigation and adaptation [201], e.g., through nature-based solutions. There are also opportunities to couple integrated, cross-scale modeling frameworks to state-of-the-art tools for sensitivity analysis [262] to identify critical sources of uncertainty (see also next paragraph). Common to all those applications is the need for models that are computationally efficient. Thus, future basin-delta modeling frameworks need to strike a balance between process representation, data needs, and computational demand.

Thirdly, there is a blatant knowledge disparity between deltas, which not only hinders the management of specific deltas but also the identification of global drivers, trends, and management responses. For instance, few deltas have data or studies available to establish a reliable baseline of current elevation and trends of rSLR over the past decades. The lack of information is likely not a result of lacking threats and pressures, but rather results from limited capacity in local institutions and weak links between local researchers and the global research community.
Those limitations can be overcome, as is demonstrated by the Mekong Delta. Within the past decade, the Mekong delta has gone from being basically unstudied to being the best studied delta in the Global South. We do not know how many resources went into this research effort, yet the expenditures were likely extremely small compared to what is at risk. It should be noted that some studies [263] aimed at comparing vulnerability across deltas in a more standardized manner (including some data-poor deltas) and future global assessment could build on previous efforts. Likely, a nested approach would be most effective, firstly aiming to consolidate knowledge for individual deltas [264,265], and secondly aiming to synthesize across deltas.

Fourthly, overlooking the fate of deltas in global assessment studies risks overlooking significant climate risks as well as opportunities for adaptation. So far, delta-scale studies incorporate downscaled results and scenarios from global assessments. Yet, results from delta-scale studies are rarely upscaled to understand feedbacks between land loss in deltas and global patterns of, e.g., migration, food supply, and trade, and thus issues for which deltas are of outstanding importance (see section 3). It is also a limitation that sea level rise is integrated as core hazard in the IPCC assessments while land subsidence, a driver that exceeds sea level rise as driver of relative elevation loss in many deltas, is not. Thus, calls have been made for an International Panel on Land Subsidence (IPLS)(www.IPLSubsidence.org) to bridge different research communities working on coastal vertical land motion and elevation dynamics, consolidate knowledge, identify knowns and unknowns and their respective importance; and design a consistent framework to integrate coastal land subsidence into rSLR projections.

Numerical models are no panacea in the efforts to mitigate the existential threats faced by many deltas. Yet, policy initiative such as the 2022 COP27 highlight the need for knowledge and the role of "*best available science*" to reduce climate risk through climate mitigation and adaptation [266]. Meanwhile also efforts for example by UNESCO's Land Subsidence International Initiative (LaSII) [267] to highlight the global hazard posed by land subsidence are increasingly gaining traction [8] . This need for knowledge is embodied for global deltas, where reliable and transparent data and numerical models will be critical to inform decision-making processes, navigate trade-offs, and provide long-term strategies that span sectors and scales to avoid catastrophic environmental degradation in the next decades.

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