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Perspective

Sedimentation-enhancing strategies for sustainable deltas: An integrated socio-biophysical framework

Frances E. Dunn,[1,*] Jana R. Cox,[1] Murray Scown,[2] Haomiao Du,[3] Annisa Triyanti,[4] Hans Middelkoop,[1] Jaap H. Nienhuis,[1] and Philip S.J. Minderhoud[5,6,7]

[1]Department of Physical Geography, Faculty of Geosciences, Utrecht University, Utrecht, the Netherlands
[2]Lund University Centre for Sustainability Studies (LUCSUS), Faculty of Social Sciences, Lund University, Lund, Sweden
[3]Utrecht Centre for Water, Oceans, and Sustainability Law (UCWOSL), Utrecht University, Utrecht, the Netherlands
[4]Copernicus Institute of Sustainable Development, Faculty of Geosciences, Utrecht University, Utrecht, the Netherlands
[5]Soil Geography and Landscape Group, Department of Environmental Sciences, Wageningen University, Wageningen, Gelderland, the Netherlands
[6]Department of Civil, Environmental, and Architectural Engineering, University of Padova, Padova, Italy
[7]Department of Subsurface and Groundwater Systems, Deltares Research Institute, Daltonlaan 600, 3584 BK Utrecht, the Netherlands
*Correspondence: f.e.dunn@uu.nl

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SUMMARY

Coastal river deltas, home to hundreds of millions of people due to their abundant natural resources, face intense internal and external pressure from human activities, which threaten to degrade essential systems vital to delta functioning. A key biophysical challenge for deltas is relative sea level rise, which enhances salinity intrusion, flooding, and land loss. Although sedimentation-enhancing strategies (SESs) that use natural delta processes to encourage land building to counter relative sea level rise are considered a potential solution, a comprehensive understanding of the extent to which SESs can be successfully deployed to enhance resilience is lacking. Here we demonstrate how diverse biophysical and societal conditions impose multidimensional challenges in the implementation of SESs before proposing transdisciplinary solutions that integrate knowledge and expertise across science, government, and local communities to advance effective and participatory opportunities for successful SESs. The insights offered here can transform delta management for long-term sustainability.

INTRODUCTION

Coastal river deltas, covering less than 0.5% of global land area, are inhabited by almost 5% of the human population,[1] contribute to over 4% of global gross domestic product (GDP) and 3% of total global crop value production,[2] and host valuable ecosystems.[3,4] However, they are threatened by relative sea level rise (RSLR),[5] which is the combined effect of geocentric sea level rise (SLR) and land subsidence[6] (Figure 1). Other threats to deltas are reductions in water and sediment delivery from upstream,[1,11] sand mining,[12] and dredging.[13,14] Approaches to cope with RSLR include engineering structures for flood protection, which are costly and have particular limitations and drawbacks. Interest in approaches under the nature-based solution (NbS) umbrella is therefore steadily growing.[15]

Sedimentation-enhancing strategies (SESs) use sedimentation, a natural delta-building process, to elevate existing land above rising water levels or create new land. SESs present a key opportunity to reconnect biophysical and societal processes in deltas and foster resilience in these complex coupled systems. SESs can be highly effective methods to combat delta elevation loss, with the potential to reduce the flooding, salinization, and land loss caused by RSLR in often densely populated and ecologically important coastal-deltaic areas. SESs require enabling physical conditions, such as adequate sediment supply, and their implementation and long-term sustainability require public support and effective management through appropriate economic, technical, and institutional approaches.[16] However, SES implementation is often hampered by both biophysical and societal limitations. Additionally, SESs are often not compatible with current land use and particular land use development plans, such as intensive agri- and aquaculture, and SES implementation can conflict with certain livelihoods and alternative modes of development.

The only way to overcome current challenges and unlock the full potential of SESs is through a systems perspective, integrating and bridging hydrogeomorphology, biophysics, socioeconomics, governance, and law into strategy development. This requires a paradigm shift from standard delta management, focusing on flood protection and immediate economic value, to integrated delta management at the river basin system level, ensuring inclusive, transdisciplinary approaches to SES implementation that are effective, fair, and sustainable. These ideas are recognized in the scientific community;[17] however, they are

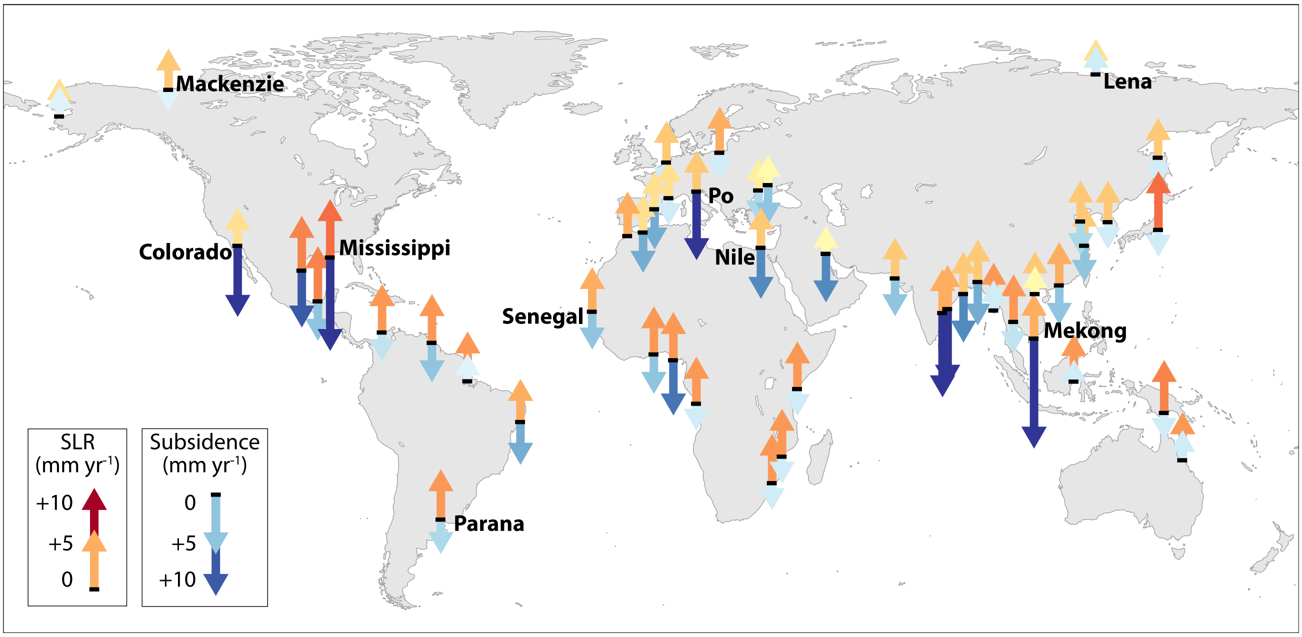

Figure 1. Global deltas threatened by present-day RSLR, the combination of rising seas (sea level rise [SLR]) and subsiding delta land (subsidence)
Yellow and red arrows show geocentric SLR from satellite altimetry (1993–2019),[7] and blue arrows show average land subsidence estimates from a variety of literature sources and instruments.[5,8–10] Note that subsidence within a delta is strongly variable and that contemporary rates may be (much) higher because data paucity on vertical land motion for many deltas likely leads to underestimation.

not generally effectively implemented in delta management, where the current fundamental theory is a piecemeal response to local expressions of environmental problems. SESs integrated with broader management plans that align with environmental systems and address the drivers of change rather than the symptoms remain underexplored in transdisciplinary contexts.

In this perspective, to derive practical and effective execution of SESs for delta sustainability, we first integrate knowledge across disciplines to examine pressing biophysical and societal barriers to successful SES implementation. We find that challenges to SES implementation are site specific and vary across biophysical and societal conditions. We show that thorough implementation of SESs can serve as a springboard toward sustainable deltas, which require integrated transdisciplinary science, governance, and reintegration of delta systems by combining expert insights and ongoing work to present transformative recommendations. We suggest a reconceptualization of deltas as interwoven biophysical and societal systems rather than static landscapes on which people operate.

Risk reduction through SESs

Deltas are, by nature, low-lying areas at the coast formed by the interplay of sediment, fluvial, and marine dynamics and are therefore intrinsically linked to sedimentation, erosion, flooding, and land-water level changes.[18] Natural delta systems exist because of the balance of flood-induced sedimentation raising the land surface, while natural sediment compaction reduces land elevation relative to local sea level.[19] Deltas' coastal location places them at the forefront to experience the negative effects of global SLR. In addition, deltas experience land subsidence[6,20,21] both from natural (e.g., natural compaction following delta evolution[19]) and anthropogenic sources (e.g., land use change[22] and extraction of groundwater and hydrocarbons[23–25]). Presently, human-accelerated subsidence in many deltas exceeds regional SLR rates,[5,26,27] considerably increasing the risk of temporary flooding and permanent inundation.

Despite these threats, deltas are hubs of human activity because of their flat fertile lands suitable for urban development as well as agri- and aquaculture, abundant groundwater and fossil fuel reserves, and easy access for shipping and trade. To sustain these activities, people require a degree of stability and protection from flooding. From a short-term perspective, most human activities favor the elimination of flooding, so hard engineering methods, such as dykes, tend to be implemented, which mostly prevent immediate flooding of deltas. These methods originate in historically prevalent human-versus-nature thinking. However, hard engineering impedes water and sediment connectivity within deltas; by preventing flooding, they also prevent sediment deposition on sinking land surfaces, often simultaneously causing channel infilling.[28–30] This disruption prevents "protected" land from gaining elevation, with rising surrounding water levels increasing the risk of flooding in these areas.[31,32]

Natural flood sedimentation is incompatible with current intensive human use of deltas; however, SESs enable sedimentation while simultaneously allowing other land uses. The main objective of SESs is to raise or create land through sedimentation on low-lying deltaic land or in shallow water, with the benefits of reducing flood risk, waterlogging, and salinization, and at the same time decreasing sediment concentrations in channels where high concentrations can damage ecology and engineering and hinder shipping. We categorize SESs as a subset of NbSs;

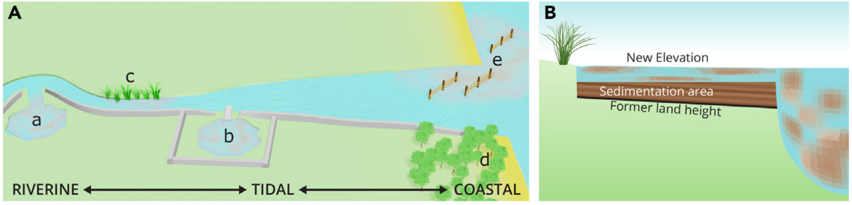

Figure 2. SES examples and process

(A) Plan view of common SESs, including intentional dike breaches (a) without and (b) with additional defenses, flood and vegetation management on (c) river and (d) coastal floodplains, and (e) engineering methods of encouraging sedimentation at coasts and riverbanks.

(B) Cross section of generic SESs where sediment-laden water is allowed onto a low-lying land surface, depositing sediment and raising the land height.

Panels are not to scale.

they are strategies that utilize natural processes for socio-environmental gain, but more specifically, SESs have the targeted aim of land raising in the face of RSLR. SESs use pre-existing sediment in the delta system and do not require sediment supplementation or deliberate sediment import by human actions. Sediment removal through sand mining and dredging has detrimental effects on sediment budgets[33] and morphology,[12] which can directly counteract the positive effects of SESs.

Sedimentation is primarily enhanced in SESs by enabling water to deposit sediment and creating favorable conditions for sedimentation by reducing water velocity with obstructions such as vegetation or permeable structures or through retention areas (Figure 2). When the water recedes, the deposited sediment remains on the flooded area, which over time results in raising of the land. Sediment deposition in deltas involves complex interwoven processes that are related to the type of sediment (e.g., sand or mud), the presence or absence of vegetation and resulting organic matter, and organisms (which can biostabilize or destabilize deposits). In many cases, vegetation can be particularly significant.[34–36] SESs harness existing processes and resources in deltas and therefore do not require additional sediment sources (e.g., sand mining or dredging sediment to create nourishment), enhancing their potential long-term sustainability. These approaches often imply temporary use of delta land, where sedimentation is encouraged for several months or years before other “dry” land uses, such as agriculture, are reintroduced.[37–39]

The first global review of existing SESs[16] identified 21 projects that fall into four categories: (1) river diversion, (2) tidal flooding, (3) sedimentation structures, and (4) vegetation planting. The projects range significantly in lifetime, from decades to centuries. Only 19% had the direct goal of trapping sediment for land raising (e.g., mid-Barataria and mid-Breton river diversions [Mississippi, US]), while the other 81% focused on water management or nature development, with sedimentation as a by-product (e.g., re-opened polders for water diversion in the Rhine delta [the Netherlands]). Many projects fall under large-scale initiatives, such as the Louisiana Coastal Master Plan or Dutch Delta Program, where sufficient funding and political will exist to pursue SESs.

Biophysical barriers to SESs

Sediment delivery and trapping

One of the primary requirements for implementing SESs is sediment availability. For many SESs, much sediment comes from river water.[40] Fluvial sediment loads are highly variable due to seasonal weather changes and trends in environmental conditions in the longer term, both of which need to be considered when planning SESs. Changes in fluvial sediment delivery to the delta may be due to climate change or other changes in river basins, such as deforestation, reservoirs, and other water resource engineering interventions. Many river basins around the world are experiencing decreases in sediment loads due to dam construction,[41] which is likely to continue in the coming decades.[1,42] A decrease in sediment delivery impacts the potential effectiveness of SESs because sediment trapping methods must be more effective or operational for longer to trap the same quantities of sediment.

Depending on SES type, the sediment required may also come from coastal waters. Sediment from coastal sources may originate from nearby rivers or resuspended coastal material that may also originally be fluvial.[43] Coastal sediment availability therefore depends on both recent and historical local fluvial sediment delivery as well as local coastal circulation, wave conditions and tidal regime. Quantifying coastal sediment delivery under varying tide and wave conditions, considering the effects of future SLR, is challenging.[14] For instance, SLR is predicted to change tidal asymmetry, propagation, and prism,[44] which, in turn, affect erosion and sedimentation trends. Both for fluvial and coastal sediment sources, sediment must be delivered through the delta channel system to the location where sediment is required. This transport depends on sediment distribution by the river channels over a delta, or the capacity of tidal channels to import sediment from coastal waters into the delta, and the subsequent transfer to the delta plain.

Trapping of sediment delivered to SESs depends on factors such as elevation and size of the site; location relative to the coast; tidal range; vegetation (if any); dimensions of any inflow, outflow, and internal channels; and the regulation of incoming and outgoing water and sediment fluxes.[45–47] Completing sediment budgets for SESs remains a challenge due to the many dynamic factors that determine sedimentation rates and, hence, potential success of SESs. Spatiotemporal variability and changing conditions are issues, where long-term trends in relevant variables such as sediment loads may change the viability of sites for SESs, unknown without continuous monitoring. Environmental changes are also caused by SESs, such as the increased demand for sediment and, therefore, competition with other sediment users (e.g., natural ecosystems or other SESs[30]) or sinks (e.g., coastal erosion feeding vertical accretion[48]).

Sedimentation, land elevation, and RSLR

The key purpose of SESs is to counterbalance RSLR by locally increasing sedimentation and raising elevation. Ideally, SESs would allow an area to keep up with RSLR or even build relative elevation. For example, in Vietnamese coastal mangroves, high sedimentation rates (33–75 mm/year) exceed local compaction-dominated RSLR (13–49 mm/year).[49] Cox et al.[16] reported that 79% of 21 reviewed SESs can

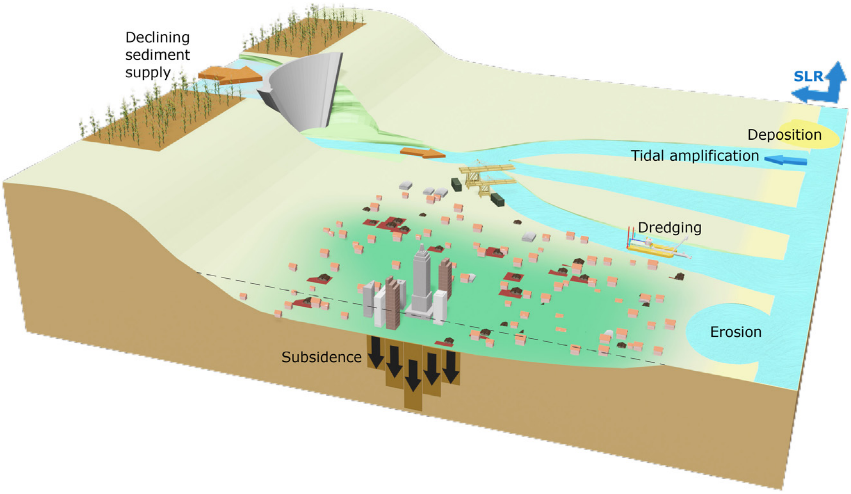

Figure 3. Physical challenges for the implementation of SESs
These include reduced fluvial sediment delivery; spatially variable rates of erosion, deposition, and coastal sediment delivery; compaction, decomposition, subsidence, and SLR. Brown arrows show sediment fluxes.

counteract even the highest global SLR rates, vertical land motion excluded. However, the effectiveness of SESs in building elevation is determined by three components that are each spatiotemporally variable: local accretion (see Sediment delivery and trapping), climate change-induced SLR, and vertical land motion (i.e., subsidence when negative). While future SLR exhibits considerable uncertainty, depending on future global warming and ice sheet responses, particularly after 2050, sea level projections are increasingly well constrained at regional and local levels.[50,51]

Vertical land motion encompasses all processes in the subsurface that cause a land surface to change elevation. In coastal-deltaic zones, many different processes happen cumulatively at different depths in the subsurface.[6,20] This includes natural processes, such as tectonics and isostacy, acting on longer timescales at slow rates[52] and sediment consolidation on shorter timescales with higher rates.[19,53] In addition, human activities can enhance natural processes (for instance, increased compaction following land use change, surface loading, and peat oxidation following drainage[22,54,55]) but also induce new processes, like extraction-induced aquifer system compaction[26,56,57] or hydrocarbon reservoir compaction.[58] *A priori* understanding and quantifying local SLR and vertical land motion dynamics is crucial for evaluating SES feasibility and effectiveness before implementation. In the case of high subsidence rates, SESs alone may be insufficient to overcome the high RSLR rates (e.g., the mangrove restoration project in Demak, Indonesia[59]) and may only be successful when combined with effective mitigation measures to reduce land subsidence to manageable rates.

Sediment deposition and compaction are intrinsically connected,[19] and when an SES is implemented, the weight of new sediment will cause underlying deposits to compact,[60] as also demonstrated under natural conditions by loading tests in Venice lagoon marshes.[61] Additionally, new SES-deposited sediments also compact under their own load, consequently reducing the initial elevation gain achieved immediately after SES implementation. The experiments in the Venice Lagoon also revealed spatial heterogeneity in compaction potential of subsurface sediments, which highlights the importance of understanding local geology and subsurface conditions prior to implementing SES as well as accounting for post-depositional compaction.[61] A new generation of numerical models that integrate sedimentation dynamics with hydrogeomechanical subsurface processes are able to numerically resolve these processes.[62,63] Such numerical advances provide promising future applications to compute and project SES sedimentation-compaction dynamics.

Dealing with spatially and temporally variable sedimentation and RSLR (Figure 3) requires a systems approach that incorporates the 3D nature of the processes involved. Often only a single dimension is considered; for example, a vertical change in sea level (in meters).[64] This simplification omits crucial internal 3D dynamics that need to be considered. To evaluate the 3D dynamics, accommodation space provides a useful concept referring to the 3D space (in square meters) in which sedimentation can occur.[65] Accommodation space for sediment is created by RSLR, which encourages fluvial sediment deposition at the coast.[66] Sedimentation potential is therefore influenced by RSLR rates, which may also have other effects on sedimentation; for instance, by changing hydrodynamics and vegetation composition, which, in turn, change sediment trapping efficiency.[67,68] Coastal marshes also have the potential to collapse at high rates of RSLR.[69]

The current limited understanding of biophysical boundary conditions and processes under changing and extreme climate conditions is causing uncertainties in prediction of long-term SES effectiveness. Reducing these uncertainties through research will provide a basis for policymakers to steer away from "proven" but, in the long run, ineffective business-as-usual strategies and pave the way toward embedding SESs in regulation and laws.

Societal barriers to SES implementation

Socioeconomic issues

The cost and benefits of SESs are often not well determined, in particular when upscaling. SESs do not fit to traditional cost-benefit analyses; development and maintenance costs may be uncertain, the diverse societal and environmental benefits (e.g., land elevation) they provide are undervalued, and private parties have different (often short) time horizons of desired return of investment.

In densely populated and intensely developed deltas, land that is available and suitable for production is typically already in use.[8,70] This scarcity of land available for SESs means that trade-offs are inevitable between currently productive and temporarily economically non-productive land uses. For example, during land flooding for SESs, and for a period afterward, traditional farming will be disrupted, and there may be tension between the SESs and food production and maintenance of livelihoods. Certain crops tolerant to, or even dependent upon, flooding (e.g., rice) may remain compatible with SESs but others will not. Similarly, areas developed with housing and infrastructure (e.g., roads and rail) cannot be intentionally flooded to deliver sediment because of inevitable damage and disruption. Thus, there is an inherent tension between SESs and many existing human land uses. In deltas where land is not fully occupied by human activities but that still need sustainable management, there is likely more space available for sedimentation; such deltas are also more likely to be ‘‘living’’ as opposed to ‘‘locked in’’[70] and thus may have less need for SESs because natural delta processes still occur, at least in part.

Tensions and trade-offs are also inevitable between SESs and economic uses of river channels. For example, channel dredging and construction of weirs and locks for navigation and dams for hydropower or irrigation affect sediment fluxes through the river system, and river sand mining directly deprives the feeding river of sediment. Such activities limit the capacity to implement SESs because of conflicting economic interests over sediment management. While SESs may be relatively low-cost adaptation strategies compared with, for example, construction and maintenance of hard infrastructure,[71] finance is still required. Costs involved in SESs may include compensation for lost earnings of land users, engineering or construction costs for infrastructure (e.g., sluice gates) required to implement and operate SESs, or funds for monitoring sedimentation during and after operation. NbSs are known to be underfinanced relative to the benefits they can bring,[72] with a potential lack of funding instruments compared with hard infrastructure funding schemes. Finding investment incentives for SESs within the constraints of short-term growth-based economies is a key challenge that must be overcome.[73]

Lack of societal acceptance is another potential barrier to SES success. Societal trust in SESs (that they will successfully achieve their goals and protect diverse local interests) is likely to be a decisive factor in whether an SES is supported by local communities, thereby affecting their chance of success.[38] However, research on trust in SESs, and NbSs in general, is currently limited and has focused more on whether investors trust and are willing to invest in the solutions.[72] Related to societal acceptance is the potential risk of an unintended ‘‘neo-colonialism’’ effect, despite traditional management often including SESs,[38] experienced by local inhabitants of developing deltas when foreign academics and experts come up with long-term sustainability plans for deltas and the need for SESs while the inhabitants already are struggling with short-term issues of, for example, income, safety, and equity.[74]

Governance barriers

Barriers related to the governance of SESs revolve around the collective action problems. The first and the most challenging barrier is to define common problems and priorities to act upon, which requires navigating conflicting interests and agendas. For SESs, RSLR is one of the main problems; however, not all stakeholders, especially policymakers, perceive it as an urgent priority. In the case of developing countries, for example, the coastal urban development sector is still the main priority due to high impact on economic growth, with (un)intended consequence for rural areas. For example, one SES-related project in Semarang-Demak[75] saw the combination of natural coastal processes and the impact of coastal development increase erosion of the adjacent rural area of Demak, which caused coastal flooding and inundation. To deal with this issue, an SES was introduced that, to some extent, helped solve short-term localized problems. However, a remaining issue is the lack of agreement on the root cause of problem, leading to conflict regarding what should be dealt with first to ensure that problems are solved at the system level.

The second challenge is to coordinate and develop coherent and interactive policies across scales and administrative boundaries. Current structures of knowledge, governance, and finance are typically organized in a sectorial way, which hampers realization of integrated SESs, where many different sectors come together. Planning and implementing SESs, particularly river sediment fluxes, requires transboundary coordination that applies at the whole catchment scale, which is the key link between governance and physical aspects of SESs. Fluvial sediment changes are not necessarily under the control of one jurisdiction, which makes it difficult to address when activities upstream cause issues for societies downstream; e.g., when upstream dams disrupt sediment delivery, which downstream deltas rely on for geomorphological and ecosystem functioning.

Last, governance capacity to implement SESs is lacking in many places. Governance capacity relates to the capacity to acquire and understand knowledge about problems and solutions and institutional and financial capacities required to plan, implement, and continually manage SESs. Some SES approaches can be considered new interventions, often using the latest technological innovations, which may require new governance capacities that do not already exist, posing potential barriers for their implementation.

Legal embedding

Law can be understood as a body of rules or customs that are recognized by a country or community for shaping social behaviors, enforced through its authorities.[76] Common legal barriers to SES implementation comprise (1) a lack of substantive rules applicable for regulating sedimentation activities and their impacts; (2) a lack of legal objectives or principles that safeguard the balancing of interests between actors, the protection of fundamental rights to enjoy a healthy environment, and conflict resolution; and (3) unclear procedural responsibilities allocated to different departments, sectors, and actors for policy- and decision-making processes and whole-process monitoring mechanisms for sedimentation activities. Depending on the location of SES activities, both domestic laws and bilateral/multilateral agreements can be relevant.

The implementation of SESs requires domestic legal norms and mechanisms in one jurisdiction or bilateral/multilateral agreements in a region (e.g., a transboundary river basin) to deal with potential adverse impacts of sediment delivery on humans' water uses and land uses in costal and deltaic regions and to resolve water use conflicts between upstream and downstream countries. Basically, the legal framework for SESs should at least cover water use and flood control, agriculture, land tenure and uses, and ecosystem conservation, possibly integrating sediment management in river basin management planning (e.g., through the European Union [EU] Water Framework Directive). A typical example of possible legal issues associated with re-allowing sedimentation on land relates to land tenure and land use regulation. Land tenure systems define how property rights to land are allocated within societies, and the main rules include the rights to use, control, and transfer land.[77] Based on the constitution and land law of a jurisdiction, land tenure rules may vary greatly.[78] For privately owned lands, because the operationalization of SESs possibly removes land parcel boundaries, effective land administration and registration for clear delimitation of land parcel boundaries is a precondition for the security of tenure and consequently influences social acceptance of SESs. The situation becomes more complicated when the proposed retention area requires relocating residents or disturbs existing habitats.[79] The availability and appropriateness of compensation mechanisms for impacted people and areas play a vital role in SES success. In a transboundary context, the promotion of SESs particularly needs bilateral or multilateral agreements on upstream river dams, which is not a special challenge for SESs but, rather, a conventional dispute between upstream and downstream countries.[80]

Second, regarding legal objectives or principles, the common legal barrier relates to a lack of recognition of distributive justice for balancing benefits and conflicts arising from SESs. Not surprisingly, seeing the potential sedimentation locations, poor people, mono-livelihoods, and vulnerable habitats are more likely to be exposed to SES activities and are also most sensitive to ecological and socioeconomic disturbances caused by SESs. Typically, law fails to incorporate SESs when liability and compensation mechanisms are unclear in response to different types of loss and damage resulting from controlled flooding.

Third, from the perspective of procedural law, the proper arrangement of departmental coordination and public engagement is a shared challenge with the governance perspective as stated above. Because SESs are still emerging solutions in delta management, procedural obligations to proceed environmental impact assessments for SES projects and to monitor the whole process of sedimentation activities, including the selection of sedimentation areas, determining sediment loads, and monitoring elevation changes and environmental impacts, are yet to be incorporated into the legal framework for SESs.

Solutions for effective SESs

Various solutions have been proposed for the different challenges that large-scale implementation of SESs are facing, but new solutions are still needed. Box 1 presents key lessons from previous SES examples. In this section, we propose solutions and their potential feasibility and argue that these together should be considered in an interdisciplinary systems approach.

Enhancing biophysical effectiveness of SES

At a basin scale, sediment connectivity and uninterrupted sediment transport are required for several SESs to be effective long term. For some deltas, investigating sediment flux restoration at the basin scale may be necessary. For instance, dam removal and sediment bypassing are often suggested as methods to increase fluvial sediment loads due to the severe impact that dam construction can have on fluvial sediment fluxes.[92–94] In recent years, various examples of dam removal and their effect on source-to-sink sediment transfer have been reported.[95,96] Similarly, re-naturalization of delta channels and river sediment connectivity are required for effective SESs due to the legacy of channel engineering (straightening and deepening) for navigation-altering sediment transport regimes, delta sediment delivery, and sediment exchange with surrounding plains.[97,98] Alternatively, controlled diversion of water and sediment over the delta plain may be used to similar effect through new[99] or existing[100] channel networks.

Before SES implementation, assessments must occur to determine ideal SES locations, considering their variable requirements.[37,47] The location should also provide optimal conditions for desired benefits (e.g., flood storage, ecological concerns, and countering RLSR). SES design should maximally support sediment trapping.[45,101] Measurements of biophysical dynamics are therefore required, including assessments of potential future changes in, for instance, elevation, local SLR, vertical land motion rates, sediment transport, river discharge, and tides. Hydromechanical modeling of SES implementation scenarios will yield insights into potential changes in elevation during and after implementation. Small-scale pilot projects can also be implemented for monitoring of dynamics and processes.

To improve knowledge of relevant fluxes and development of nature-based measures, high-frequency monitoring and increased model accuracy are necessary. While variable conditions may be understood with thorough monitoring, it is not feasible to expect inter- and intra-annual monitoring of every relevant variable at each site where SESs are considered. The exact conditions that determine the effectiveness of SESs in each location are rarely known in full before SESs are planned and implemented due to both minimal monitoring and variable or changing conditions. However, having a full understanding of conditions is not necessary when SESs are implemented under an adaptive management approach, which emphasizes experimentation and learning through monitoring and adjustment as interventions proceed.[102,103]

During SES operation, spatial variation in sedimentation rates must be measured and reported, including additionally monitoring sediment concentrations, erosion, and deposition in adjacent channels. If sediment flux is no longer reliable in a particular location, then some SESs may be relocated or terminated to allow new land use development in the previous SES area. SESs are relevant for all deltas globally, and regularly publishing these measurements, including reflections, caveats, and discussions, will help to assess the strategies' effectiveness elsewhere. After SESs are terminated, it is important to continue monitoring changes in elevation and other parameters. In some cases, SESs may be restarted if significant land loss occurs.

Enabling SESs to cover larger delta areas or assisting SES implementation elsewhere requires a combination of the above factors: initial assessment of ideal locations, sedimentation patterns, and rates and post-SES assessment of physical changes, including comparison with other projects. Building knowledge by gathering this kind of detailed information on SESs will grow our understanding and enable identification of optimal, site-specific SESs to achieve their intended goals. However, conditions in specific locations in a delta will change over time and, therefore, their suitability for a specific SES may also change. Therefore, considering large-scale application of SESs in a delta,

Box 1. 10 lessons learnt from implemented SESs to enable successful future implementations

(1) Consider current delta dynamics. Sediment in the southwest Bengal delta branches comes via the sea, previously delivered by the Ganges to its mouth. Upstream connections between channels in the southwest delta and the Ganges have been nearly closed.[81]

(2) Monitor local factors, including land subsidence, slope, vegetation cover, and annual sediment delivery. High rates of accelerated land subsidence may render SESs ineffective as single measure[59] and should be combined simultaneously with subsidence mitigation measures. Sedimentation varies within an SES, as was found in the Mississippi and elsewhere.[47,82]

(3) Plan for extreme events. A high-discharge storm event breached dikes in Bangladesh and resulted in the deposition of large volumes of sediment inside polders.[31] High-discharge events can represent up to 70% of total annual sediment loads, particularly in systems with relatively low sediment concentrations; e.g., the Rhine.[83]

(4) Pilot studies improve success rates. In the Ems Dollard, three projects were designed, researched, and piloted in discussion with stakeholders, which was very effective in finding potential issues before implementation.[84]

(5) Use existing local practices. Tidal river management strategies in the lower Ganges delta include temporary re-opening of tidal delta polders to enhance sedimentation and prevent sediment clogging of the delta channels.[37]

(6) Stakeholder engagement is crucial for success. In Bangladesh, SESs were initially locally driven, using local knowledge to great success. When later action was taken by the government, sedimentation rates were lower, and there was conflict between stakeholders.[38] In Shanghai, vegetation planting for an SES was implemented without input from local stakeholders, resulting in an invasive plant species damaging local ecology and requiring expensive removal.[85]

(7) Institutional cooperation is vital. Many projects are government led, involving research institutions and universities or conglomerates of several organizations (e.g., Canal del Dique, Colombia[86]) but led by Global North institutions. A balance between local actors, national actors, and international actors is key. The Mekong River Commission is an example of river basin commissions as collaborative platforms,[87] and the Vlaams-Nederlandse Scheldecommissie also includes formal representation of local community organisations.[88]

(8) Integrated governance strategies are needed. Bottom-up initiatives increase ownership of strategies and social resilience, whereas top-down approaches in the form of coordinated interventions improve integrated coastal zone management. This was observed in Indonesia, where SESs involving mangroves with permeable dikes needed a combination of bottom-up and top-down approaches.[75,89]

(9) Take local history into account. Local farmers at the Flemish-Dutch border protested a plan to reconnect a polder to the Scheldt estuary.[90] The area had a long tradition of protecting agricultural land from the sea, and locals viewed the project as "giving up" land. Many also remembered the catastrophic 1953 flood. This "U turn" in flood protection and land management policy took decades before the project was implemented.

(10) Delta management plans are essential. Many of the recommendations here may be addressed by thorough and effective integrated delta management planning. The coastal Master Plan for the Mississippi[91] is currently one of the most far-reaching in its inclusion of SESs and consideration of other NbSs.

tailor-made patchwork or mosaic landscapes of different, site-specific SESs will likely be more successful than simply making a single large SES.

Realizing societal solutions

The socioeconomic, governance, and legal barriers to successful SESs are intertwined and, thus, require solutions spanning these domains of society. Barriers within each of the three domains can be distilled into three main types that interact and require solutions in four main contexts (Figure 4). The socioeconomic barriers are, broadly, (A) tension between SESs and economic uses of deltas, (B) necessity and scarcity of funding, and (C) limited local trust and acceptance of SESs. The governance concerns are (D) the collective action problems, (E) policy coherence and coordination, and (F) governance capacity. The legal issues to address are (G) substantive rules, (H) normative principles, and (I) procedural responsibilities. The four non-mutually exclusive tasks across which these barriers interact and solutions are required, elaborated below, are to (1) clarify and strengthen rights, procedures, and conflict resolution; (2) improve policy coherence and institutional fit; (3) take a broader perspective of costs and benefits and improve governance capacity; and (4) achieve societal inclusion and acceptance.

Rights, procedures, and conflict resolution

Resolving tensions between SESs, competing interests, and resource use rights in deltas requires cooperative resource use planning. To mediate land use conflicts, maintenance of food production and land-based livelihoods can be cooperatively planned and managed before and during operation of SESs. For example, SESs can be implemented in rotation, where alternating polders are temporarily opened for sediment deposition.[104] This process should aim for equitable adaptation planning based on fairness among stakeholders and sectors, not on regional economic or ecological optimization only.[105] Uncertainty and unexpected outcomes of SES interventions in complex delta systems can be handled through adaptive management[102,106] and other approaches for dealing with complexity.[107] Sectoral innovations can also play a role in mediating resource use conflicts. For example, technological improvements in ship design and shipping efficiency on rivers could reduce the need for interventions such as dredging and groynes to maintain navigable channels, which can constrain SES potential. Alternative construction materials (e.g., wood) to reduce demand on river sand for concrete could also alleviate resource conflicts. In cases where livelihoods are disrupted or

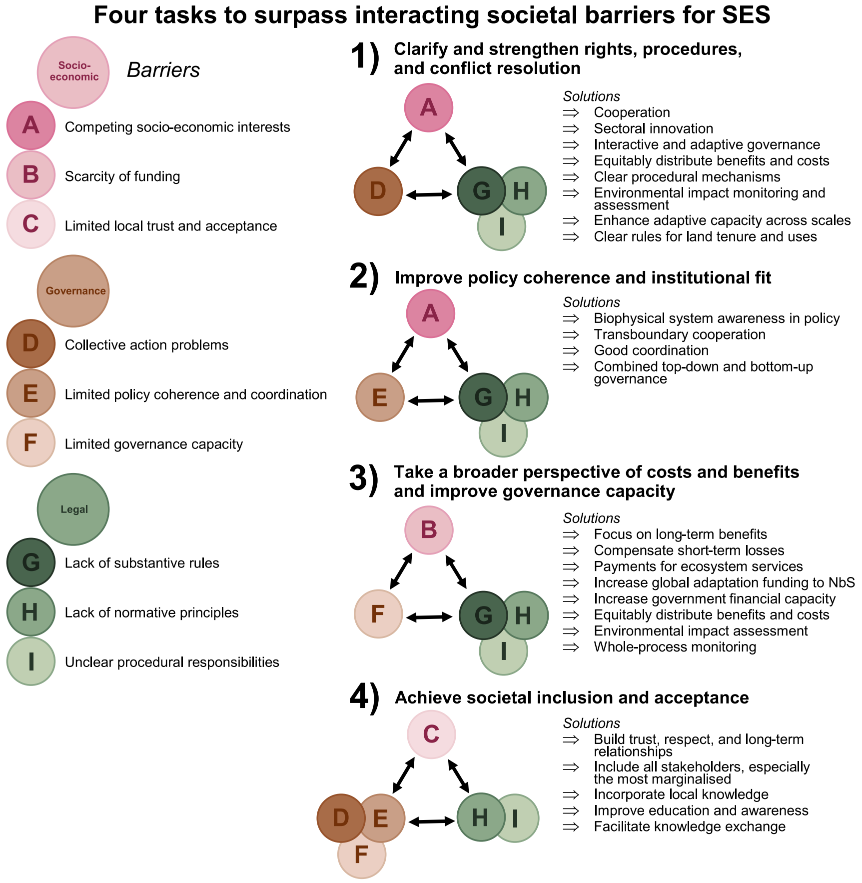

Figure 4. Four tasks to surpass interacting societal barriers for SESs
These comprise socioeconomic, governance, and legal aspects with shared barriers and individual solutions.

lost, alternative opportunities should be created, and procedures should be in place to manage just transitions.

The core legal enabler relates to the successful legal responses to the potential adverse impacts of SESs. First, the selection of SES locations may cause conflicts. Thus, it is crucial that the legal values of equity in the distribution of benefits and costs between the positively and negatively affected groups and regions are embedded in relevant legal frameworks because they safeguard the broad acceptance and long-term success of SESs. The relevant legal framework should explicitly address normative considerations, in particular distributive justice.[105,108] A more radical approach could be to reconnect human-nature relationships, which requires humans to go beyond anthropocentrism and recognize the rights of nature.[109–112] Such a rights-based approach could bring added value to SES implementation by empowering local governments, communities, and Indigenous peoples who are the representatives or guardians of, for example, a river in the decision-making process.

Second, regardless of the legal status of private, communal, or state lands, clear procedural mechanisms for assessing and permitting controlled flooding are needed because the (seasonal) change of land use purposes from agriculture to flood retention impacts livelihoods in retention areas.[113,114] A permit for such (seasonal) land use change requires balancing short-term loss of yields versus long-term benefits of SESs.[115] Third, relevant laws (not necessarily directly addressing SESs) also need to systemically enhance the adaptive capacity of individuals, households, communities, and institutions at different scales, enabling the development of diversified livelihoods and establishing liability and compensation mechanisms for different types of loss and damage. More recently, enabling laws also broadly include policies that facilitate climate adaptation and coastal restoration via NbSs.[116]

Policy coherence and institutional fit

Surpassing barriers related to lack of coordination and policy coherence requires improving vertical and horizontal coherence and fit. The first concern is the fit of institutions to the natural systems for which they are responsible.[117] National boundaries rarely consider hydro-, eco-, or geomorphological systems, although they are interdependent, and many major river basins that drain to delta systems span multiple national boundaries. Effective management of these vital physical systems therefore often requires cooperation across socially constructed boundaries. Functional SESs and other NbSs require identification of the essential biophysical and societal systems and the appropriate scales at which cooperation is necessary for effective functioning of management solutions. At the local level, a holistic understanding is required of hydraulics, sediment deposition, and RSLR in conjunction with land use, property rights, and infrastructure systems. Local implementation of SESs must be situated within broader economic and sustainable development goals that may be pursued by upstream basin states (e.g., hydropower for renewable energy), and the associated trade-offs must be illuminated and negotiated.[42,118] At the basin level, particularly in international river basins, understanding and awareness are required of how upstream land use and dams affect sediment transport through the basin[1,41,42] and, thus, delivery to the site of an SES. The processes required for transboundary cooperations to function, with free communication and flow of information, require focused attention on sovereignty, national self-interest, international politics, and governance of the global commons.[119,120]

Good coordination is important in enabling SESs as they deal with transboundary, interconnected natural systems (deltas and coastal areas) across jurisdictions. A pre-requisite for effective coordination is a working governance mode. In most contexts, a combination of top-down or hierarchical mode and bottom-up mode works. These situations require careful consideration of the costs and benefits of both upstream and downstream activities as well as negotiation and compromise. Effective coordination will enable development of interactive policies, which is defined as processes where multiple parties are actively part of joint decision-making.[121] This will involve clarified division of labor between each party involved and conducive early-stage participation, stability, and transparency.[122] Similar mechanisms with the same purpose could be translated as well at the national and subnational levels. In cases where transboundary institutions are missing, new forms of institutional structure are sometimes needed. The Mekong River Commission (Box 1) is an example of a regional institution improving fit of stakeholder interests and increasing coordination and capacity to deal with existing and future problems through innovation such as SESs. The commission has a long-standing influence in bringing Mekong River nations together to frame both problems and solutions that could be taken into consideration by the members, including countries, ministries, and agencies, involving local community organizations.

Costs, benefits, and improving governance capacity

Finding the balance between costs and benefits is the economic crux of any adaptation problem. Short-term myopic thinking about the economic costs of SESs must be put in the context of broader considerations across spatial and temporal scales and among actors. Temporary economic losses must be considered relative to long-term gains in ecosystem services and avoided losses and damage that are provided by SESs.[123] Research has shown that short-term costs of climate change mitigation are far outweighed by avoided losses and damage from national to global scales,[124] and the benefits of mangrove protection and restoration in particular are up to 10 times the cost.[72] At the same time, benefits of SESs (and adaptation strategies in general) that cannot be easily quantified and monetized are likely to be obscured in decision making, which can introduce socially constructed limits to adaptation.[125] The view of deliberately flooding land for sedimentation as an "unproductive" use and a "loss" of potential income should be reframed to see SESs as public goods providing vast future benefits; e.g., in the case of some types of traditional rice paddy agriculture. Such a shift involves rethinking values from private and monetary terms to broader ecological, landscape, and cultural values and benefits provided by SESs. More research into such non-economic values and benefits of SESs is required.

Still, actors face present economic realities, so compensation for lost earnings or inconvenience is required, which could also help to manage societal acceptance, as evidenced for the development of wind farms.[126] In some cases, new business models or livelihoods might be found (e.g., based on adapted types of agriculture, such as mixed mangrove-shrimp cultures) or other uses that may have direct economic benefits (water storage and tourism). A useful model for compensation may be payments for ecosystem services,[127] where payments are made for intermittent flooding that provides the supporting services of sedimentation and land elevation. Traditionally, financial instruments for adaptation and risk management include solidarity funds (national and international), savings and credit, and insurance.[128] Of these, solidarity funds and government savings and credit (state budgets) are the most relevant for SES implementation and associated payments for ecosystem services. The United Nations Framework Convention on Climate Change solidarity funds for climate change adaptation are the Global Environment Facility, Green Climate Fund, and Adaptation Fund. Gray infrastructure projects still receive the vast majority of this funding,[72] so more must be directed to NbSs such as SESs. Private sector investment could also play a role in financing SESs under an equity model to share risk[65,72] and lower investment hesitancy coming from uncertainty about what returns might look like.

Last, and connected to economic capacity, is the drive to improve governance capacity to plan, implement, and monitor SESs. This will require appropriate technical knowledge not only by experts (scientists, engineering companies, or consultancies) but also relevant governmental and non-governmental stakeholders (non-governmental organizations and funding agencies). In the case of developing countries, this is especially important to enforce at the local level, where governance capacity is generally low.

Achieving societal inclusion and acceptance

Building inclusive environments of trust and respect and valuable long-term relationships among stakeholders is central to building societal acceptance and ownership of SESs,thereby increasing chances of success, as for other NbSs.[129] An important condition for successful SESs is stakeholder engagement and inclusivity, linking to the question of who should be involved, when (at what stage), and how.[130] From a legal perspective, inclusive participation and decision-making for SES strategies can be ensured by relevant procedural rules embedded in, among others, laws on land uses, flood control, and ecosystem conservation.

Participatory governance to encourage positive societal integration of SESs is enabled by specific knowledge of stakeholders and other governance actors. In some deltas, such as the Bengal delta in Bangladesh, there is already abundant local knowledge on working with nature because there are often no means to choose more expensive hard engineering measures, not because people have chosen to do so for long-term sustainability reasons (Box 1). This means that, in the design and development phase of SESs, local interests, perspectives, and knowledge should be taken into account.

SESs as a springboard toward sustainable deltas

SESs present an opportunity to springboard transformation to sustainable deltas. Such a transformation requires an understanding of deltas as complex adaptive systems in which biophysical and societal components (e.g., sediment, vegetation, people, and infrastructure) and processes (e.g., SLR, subsidence, erosion, flooding, farming, and trade) interact and evolve over time and across spatial and temporal scales to shape and reshape the landscape and all that occurs within it. SESs involve intervening in these components and processes, so their interactions and feedback must be considered in integrated ways across multiple scales. Moreover, SESs can be seen as an opportunity for just and inclusive transformation, embodying the shift toward understanding and dealing with change in deltas as complex adaptive systems that transcend current disciplinary and institutional boundaries.

The implementation of SESs must work within hard physical limits, but the current state of physical systems does not necessarily exemplify these limits. The delivery of sediment must be assured and can be adjusted through national and international actions,[131,132] including reservoir management focused on sediment bypassing and other sediment management

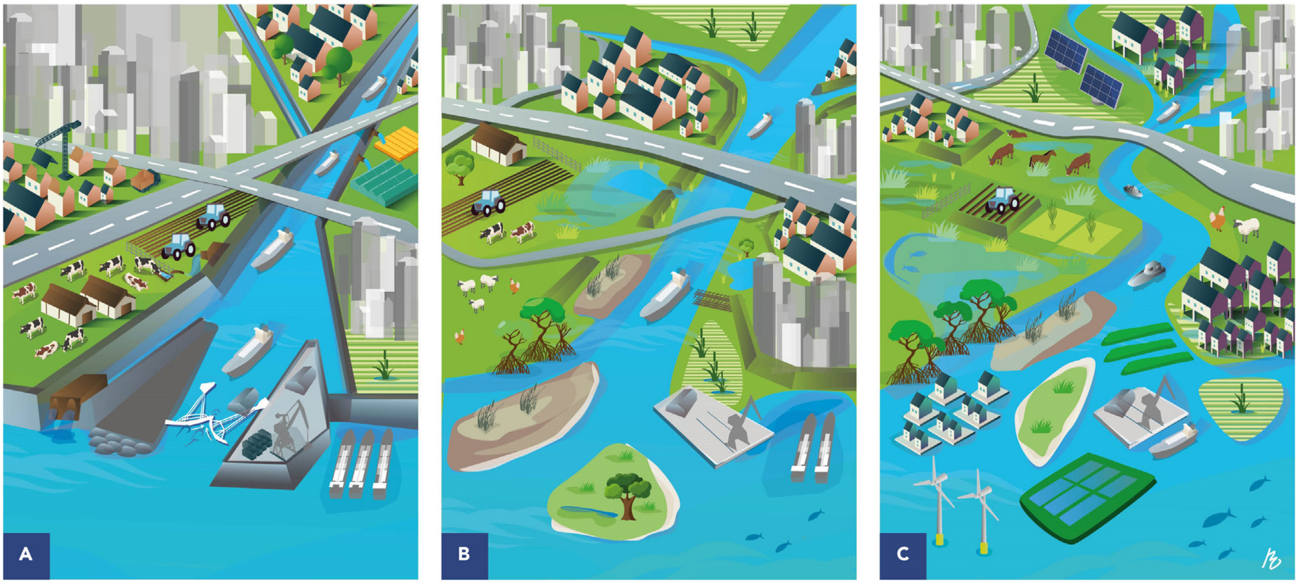

Figure 5. Continuum of the results of coastal river delta management

Illustrated are the degrees of SES implementation, from a closed traditionally intensive management strategy (A) to an open, radically integrated management strategy (C).

(A) Defensive: hard/classic engineering such as fixed (non-erodible) dikes, storm surge barriers, and sea walls; low-lying protected polders containing urban areas, infrastructure, and intensive land agriculture; groundwater, oil, and gas extraction; land drainage and increasing costs due to RSLR; channelization; straightened and maintained waterways.

(B) Current paradigm best practice: integration of soft engineering and natural protection such as vegetation, dunes, and temporary sedimentation polders; some hard engineering to protect infrastructure; some natural protection (sediment and vegetation); low dikes with sluices enabling water-land connection; some rivers reconnected to floodplains; previous points enabling some wetland restoration; some hard engineering to protect infrastructure; less intensive and hybrid agriculture; some rivers reconnected to floodplains.

(C) Fundamental change: large-scale land-water connection, coasts and rivers free to migrate, full sediment connectivity; space for ecosystems through managed realignment; adapted cities with raised infrastructure and repositionable and floating structures; more frequent land cover change to accommodate SESs; aquaculture, floating farms, extensive and hybrid agriculture, and rotational farming and flooding; new modes of land use governance, products and production systems, business models, and sustainable resource management.

techniques.[133,134] Where river sediment cannot be made sufficient for SESs, other sediment inputs should be considered, including from coastal areas.[37] The available sediment must be distributed to where it is needed within deltas, considering channel capacity to convey sediment and the potential to reserve land for SESs. The implementation of SESs would benefit a change in mindset to consider delta elevation and sedimentation as common goods, including consideration of the balance of short- and long-term costs and benefits. For instance, river sediment mining provides short-term economic gains but long-term costs to all systems, and so strict regulation is necessary to ensure long-term sustainability, including SESs. The actions that can be taken to maximize basin sediment connectivity can have far-reaching benefits for society and ecosystems, such as water and nutrient distribution.

While physical capacities for SESs can be maximized, societal systems must also enable SES implementation. International sediment monitoring and management systems are required at the catchment scale to ensure sediment delivery to deltas.[135] Transdisciplinary approaches that spatially align to natural system boundaries are needed to fully grasp the complex and transboundary nature of delta systems and their interconnected problems. Transdisciplinary approaches in this context start with the integration of knowledge across disciplines (interdisciplinary) as well as across stakeholders, including policy actors, local communities, and non-governmental organizations, to generate mutual benefit.[136–138] This integration will increase the legitimacy of SESs and the quality of inclusion and participation,[139] especially in the policymaking arena. Local legitimacy and inclusion are important because SESs are implemented locally, and their direct impacts are also at the local level. To effectively implement such strategies, it is important to consider diversity of contexts and interests at the planning phase. Inclusive decision-making and trust-building, which can be built through transdisciplinary approaches,[140] are essential for successful SES implementation.

Knowledge sharing is crucial; for instance, farmers need to be equipped with knowledge of the benefits of sedimentation through regular inundation (e.g., elevation gain and nutrient delivery) as well as how they can diversify production and maintain their livelihoods alongside SESs. Diversifying livelihoods, encouraging hybrid farming, and modifying land use restrictions must happen without sacrificing food security and rural livelihoods. Similarly, rethinking delta cities and other human infrastructure requires cross-cultural imagination and experimentation because modern cities are unable to effectively coexist with delta maintenance processes such as flood sedimentation.[141] Flooding in cities is undesirable within the current paradigm due to economic and other losses, and sedimentation for elevation gain is impossible due to the maintenance of permanent infrastructure and impermeable surfaces, although renewal of infrastructure provides opportunities. Crucially, SESs are not the opposite of engineering but need new, flexible engineering for more dynamic and integrated management of water and sediment in deltas.[142] Any rethink requires innovation and investment in appropriate engineering to ensure the sustainability of the built environment, whether it is to grow with rising land levels or to be de- and re-constructed in time and space, enabling sustainability and avoiding waste.

Part of the transdisciplinary approach includes integration of these topics into ''delta management plans'' which can often bridge natural systems with institutional fit and include stakeholders with varying interests. In most cases, these plans are designed to outline proposed adaptation plans (either maintenance or new programs) and estimate cost and budget and, in some cases, the ecological impact of strategies. Many major deltas, including the Rhine-Meuse (the Netherlands), Mississippi (US), Ganges-Brahmaputra-Meghna (Bangladesh), and Mekong (Vietnam), have devised delta plans but with vastly different content, goals, and degree of transdisciplinarity (Box 1). These plans, to varying degrees, attempt to focus on long-term strategic planning for deltas.[143] Seeing SESs as an emerging method not yet widely understood by policy makers, law can contribute to integrating SESs into various planning processes. The proposed EU Nature Restoration Law provides a new opportunity for integrating natural sedimentation processes into national restoration plans.[144] The recent legal and policy development for a climate-resilient and sustainable Vietnamese Mekong delta illustrates such an enabling environment under the guidance of the Vietnamese Law on Planning, the new Mekong River Delta Master Plan, and other relevant climate policies.[145] Many follow the original Dutch model of delta planning,[146] and, as a result, many delta plans rely on classic hard engineering strategies[147] based on the 1950s Dutch delta plan (Figure 5, 1). While some delta plans (e.g., Mississippi[91]) attempt to integrate SESs, they are still not widely considered for large-scale adaptation in deltas around the world. Different frameworks and assessments have been proposed to optimize delta plans' effectiveness, determining that they should be (1) focused on actors, (2) include innovative solutions, and (3) include participatory planning tools.[148]

Reconnecting societal development with delta biophysical processes (as opposed to controlling and suppressing the latter) via SESs presents an opportunity to foster delta resilience (i.e., the capacity of a system to absorb, adapt, and sustain development in the face of change[149]), which is central to a transformation to sustainable deltas (see also Elmqvist et al.[150] regarding sustainable cities). In complex adaptive socioecological systems such as deltas, societal development should not be divorced from biophysical processes, particularly geomorphological processes in deltas.[151] However, many of the world's deltas have become locked into a heavily modified artificial state where biophysical and societal processes are disconnected and resistance strategies for flood protection, such as hard engineering measures, have been adopted (Figure 5).[70,152] This disconnection and lock-in leads to a loss of resilience and may also become more expensive to achieve and maintain.[153] Command and control of delta processes via hard infrastructure may be highly effective to pursue a small set of goals; e.g., flood protection and agricultural production, but when external changes such as SLR render the narrow optimization of the system untenable, such locked-in systems are difficult to transform. Thus, restoring dynamic interactions between biophysical and societal processes in deltas through SESs provides added benefits in terms of future resilience of delta socioecological systems.[154]

Sustainable deltas and SESs should be considered within a broader push for systemic transformations to sustainability.[155] Actions promoting SESs can be considered ''leverage points,''[156] particularly transforming structures and rules of current delta agricultural and urban systems as well as their goals and the paradigms upon which they have been constructed. Rethinking delta agriculture and cities to accommodate SESs also aligns with leverage points for sustainability transformation to reconnect people to nature, restructure institutions, and rethink knowledge creation.[157] Experimentation and participation are central to such transformations to sustainable deltas.[102] SESs and other NbSs that reconnect delta societal development with biophysical processes can be placed within and contribute to a transformative rethinking of human activities, such as agriculture and urban development within deltas (Figure 5). The optimal solutions to create sustainable deltas are unknown, but with imaginative (re)design, collaborative experimentation, and learning among local communities, policymakers, funders, and researchers, the full potential of SESs may be realized. We believe SESs form a crucial and effective springboard from which we can pursue sustainability transformations in these globally important systems.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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