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A global synthesis of the effectiveness of sedimentation-enhancing strategies for river deltas and estuaries

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ABSTRACT

Deltas worldwide are at risk of elevation loss and drowning due to relative sea-level rise. Management strategies to restore or enhance sedimentation on delta plains, Sedimentation-Enhancing Strategies (hereafter SES), are now being pursued in many deltas but there has been limited cross-disciplinary and cross-delta review. Here we compare 21 existing and planned SES, synthesizing their physical characteristics, funding, governance arrangements, stakeholder engagement, process of implementation, environmental impact, land use change, and potential for upscaling. Strategies exist at various scales, from ~0.05 km^2 - 500 km^2. 79% of strategies are capable of outpacing high rates of sea-level rise. Cheaper strategies are limited to short term impacts and small spatial scales, while more expensive strategies can have longer lifetimes. Most strategies create wetlands and flood water storage. Some create opportunities for agriculture, aquaculture, housing, or recreational land use. Combinations of SES will likely be the most effective and sustainable method for maintaining elevation in river deltas.

1. Introduction

1.1. The need for sedimentation strategies

Deltas are at risk of elevation loss and drowning due to insufficient sediment supply in the face of relative sea-level rise (RSLR) (Ericson et al., 2006; Giosan et al., 2014; Nienhuis and van de Wal, 2021). For many deltas, sediment supply from upstream sources is dwindling (Dunn et al., 2019) and hard flood protection methods (embankments, channel deepening, dikes, groynes and dams) have further reduced river sediment connectivity with delta plains (Wesselink et al., 2016), disrupting the sources, sinks, and pathways.

In addition to drowning and land loss (Dunn et al., 2019; Edmonds et al., 2020; Tessler et al., 2015, 2018), deltas continue their rapid

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urbanisation and population (Loucks, 2019; Nicholls et al., 2020) growth. Resulting land use changes in many deltas (Abd El-Kawy et al., 2011; Ma et al., 2019) have come at the expense of wetland ecosystems, which historically have been an important agent for sediment trapping and elevation gain (Renaud et al., 2016; Vörösmarty et al., 2009). Moreover, both natural and human-induced subsidence are further lowering delta elevation (Schmidt, 2015; Shirzaei et al., 2021) and available sediment is often removed by sand-mining and dredging (Bendixen et al., 2019; J. R. Cox et al., 2021; Hackney et al., 2020). Consequently, many deltas are losing land (Nienhuis et al., 2020; Nienhuis and van de Wal, 2021), elevation (Shirzaei et al., 2021), and their natural capacity to grow with sea-level rise.

In recognition of these existential threats, strategies to promote sedimentation and maintain elevation are increasingly undertaken. Sometimes sedimentation is a primary goal of delta management and other times it is a secondary goal alongside flood safety or navigation measures (Rahman et al., 2019; Renaud et al., 2016; Vörösmarty et al., 2009). Sedimentation strategies are often nature-based. They are inspired and supported by natural delta processes and provide a cost-effective and sustainable alternative to traditional engineering methods (Liu et al., 2021; Temmerman et al., 2013; van Wesenbeeck et al., 2014). Besides reducing risks of flooding and land loss, sedimentation strategies may also reduce other environmental risks such as salinisation (Haasnoot et al., 2012; Rahman et al., 2019).

This synthesis compares the functioning and effectiveness of sedimentation-enhancing strategies (SES) in deltas globally. Some SES are well-documented (Gain et al., 2017; van der Deijl et al., 2018; Xu et al., 2019), but most existing studies focus on single cases. This synthesis enables intercomparison between SES and helps to further evaluate advantages and drawbacks of each SES. It can also help to guide the design of future strategies in other deltas. Our comparison includes their cost, their (projected) elevation gain, spatial footprints, lifetime, land-use, and required governance arrangements.

1.2. *What are Sedimentation-Enhancing Strategies (SES)?*

We define sedimentation-enhancing strategies (SES) as environmental management interventions that enhance or restore natural sedimentation. SES on deltas primarily focus on restoring water and sediment flows from rivers and water bodies towards delta plains and promoting the deposition of sediment.

SES are nature-based solutions (Cohen-Shacham et al., 2016; de Vriend et al., 2015), but not all nature-based solutions are SES. Similarly, SES has the same aims as "restoration sedimentology" but also acknowledges the interaction of both sedimentation and ecological processes in building land (Edmonds, 2012). Our definition for SES does not include artificial sedimentation strategies such as beach nourishments (e.g., Sand Engines (Stive et al., 2013)) or beneficial relocation of dredged sediment (Baptist et al., 2019; de Vincenzo et al., 2018; Frihy et al., 2016). These activities can be helpful in enhancing local sedimentation but require active management to import external sediment while SES focus on reuse or redistribution of sediment by harnessing existing natural river, tidal, and vegetation processes. SES includes projects such as managed realignment and wetland restoration (Esteves, 2014; Liu et al., 2021).

2. Methodology

2.1. *Sedimentation-enhancing strategies in practice*

SES have been implemented and are planned in many deltas. We collected and synthesized data on SES based on a workshop at Utrecht University, extensive literature searches and discussion with experts on different deltas. Our efforts resulted in data for 21 SES globally (Table 1). This is not exhaustive as other SES exist; however, we aimed to include all major planned or existing projects where sufficient documented information is available for a comparative analysis.

For our collection of 21 SES, we found that some enhance sedimentation on a small scale (<100 m^2) or have been pilot projects to test the potential for larger scale SES (>100 km^2). Included are projects with a variety of spatial and temporal scales, which span deltas in multiple climates which face different physical and socioeconomic challenges (Fig. 1). We identify four broad categories of SES:

1. River sediment diversions
2. Tidal flooding
3. Sedimentation structures
4. Vegetation planting

2.1.1. *River sediment diversions*

River sediment diversions aim to solve the problem of "sediment disconnectivity" in deltas (Day et al., 2016; Fryirs, 2013), using sluice gates to divert riverine water and sediment through levees into adjacent wetlands. Construction of sluice gates allows for managed water and sediment intake, thereby limiting potential negative consequences for sedimentation area ecology and river navigation while maximizing the diversion of sediment (Coastal Protection and Restoration Authority, 2017a). Sediment settling and aggradation in low energy conditions then builds land, mimicking the natural process of crevasse splays (see Fig. 2a and Fig. 3a).

We have identified 10 river sediment diversion SES, of which 7 are operational and a further 3 are under construction or being planned (Table 1). The size of river sediment diversions varies. Some divert as much as 10–15% of the river sediment and have a sedimentation area of 325 km^2 (MBRA) (Coastal Protection and Restoration Authority, 2017a).

Of these 10 projects, 4 are in the Mississippi River Delta. One large-scale sediment diversion that is currently active (MWB) is located 8 km upstream of the head of the passes of the main river channel at West Bay (Allison and Meselhe, 2010; Yuill et al., 2016). Future large river sediment diversions are planned further upstream (MBRA & MBRE). They will divert >2100 m^3/s, approximately 10–15% of total river discharge, to build and sustain land in adjacent wetlands (Army Corps of Engineers, 2020; Coastal Protection and Restoration Authority, 2017b, 2021). There are also numerous smaller scale diversions and crevasses, i.e., order of 10–100 m^3/s, in the unleveed reaches near the mouth of the river (Boyer et al., 1997; Cahoon et al., 2011; Yocum, 2016) that provide valuable examples where diversions have created wetlands. Since their conception, the river diversions in the Mississippi River Delta have been extensively studied (White et al., 2019; Xu et al., 2019) and monitored (Kolker et al., 2012) and are used as the basis for designing and improving river sediment diversions elsewhere.

In the Magdalena delta, Colombia, the project "Canal del Dique locks" (CDD) is designed and undertaken by a consortium of local partners to restore nature areas, improve flood safety and to enhance navigation. The consortium includes state government, national government, private parties, research institutes and engineering firms (Sokolewicz et al., 2016). It is funded by *Fondo Adaptación Colombia,* a public institution for construction and restoration of infrastructure affected by the 2010–11 La Niña (Sokolewicz et al., 2016).

As part of the larger "Room for the River" project in the Rhine-Meuse delta, river diversions have been constructed in the depoldered Zuiderklip and Noordwaard areas (RNW & RZK). Dikes were removed to divert river water and sediment into new wetlands (van der Deijl et al., 2017, 2018). Although the primary goal was nature development and water storage, river floods unintentionally resulted in sedimentation that decreased over time (van der Deijl et al., 2017, 2018). But, in this case, due to the low sediment concentrations in the feeding river, annual average rates of accumulation on tidal flats are low, the lowest of any of the river diversion projects (~6 mm/yr).

In the Danube delta, extensive agriculture, fisheries and forestry had caused salinisation and nutrient imbalance in its floodplain (Schneider

Table 1
Information on SES included in this study (Army Corps of Engineers, 2020; Auerbach et al., 2015; Boyer et al., 1997; Cado van der Lely et al., 2021; California Department of Water Resources, 2021; Chen et al., 2001; Chen et al., 2004 Chen et al., 2008; Coastal Protection and Restoration Authority, 2017a, 2021; ComCoast, 2007 CWPPRA, 2016; Department of Public Works Sydney, 1996; Eems-Dollard 2050, 2020; Ems Dollard 2050, 2021.; Gain et al., 2017; He et al., 2007; Huang and Zhang, 2007; Islam et al., 2021; Ismanto et al., 2017; Jannick, 2010; Ju et al., 2017; Li et al., 2009; Li and Zhang, 2008; Liao et al., 2007; Ju et al., 2017;Louisiana Coastal Wetlands Conservation and Restoration Taskforce, 2021; Newsom et al., 2019; Nijland and Cals, 2001; Oosterlee et al., 2018; Perkpolder Website, 2021; POV Waddenzeedijken, 2020; Rayner et al., 2021;Oosterlee et al., 2020; Rijkswaterstaat, 2013; Sadat-Noori et al., 2021; Schneider et al., 2008; Tonneijck et al., 2015; Turner and Boyer, 1997; van der Putten and Ruiter, 2010; Wang et al., 2014a; X. Wang et al., 2021; H. Winterwerp et al., 2014; Yang, 1998; Yuill et al., 2016; X. Zhang et al., 2020; Zhao et al., 2020) where ^{p} indicates projects that are in the planning or implementation stage and the reported data refers to estimates or models, * is an estimate for similar projects (Bayraktarov et al., 2016) as the exact cost information was not available and † is an average for similar projects (Chung, 2006) in the region as exact measurements were unavailable. In the Ems, several projects were explored: the chosen project EWG, and two alternatives which are included in this table but not in further analysis (EWG-ALT1 and EWG- ALT2).

Strategy Code	Name of strategy	Lat	Lon	Location	Country	Type of strategy	(Projected) start year	(Projected) planning horizon	Outfall sedimentation area	Implementation costs (inflation adj.)	(Projected) elevation gain
		dec deg.	dec deg.	Delta/estuary			yr	yr	km^{2}	USD$	mm/yr
MWB	West Bay Diversion (7.6 RK)	29.211	-89.292	Mississippi	USA	Sediment Diversions	2003	2023	20	73,202,349	167
MCC	Crevasse Cut Program	29.153	-89.251	Mississippi	USA	Sediment Diversions	1997	ongoing	2.00	35,134	62
MBRA^{p}	Mid Barataria Sediment Diversion	29.656	-89.976	Mississippi	USA	Sediment Diversions	2023	2073	450	517,278,621	335
MBRE^{p}	Mid-Breton project	29.749	-90.019	Mississippi	USA	Sediment Diversions	2024	2074	260	1,078,392,584	335
CDD^{p}	Canal del Dique locks	10.119	-75.483	Magdalena	COL	Sediment Diversions	2019	3027 (or longer)	250	722,670,000	20
RNW	Noordwaard / Kleine Noordwaard	51.777	4.781	Rhine-Meuse	NL	Sediment Diversions	2015	2100 (or longer)	6	20,678,784	6
RZK	Zuiderklip	51.741	4.832	Rhine-Meuse	NL	Sediment Diversions	2011	2100 (or longer)	5	11,974,640	5
DBP	Babina polder	45.424	29.411	Danube	RO	Sediment Diversions	1994	Ongoing	22	83,176	13.85
DCP	Cernovca polder	45.261	29.294	Danube	RO	Sediment Diversions	1996	Ongoing	15.8	83,176	19.3
STW	Twitchell Island	38.106	-121.643	San Joaquin-Sacramento	USA	Sediment Diversions	1997	2006	0.06	41,679,732	40
GBB	Beel Bhaina	22.930	89.215	Ganges-Brahmaputra	BD	Tidal Flooding	1997	2001	6	none	250
GBK	Beel Khukshia	22.894	89.351	Ganges-Brahmaputra	BD	Tidal Flooding	2006	2013	11	648,400	150
GBP	Beel Pakhimara	22.682	89.232	Ganges-Brahmaputra	BD	Tidal Flooding	2015	2020	7	37,956,400	120
GBP32	Polder 32	22.516	89.45	Ganges-Brahmaputra	BD	Tidal Flooding	2009	2011	60	none	180
WPP	Perkpolder	51.400	4.016	Western Scheldt	NL	Tidal Flooding	2015	2029	0.75	33,654,318	60
EDD	Double dykes/ Dubbele dijk	53.393	6.888	Ems	NL/DE	Tidal Flooding	2018	2022	0.25	7,500,000	20
HKI	Tidal Replicate Method	-32.866	151.715	Hunter, Kooragang Island	AU	Tidal Flooding	2017	2020	4	28,925	2
WPS	Building with Nature Indonesia	-6.888	110.504	Wulan/Demak	ID	Sedimentation Structures	2015	2020	4.5	6,372,963	83
EWG^{p}	Pilot Buitendijkse Slibsedimentatie: willow groynes	53.164	7.090	Ems	NL	Sedimentation Structures	2022	2032	1.25	4,800,000	20
EWG-ALT1^{p}	Pilot Buitendijkse Slibsedimentatie: lagoon excavation alternative	53.164	7.090	Ems	NL	Tidal Flooding	x	x	0.25	4,800,000	40
EWG-ALT2^{p}	Pilot Buitendijkse Slibsedimentatie: wetland rejuvenation alternative	53.164	7.090	Ems	NL	Vegetation planting	x	x	0.25	4,800,000	5
YJW	Jiuduansha wetlands	31.207	121.948	Yangtze	China	Vegetation planting	1997	Ongoing	0.5	137, 500*	15†
YCI	Chongming Island (Dongtan)	31.416	121.833	Yangtze	China	Vegetation planting	2001	2012	3.37	137, 500*	32

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Table 1 (*continued*)

Strategy Code	Primary objective of the project	Who planned and funded the project?	Land use type that is gained	Land ownership	Degree of non-govermental, local stakeholder engagement	Tests and simulations undertaken	Upscale modelling undertaken (to expand project to new areas)?	Environmental Impact Assessment (EIA) undertaken (Y/N) and outcome (see below)	References
Strategy Code	Primary objective of the project	Who planned and funded the project?	Land use type that is gained	Land ownership	Degree of non-govermental, local stakeholder engagement	Tests and simulations undertaken	Upscale modelling undertaken (to expand project to new areas)?	Environmental Impact Assessment (EIA) undertaken (Y/N) and outcome (see below)	References
	Land raising/Creation of new land types/ Nature/Flood safety	Regional government/ Regional body/National government/National body/NGO/ Local people/ Research Institute/ University/Private contractor/Other	Agricultural/ Aquaculture/ Nature/ Recreation/ Residential/ Other	State/Private/ Other	No engagement/ Informing/ Consulting/ Advising/ (Co-) decision-making	This is a pilot project/ pilot projects were undertaken/ experiments were done/modelling was undertaken	Yes/No/ Ongoing	Degree of positive impact (Low/Moderate/High/Very High) & Degree of negative impact (Low/Moderate/ High/Very High) -	Literature and reports
MWB	Returning a subsided open water bay to its previous state of vegetated wetland.	Local sponsor is Louisiana Coastal Protection and Restoration Authority (CPRA), federal sponsor is the US Corps of Engineers. Funding is federal	Freshwater and brackish marsh	State	Consulting and advising	Field data collection and montioring	Yes	Very high positive impact on land creation in the basin. However this impact was only seen after the installation of several terraces in 2009. Prior to that deposition was entirely subaerial.	West Bay CWPPRA Fact Sheet Yuill et al. (2016)
MCC	Returning a subsided open water pond to vegetated wetland. Waterfowl habitat is a primary management target.	Funds are through Coastal Wetland Planning Protection and Restoration Act (CWPPRA). Local sponsor is CPRA, federal sponsor is National Oceanic and Atmospheric Administration (NOAA). Other related activities are funded by private and state organizations.	Freshwater and brackish marsh	State, federal	Consulting and advising	Field data collection and montioring	Yes	Very high positive impact for flora and fauna.	MR-09 fact sheet Turner & Boyer (1997)
MBRA^p	Sustaining and creating new land for ecosystem services and infrastructure protection	Planning is primarily done at the state level. Funding involves federal funds	Freshwater and brackish marsh.	State, private	Extensive consulting and advising	Numerical modeling and field data collection both on the river side and in the receiving basin	This is an upscaled project	Predicted to have a very high positive impact on land area in the receiving basin, but with short term negative effects e.g. significant disruptions to commercial and recreational fisheries, and some flooding increases near the diversion.	Louisiana Coastal Master Plan 2017, and supporting documents
MBRE^p	Sustaining and creating new land for ecosystem services and	Planning is primarily done at the state level. Funding involves federal funds	Freshwater and brackish marsh.	State, private	Extensive consulting and advising	numerical modeling and field data collection both on the	This is an upscaled project	Predicted to have a very high positive impact on land area in the receiving basin, but	Louisiana Coastal Master Plan 2017, and supporting documents

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Table 1 (*continued*)

Strategy Code	Primary objective of the project	Who planned and funded the project?	Land use type that is gained	Land ownership	Degree of non-govermental, local stakeholder engagement	Tests and simulations undertaken	Upscale modelling undertaken (to expand project to new areas)?	Environmental Impact Assessment (EIA) undertaken (Y/N) and outcome (see below)	References
	infrastructure protection					river side and in the receiving basin		with short term negative effects e.g. significant disruptions to commercial and recreational fisheries, and some flooding increases near the diversion.	
CDD^{p}	Flood protection and ecological restoration (integral solution optimized for the requirements of flood safety, navigation, agriculture and the environment)	Fondo Adaptación Colombia + ANI (National Infrastructure Authority)	Mangrove forests, and specifically in Corchales national natural parks (freshwater trees).	Local stakeholders and National Natural Parks	Extensive, 1279 stakeholder meetings: consulting/ advising	Yes; hydrological and flow routing modelling (Delft-FEWS); 1D, 2D and 3D numerical models to simulate hydraulics, water quality, sediment transport and morphological changes within the project area (coastal and river, over 2000km^2).	No	Environmental Impact Assessment was undertaken in advance. Multi-Criteria analysis & cost-benefit analysis also undertaken. The project was designed to have a high positive environmental impact and reduce flood risk and minimal negative impacts.	Sokolewicz et al. (2016), Internal project description RHDHV.
RNW	Primarily: nature development , secondary: Room for the River/ flood protection	Planning: two provinces, Ministry Agriculture Nature and Food Quality (LNV), Rijkswaterstaat, municipality, State forestry, waterboards. funding: 50% Rijkswaterstaat & 50% Ministry LNV	Nature, intertidal freshwater wetlands	Private (75% agriculture), municipality/state	Project group comprising two provinces, Ministry LNV, Rijkswaterstaat, municipality, state forestry, waterboards	MER (Environmental Impact Assessment) procedure with monitoring afterwards	No	Environmental Impact Assessment was undertaken in advance. Very high positive impact for nature and landscape. Low negative impact on shipping/ maintenance of main channel from which diversion is created.	van der Deijl et al. (2017), van der Deijl et al. (2018), Milieueffectrapport (2010), Ministerie document (2002), van der Putten and Ruiter (2010), Jannick (2010)
RZK	Primarily: Room for the River/ flood protection, secondary: nature development	Rijkswaterstaat & Ministry LNV	Nature, intertidal freshwater wetlands	Water extraction company, state forestry	State forestry, province, and municipality planned the project. There were information sessions with possibilities for reactions/ input for stakeholders	MER (Environmental Impact Assessment) procedure with monitoring afterwards	No	Environmental Impact Assessment was undertaken in advance. Very high positive impact for nature, flood safety and recreation. Moderate negative impacts for bed and water quality because of high input of cadmium and zink which will arise after the implementation of a diversion from the river Meuse	van der Deijl et al. (2017), van der Deijl et al. (2018), Milieueffectrapport (2010), Ministerie document (2002), van der Putten and Ruiter (2010), Jannick (2010)
DBP	Nature	Funded: World Bank. Planned: WWF Germany, Danube Delta National Institute for research and development	Nature	During the restoration of the wetlands, the polders became public property.	Consulting	Pilot project	No	Environmental Impact Assessment was undertaken in advance. High positive impact and low negative impact.	Nijland and Cals (2001), WWF Factsheet Babina and Cernovca islands, World Bank (2005), Ebert et al. (2009), Schneider et al. (2008), Schneider (2015)
DCP	Nature	Funded: World Bank. Planned: WWF Germany, Danube Delta National Institute for research and development	Nature	During the restoration of the wetlands, the polders became public property.	Consulting	Pilot project	No	Environmental Impact Assessment was undertaken in advance. High positive impact and low negative impact.	Nijland and Cals (2001), WWF Factsheet Babina and Cernovca islands, World Bank (2005), Ebert et al. (2009), Schneider et al. (2008), Schneider (2015)
STW		Regional (state) government & US	Peat and natural wetlands	Former agricultural land	Government & research institutes - for further projects	This was a pilot project, extensive		Environmental Impact Assessment was undertaken in	Miller et al. (2008), Newsom et al. (2019), Bates and Lund

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Table 1 (*continued*)

Strategy Code	Primary objective of the project	Who planned and funded the project?	Land use type that is gained	Land ownership	Degree of non-govermental, local stakeholder engagement	Tests and simulations undertaken	Upscale modelling undertaken (to expand project to new areas)?	Environmental Impact Assessment (EIA) undertaken (Y/N) and outcome (see below)	References
	Land raising/ counteracting subsidence	Geological Survey (NGO) in conjunction with researchers/universities	(ecological), also flood storage area and recently rice farming	(private) purchase by the state of California (now government owned)	stakeholder engagement is occurring	measurements and modelling untertaken, including upsale modelling	Yes. Also new projects now ongoing.	advance. Very high positive impact (creation of new habitats) - extensively monitored for water quality and chemical composition, low negative impact.	(2013), West Delta Program website
GBB	Improved water drainage of polders, increasing capacity of peripheral river	No planning/citizen action	Agriculture	Private	Local inititive by farmers. No governmental involvement	No	No	High positive impact. Moderate to high negative effects as the peripheral river (Hari) became 10–12 m deeper and 2–3 times wider. Uneven sedimentation led to other water drainage issues.	Gain et al. (2017)
GBK	Improved water drainage of polders, increasing capacity of peripheral river	The Water board (BWDB)	Agriculture	Private	Poor communication & stakeholder involvement	No	No	Moderate negative effects as siltation in polders and deeper / wider peripheral river and the water drainage was only marginally improved. Partly because of low degree of local participation (due to poor stakeholder involvement)	Gain et al. (2017)
GBP	Improved water drainage of polders, increasing capacity of peripheral river	The Water board (BWDB)	Agriculture	Private	Consulting & advising	No	No	Moderate negative effects: highly variable siltation rates, unexpected erosion of river banks near intakes.	Gain et al. (2017), Islam et al. (2021)
GBP32	Not TRM, but storm-induced equivalent of TRM with larger spatial scale	Unplanned	Agriculture	Private		No	No	More evenly distributed siltation compared to TRM because of uncontrolled opening, resulting in deep central channel in the polder conveying water and sediments	Auerbach et al. (2015)
WPP	Tidal ecosystem creation	National and regional government also EU and national govnerment involvement.	Recreation, housing and nature areas	Provincial or government owned land	Yes workshops about design and functioning attended by local governments, NGOs, engineering firms, knowledge institutes, architects, urban planners - public participation and communication was encouraged and thought to be successful	This is a pilot project, extensive measurements and modelling untertaken	Yes and compared with other EU projects (COMcoast)	Environmental Impact Assessment was undertaken in advance. Initial moderate, negative impact but fast recovery and since, very high positive impact. Loss of one rare species, which is accommodated for in a different area. Medium negative environmental impact with mitigation and compensation measures	Brunetta et al. (2019), Oosterlee et al. (2020), ComCoast (2007), Perkpolder website, Perkpolder factsheet (RWS)

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Table 1 (*continued*)

Strategy Code	Primary objective of the project	Who planned and funded the project?	Land use type that is gained	Land ownership	Degree of non-govermental, local stakeholder engagement	Tests and simulations undertaken	Upscale modelling undertaken (to expand project to new areas)?	Environmental Impact Assessment (EIA) undertaken (Y/N) and outcome (see below)	References
								undertaken to fulfil the flora and fauna act. Effect on fish negligible.	
EDD	Nature, agriculture & flood safety	Regional government & regional water board	Agricultural, nature & aquaculture	State owned	Co- decision making	Pilot project, modelling was undertaken	Ongoing	Environmental Impact Assessment was undertaken in advance. Very high positive impact. Low negative impacts	Evaluation Report Dubbel Dijk (2020), Ems Dollard 2020 website, Deelprogrammaplan Vitale Kust (2020)
HKI	Nature	University (of New South Wales). Funded by private engineering firm (NCIG)	Nature, recreation	State (National Park)	Limited to research institute and partners	This is a pilot project	No	Environmental Impact Assessment was undertaken in advance. Surveys were undertaken to determine the tidal range optimal for the wetland vegetation in the area. Very high positive impact on the vegetation, low negative impact on surrounding ecosystem.	Sadat-Noori et al. (2021), Rayner et al. (2021), Kooragang Project Report (1996)
WPS	Trapping sediment, space for mangroves, and reduce coastal erosion	EcoShape consortium (local partners, NGOs and private partners)	Mangroves, aquaculture	State owned	Co-decision making	Pilot project, no pre-feasibility	Yes	No environmental Impact Assessment was undertaken in advance. Very high positive impacts, low negative impacts.	de Vriend et al. (2015), Winterwerp et al. (2014), Tonneijck et al. (2015), Cado Van Der Lely et al. (2021), Triyanti et al. (2017), Ismanto et al. (2017)
EWG[p]	Reduce turbidity by sediment extraction, nature, growing with SLR, knowledge gathering	Rijkswaterstaat & Ministry LNV	Estuary, mudflat, salt marsh	Private / State / NGO	Consulting / Advising	Pilot project, modelling was undertaken	Yes	Environmental impact assessment is ongoing, predicted high positive impact and low negative impact.	MIRT2-end report, Ems Dollard 2050 website and accompanying reports/ documents
EWG-ALT1[p]	Reduce turbidity by sediment extraction, nature, growing with SLR, knowledge gathering	Rijkswaterstaat & Ministry LNV	Estuary, mudflat, salt marsh	Private / State / NGO	Consulting / Advising	Pilot project, modelling was undertaken	Yes	Environmental impact assesment is ongoing. Low positive and moderate negative impact.	MIRT2-end report, Ems Dollard 2050 website and accompanying reports/ documents
EWG-ALT2[p]	Reduce turbidity by sediment extraction, nature, growing with SLR, knowledge gathering	Rijkswaterstaat & Ministry LNV	Estuary, mudflat, salt marsh	Private / State / NGO	Consulting / Advising	Pilot project, modelling was undertaken	Yes	Environmental impact assessment is ongoing. Low positive and moderate negative impact.	MIRT2-end report, Ems Dollard 2050 website and accompanying reports/ documents
YJW	Ecological engineering, accelerate marsh accretion & draw migratory birds away from airport construction nearby	State Key Laboratory of Estuarine and Coastal Research (university) & Jiuduansha Research Group of East China Normal University	Wetland, salt marsh	National/ municipal	No engagement	Based on earlier experiences on coastal projects from 1970s	This is a form of upscaling	Moderate positive impact, moderate negative impact. Birds successfully migrated, but native plants became excluded	Bayraktarov et al., 2016, Chen et al., 2001, Chen et al., 2008, Chung, 2006, He et al., 2007, Huang and Zhang, 2007, Liao et al., 2007, Zhang et al., 2020
YCI	Ecological engineering, reduce tidal wave energy, mitigating erosion, trapping sediment	Shanghai Municipality & Chongming Dongtan Wetland reserve	Wetland, salt marsh	National/ municipal	Consulting (with Chongming Dongtan Wetland Reserve as local stakeholders)	Based on earlier experiences on coastal projects from 1970s	This is a form of upscaling	Moderate negative impact. Ecosystem functioning is altered. Native species outcompeted and bird population habitat altered.	Bayraktarov et al., 2016, Chen et al., 2004, Ju et al., 2017, Li and Zhang, 2008, Li et al., 2009, Wang et al., 2021, Yang, 1998, Zhao et al., 2020

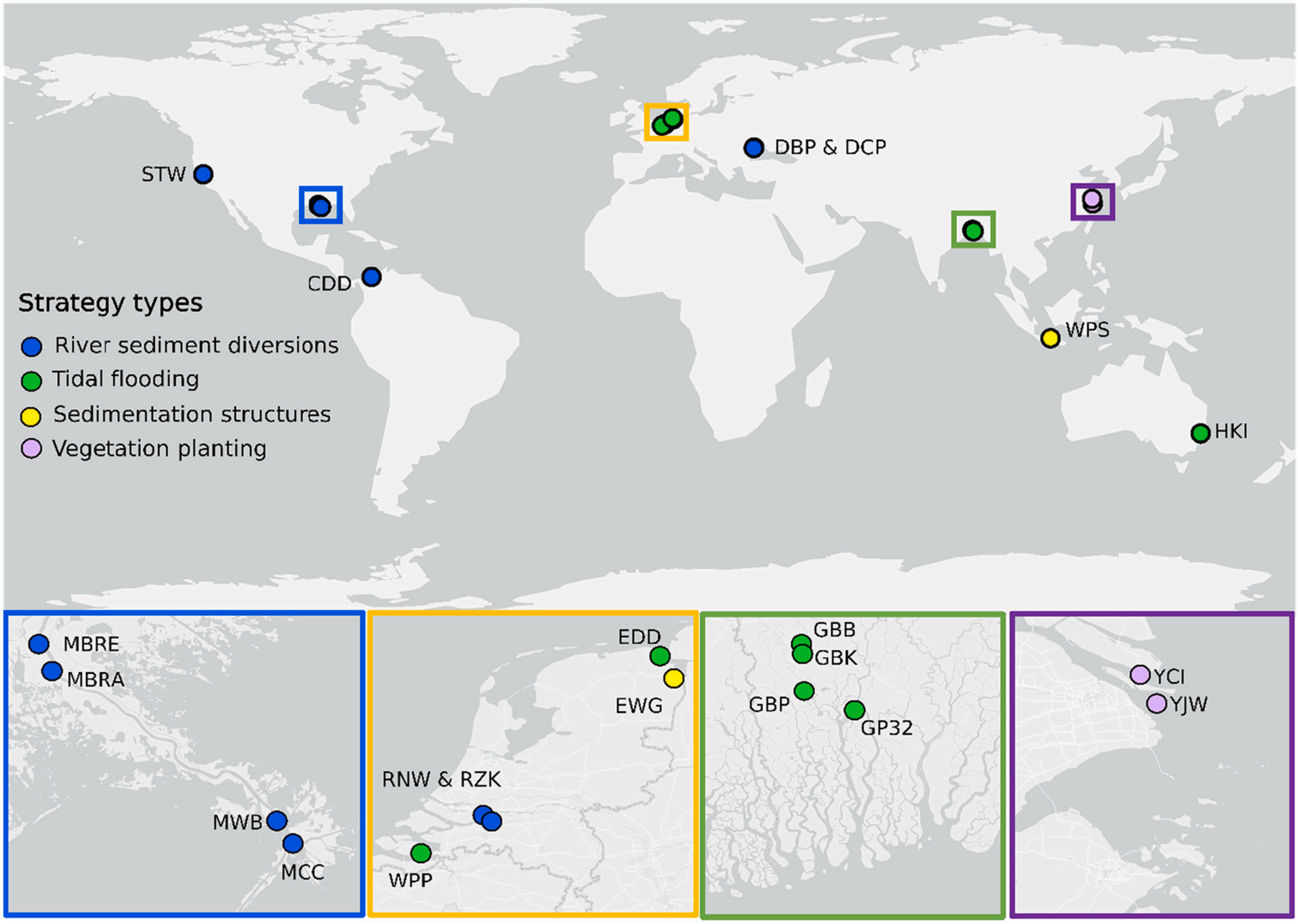


Fig. 1. Map of SES covered in this study with insets of: the Mississippi, northwest Europe, Bangladesh and the Yangtze estuary where several strategies are being implemented. Each strategy is marked with an abbreviation where: CDD = Canal del Dique, Colombia, DBP = Danube Babina Polder, DCP = Danube Cernovca Polder, EDD = Ems Double Dikes, EWG = Ems Willow Groynes, GBB = Ganges Beel Bhaina, GBK = Ganges Beel Khukshia, GBP = Ganges Beel Pakhimara, GP32 = Ganges Polder 32, HKI = Hunter Kooragang Island, MBRA = Mississippi Mid-Barataria Diversion, MBRE = Mississippi Mid-Breton Diversion, MCC = Mississippi Crevasse Cuts, MWB = Mississippi West Bay Diversion, RNW = Rhine-Meuse Noordwaard, RZK = Rhine-Meuse Zuiderklip, STW = Sacramento Twitchell Island, WPP = Western Scheldt Perk Polder, WPS = Wulan Permeable Structures, YCI = Yangtze Chongming Island (Dongtan) and YJW = Yangtze Jiuduansha Wetlands.

et al., 2008). To combat this, river sediment diversions were installed in the Babina and Cernovca polders in 1994 with the primary goal of restoring wetlands (DBP & DCP). The project involved extensive planning and stakeholder engagement with government and scientific bodies to identify priorities and projects for action (Schneider, 2015). The project was assessed as a “no regret” sustainable measure as it successfully restored wetlands, fisheries, recreation, tourism and raised land (Ebert et al., 2009). However, sedimentation rates are much lower than in the West Bay and Crevasse Cut (MWB & MCC) river diversions (~15–20 mm/yr).

In the Sacramento-San Joaquin Delta, a long-term field scale river sediment diversion project was implemented at Twitchell island from 1997–2006 (Miller et al., 2008) (STW). This project followed a successful pilot study and aimed to resolve land subsidence issues of drained peat wetlands. New water inflow and outflows were constructed to re-establish water and sediment flows (Miller et al., 2008) that also encouraged vegetation development and peat growth (Bates and Lund, 2013). The project successfully raised land, sequestered carbon, created new ecosystems and can be used for rice production (Deverel et al., 2020). It was generally accepted as a productive and useful SES, though, again, sedimentation rate is lower than the West Bay and crevasse cut projects of the Mississippi (MWB & MCC). Upscaled versions are being executed in other islands in the Sacramento-San Joaquin Delta as part of the West Delta program, however they have had only limited effectiveness for offsetting sea-level rise in some places (Bates and Lund, 2013). The project is projected to last 50–250 years depending on future sea-level rise (Deverel et al., 2014).

In general, our synthesis shows that river diversions are a powerful but long-term land building measure (Chamberlain et al., 2018). They require long-term maintenance (Day et al., 2016), large-scale planning, and cooperation between many parties to minimise stakeholder conflicts (Ko et al., 2017; Wescoat, 2013). Furthermore, it has been suggested that only large-scale diversions are cost effective in land raising (Kenney et al., 2013) and sufficient to offset land and elevation loss considering relative sea-level rise (H. Wang et al., 2014).

Not all river sediment diversions had land elevation gain as a primary goal. Project “success” therefore also varied depending on specific primary aims. In the case of Canal del Dique (CDD), goals are improvement of flood protection and ecological habitats while ensuring navigation (Sokolewicz et al., 2016). Even though the project has a similar sedimentation area as the Mississippi (MBRA & MBRE) diversions (Fig. 7), it has lower predicted sedimentation rates, which vary both temporally (highest rates expected in the first 10–20 years) and spatially (Sokolewicz et al., 2016). Many strategies convert agricultural land wetlands (see Fig. 4). They also provide flood storage areas and in many cases aquaculture opportunities.

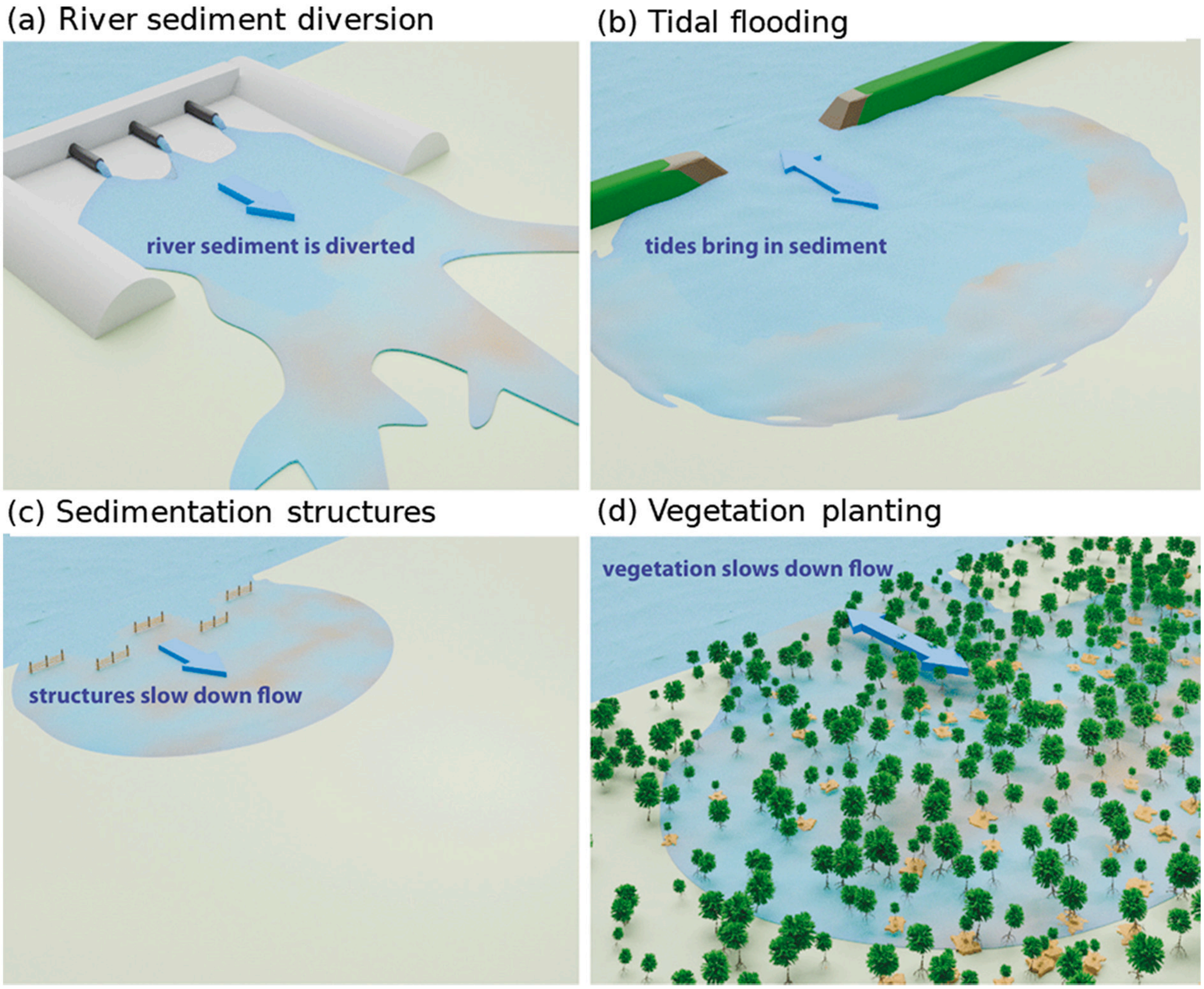


Fig. 2. Illustrations of four common types of SES: a) River sediment diversion, b) tidal flooding, c) sedimentation structures, d) sediment trapping vegetation. Arrows indicate flow direction.

Funding sources for river sediment diversions vary. Two large and expensive river diversions (MBRA & MBRE) along the Mississippi river are currently being planned by the state government and funded by a combination of federal and state resources, including settlement funds from the Deepwater Horizon oil spill (Coastal Protection and Restoration Authority, 2017b). The structures will be operated by the Coastal Protection and Restoration Authority, a state authority, with input from other state and federal organisations (Louisiana Coastal Protection and Restoration Authority, 2021).

Stakeholder engagement and collaboration were key in all river sediment diversions. SES often required collaboration between local and national government bodies and the formation of a project group to enhance stakeholder collaboration (Jannick, 2010). In the Danube, depoldering projects (DBP & DCP), some conflict occurred due to poor stakeholder engagement with residents and late communication with the public related to perceived loss of land, fishing areas and economic opportunities (World Bank, 2005).

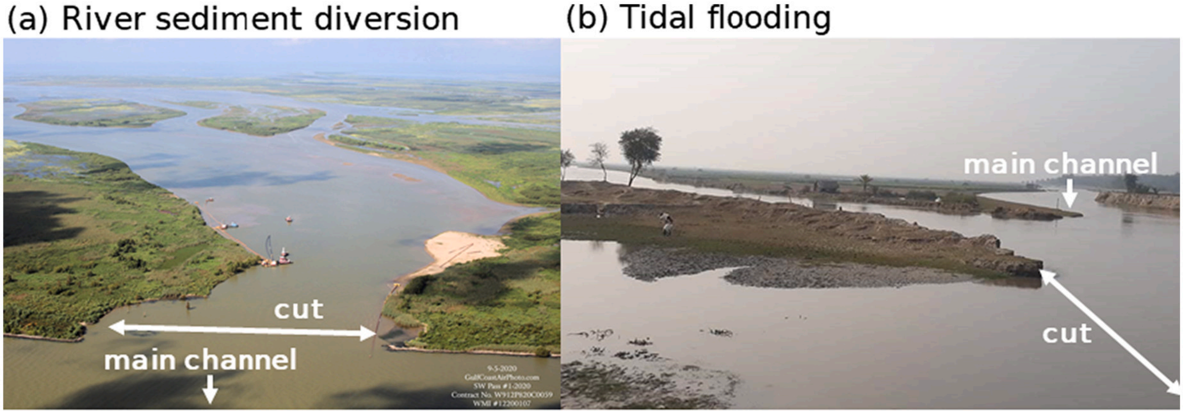
River sediment diversions can lead to ecological loss in their initial phases. Ecological concerns arose in the planning and construction phases of smaller Mississippi river diversions concerning salinity decreases and potential negative effects on fisheries and changing nutrient concentrations (Day et al., 2016). Water and sediment delivered by sediment diversions can decrease wetland biomass production by increasing nutrient availability in the shallow subsurface. This may reduce root growth. Diversions can also change species composition due to altered salinities and hydroperiods (Elsey-Quirk et al., 2019; Snedden et al., 2015). This includes fish species (Rose et al., 2014). However, the long-term effects on fisheries in the Mississippi case have been found to be minimal (de Mutsert et al., 2017) and new habitats can be created for oysters, finfish, and shrimp (Day et al., 2016). Similarly, environmental impact assessments and subsequent monitoring in the Rhine-Meuse diversions indicated an overall positive effect on nature and landscape, but with some negative effects on water quality (changing nutrient chemistry) and navigation (Ministerie van LNV, 2002; van de Weijer, 2009).

2.1.2. *Tidal flooding*

Tidal flooding for land building involves the removal, lowering or breaching of infrastructure, e.g., dikes, to allow tidal inundation of previously protected land (see Fig. 2 and Fig. 3). Tides carry sediments that can settle under low energy conditions, typically in a former polder or between two parallel dikes ("double dike" (Marijnissen et al., 2021)). Most strategies use a single in- and outflow gate and therefore differ from river sediment diversions.

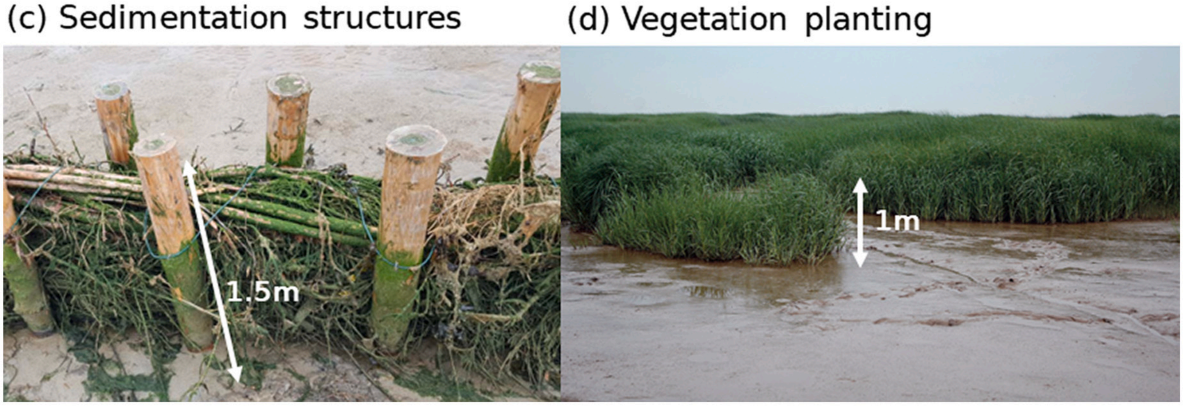
We have identified 5 past and 2 active projects which use tides to enhance sedimentation, typical in conjunction with enhanced vegetation growth (Section 3.4). Some have a small sedimentation area e.g. 0.25 km^2 (EDD) and others are larger e.g. 60 km^2 (GP32).

Many tidal flooding SES are in the polders of the low-lying floodplains of the southwest Ganges-Brahmaputra delta in Bangladesh, where tidal flooding is known as Tidal River Management (TRM). Levee construction in Bangladesh in the 1960s prevented sediment deposition in the polders ("beels") and caused river channels to silt up, dramatically



(a) River sediment diversion

(b) Tidal flooding



(c) Sedimentation structures

(d) Vegetation planting

Fig. 3. Photos of examples of the four common types of SES: a) River sediment diversion (photo courtesy of Gulf Coast Air, 2020, b) tidal flooding (photo courtesy of Dr. Mahmuda Mutahara), c) sedimentation structures (van de Laar et al., 2020), and d) sediment trapping vegetation (Weber and Li, 2008), indicating scale.

reducing discharge capacity during monsoon floods (Gain et al., 2017). Furthermore, rain flooding inside these polders (waterlogging) became progressively more persistent, as land subsidence and silted river channels dramatically reduced drainage possibilities for excess water.

In response, in 1997 in one of the earliest examples of tidal flooding (GBB), residents of Beel Bhaina decided to breach levees for 3–5 years (Gain et al., 2017). Re-established floods with sediment-rich water were able to elevate poldered land. This tidal flooding SES had a negligible cost and high success, obtaining sedimentation rates of 150–250 mm/yr (Gain et al., 2017). It decreased waterlogging and increased opportunities for agriculture (Gain et al., 2017).

Following the success of Beel Bhaina, government agencies, including the Bangladesh Water Development Board, implemented tidal flooding in several other polders. We include two major examples here: Beels Khukshia (2009, GBK) and Pakhimara (2015, GBP), but also a natural polder breach, Polder 32 in 2009 (Auerbach et al., 2015). Although these projects also achieved their objectives and raised land, other aspects have been challenging. There was unexpected flooding, bank erosion and uneven sediment deposition within the beels. The government-led tidal flooding projects (Gain et al., 2017) also suffered from inadequate institutional arrangements (poor communication, unfair compensation of affected farmers) which resulted in social conflicts (Mutahara et al., 2019).

The Perkpolder project (WPP) in the Western Scheldt (Netherlands), in contrast, is a cooperative tidal flooding project involving many parties, thorough stakeholder engagement (Verweij et al., 2013) and a detailed communication plan to foster engagement and collaboration (Dienst Landelijk Gebied, 2013). It is primarily a development project and includes creation of housing and recreation areas in addition to wetlands (Brunetta et al., 2019). It is the only SES in this study that has a primary goal of creating space for housing, which comes with its own permitting and legal implications of management of sewers, cables, pipes adjacent to a nature area (van Berchum et al., 2014).

In an alternative tidal flooding design, the project “Dubbele Dijk” (double dike) in the Ems estuary (EDD) includes a culvert in the outer dike to restore tidal sedimentation in front of an inner dike to help protect the coast. New intertidal area is divided into several land-use types including agriculture, nature areas, and aquaculture as a pilot study to identify which land-use types can exist and thrive under tidal flooding (Kwakernaak and Lenselink, 2015). It is part of the Ems-Dollard 2050 project, an ongoing collaborative effort with international (German and Dutch) stakeholder engagement aimed at strengthening ecological value and resilience to climate change (van Es et al., 2021). Several SES options were investigated by private firms and the outcomes were assess bed all stakeholders to choose the most suitable project. The choice for double dikes was motivated in this case by the loss of natural historic sedimentation areas by construction of embankments and closure of tidal basins, leading to a sediment-stressed estuary with poor ecological value (van Maren et al., 2015, 2016). Physical limitations of the SES including erosion or morphology were crucial in making this decision.

Two other alternative sedimentation strategies assessed by the Ems-Dollard 2050 project were: lagoon excavation and salt marsh rejuvenation (ELE & ESM). Lagoon excavation involves digging a new lagoon in an existing salt marsh area to act as a sediment accumulation basin, however it was projected to create undesired erosion and channelisation. Salt marsh rejuvenation required lowering salt marsh elevation to encourage sedimentation. Both lagoon excavation and salt marsh rejuvenation would require sediment removal which could be used for other purposes. Salt marsh rejuvenation was rejected because of fears of limited effective sedimentation when designed at the elevation required for salt marsh formation. Lagoon excavation was determined to be an efficient sediment trap but was also discarded as it would result in unwanted erosion at the lagoon opening (van Es et al., 2021) (in contrast to

Fig. 4. Development of Beel Khukshia, Bangladesh (GBK). Map imagery: Google Earth.

TRM in Bangladesh where erosion at the entry point to the Beel was deemed favourable (Gain et al., 2017)).

Another novel method which makes use of tidal flooding for sedimentation is a pilot project on Kooragang Island, Australia (HKI). The project consists of gates which periodically open and close to create a synthetic tidal effect. Conditions were chosen to ensure the unvegetated tidal flats were actively colonized by salt marsh vegetation. The project was developed by the University of New South Wales who undertook modelling and monitoring in conjunction with a private engineering firm. HKI resulted in rapid vegetation establishment (1–2 years), providing protection against land loss due to RSLR (Sadat-Noori et al., 2021).

2.1.3. Sedimentation structures

A third method we identified for enhancing sedimentation are permeable sedimentation structures (Amrit et al., 2021; H. Winterwerp et al., 2014; J. C. Winterwerp et al., 2020). Sedimentation structures (e.g., fences) reduce water flow velocities and shelter the coast, tidal basin, or estuary, facilitating sediment deposition (Fig. 2c and Fig. 3.). Land reclamation using permeable wooden structures was common practice in the Netherlands from the 17th–20th century (Bakker et al., 2002) and resulting in a coastline expansion of several kilometres. Here, we report on two modern, active SES, in the Wulan and Ems deltas (WPS & EWG), which use sedimentation structures. Both projects have similar accretion rates (20–85 mm/yr). These SES are set up offshore and do not require the conversion of existing land which helps to minimise concerns of residents and ease potential stakeholder conflicts.

Sedimentation structures can be made of materials such as willow or other brush wood, making them a relatively inexpensive and adaptive SES. However, frequent maintenance (every year) is necessary for success, and maintenance often relies on local stakeholders including local governments and communities.

In the Wulan Delta (Demak, Java, Indonesia) (J. C. Winterwerp et al., 2020) permeable structures for sedimentation using bamboo, twigs, and

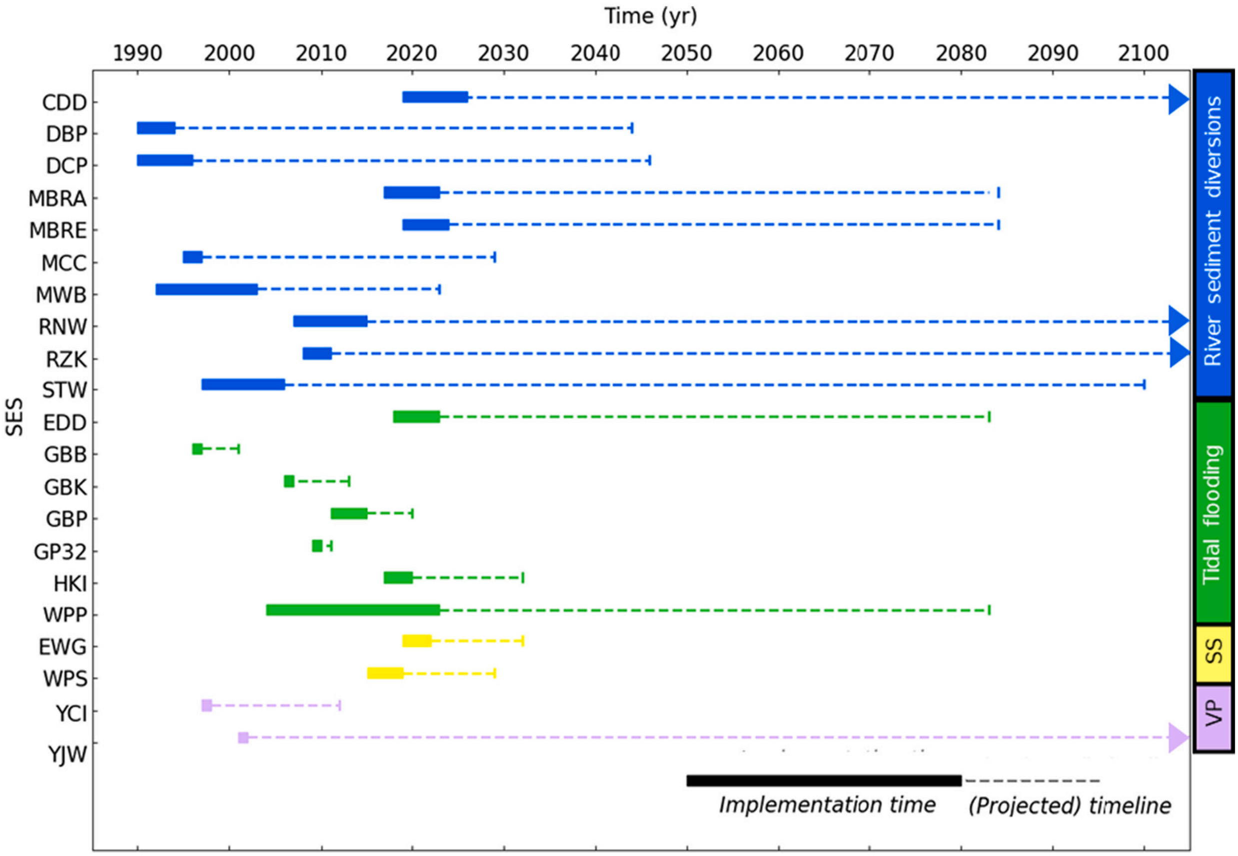
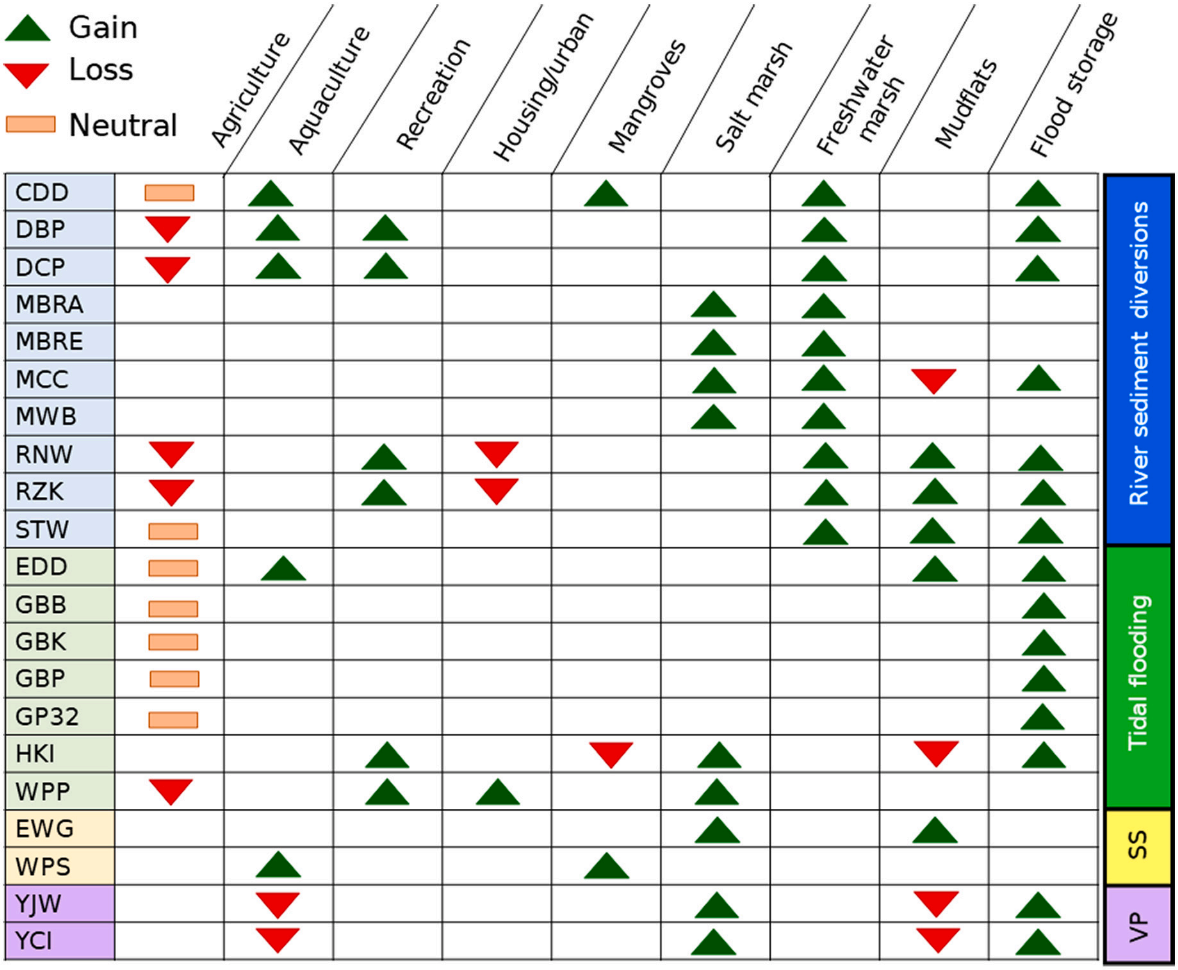


Fig. 5. Implementation time and (projected) timeline for implemented sedimentation-enhancing strategies (SES). SES with no projected end date or end date of >100 years are marked by an arrow at the end of the dashed timeline line. For codes/names for each strategy see Table 1.



▲ Gain
▼ Loss
▬ Neutral

	Agriculture	Aquaculture	Recreation	Housing/urban	Mangroves	Salt marsh	Freshwater marsh	Mudflats	Flood storage	
CDD	▬	▲			▲		▲		▲	River sediment diversions
DBP	▼	▲	▲				▲		▲	
DCP	▼	▲	▲				▲		▲	
MBRA						▲	▲			
MBRE						▲	▲			
MCC						▲	▲	▼	▲	
MWB						▲	▲			
RNW	▼		▲	▼			▲	▲	▲	
RZK	▼		▲	▼			▲	▲	▲	
STW	▬						▲	▲	▲	
EDD	▬	▲						▲	▲	Tidal flooding
GBB	▬								▲	
GBK	▬								▲	
GBP	▬								▲	
GP32	▬								▲	
HKI			▲		▼	▲		▼	▲	
WPP	▼		▲	▲		▲				
EWG						▲		▲		SS
WPS		▲			▲					
YJW		▼				▲		▼	▲	VP
YCI		▼				▲		▼	▲	

Fig. 6. Land use types gained and lost by implementing each SES. Neutral indicates that land loss and land gain areas are approximately equal. For codes/names for each strategy see Table 1.

brushwood were applied in 2013. Objectives were to mitigate erosion of mangrove-mud coasts where coastal erosion was causing multi-billion USD loss of housing, roads, agriculture and aquaculture (H. Winterwerp et al., 2014). Incorporating the needs and voices of residents was a cornerstone of the Wulan project, with the planning and funding coming from NGOs and international partners (Tonneijck et al., 2015).

In the Ems, as part of the Ems-Dollard 2050 project (van Es et al., 2021), sedimentation structures use brushwood willow groynes to trap mud. Modelling and pilots undertaken to find the most effective orientation for sedimentation (van Es et al., 2021). As with the double dikes, there was stakeholder engagement in all phases of the project.

In both cases modelling, monitoring upscaling is currently ongoing. In the Ems, a monitoring programme is being developed to learn from the pilot (RWS Informatie, 2019). Similarly, after the Wulan Delta pilot, the structures were adopted in coastal rehabilitation projects on the Indonesian Islands of Java, Sumatra, Sulawesi and Kalimantan (J. C. Winterwerp et al., 2020). Around the same time, different types of structures using bamboo poles were applied in the deltas of the Mekong (Vietnam) and Chao Prayo (Thailand) to combat coastal erosion, albeit with different success rates and varied spatial sedimentation (J. C. Winterwerp et al., 2020).

2.1.4. *Vegetation planting*

Wetland vegetation (mangroves, saltmarsh, weeds, ferns) stimulates biomass production, stabilizes the soil, and can increase sedimentation (see Fig. 2 and Fig. 3.). Managed planting of wetland vegetation is often used as an SES (Li et al., 2009; Wang et al., 2014; Yang, 1998).

For example, vegetation planting of smooth cord grasses (*Spartina alterniflora*) has been used along the east Chinese coast (regions of Jiangsu, Zhejiang, Tianjian) since 1979 (Chung, 1993, 2006; Zheng et al., 2018) to halt coastal erosion, with several projects undertaken and funded by national and local governments (X. Zhang et al., 2020). Recorded rates of sediment accretion within these types of planted wetlands ranged from ~70–300 mm/yr (Chung, 2006). Following success in coastal restoration, individual planting projects were introduced in the Yangtze estuary (Chen et al., 2008). We review 2 examples where vegetation planting was used to enhance sedimentation: the eastern Chongming Island (YCI) and Jiuduansha wetlands (YJW).

On eastern Chongming Island (located in the mouth of the Yangtze estuary) ~3 km^2 of *Spartina alterniflora* was planted in a national nature reserve in 2001 to reduce flow velocities, increase sedimentation and to accelerate land reclamation land (Chen et al., 2008; Zhao et al., 2020). It successfully halted soil erosion and the *Spartina alterniflora* spread quickly (X. Zhang et al., 2020). However, the choice of introducing a non-native invasive species *Spartina alterniflora* was quickly criticized as the long-term consequences for ecology and soil are considered to be generally negative for the nature reserve (Chen et al., 2008; G. Zhang et al., 2020). As the consequent negative effects became increasingly difficult to control, in 2012, the government of Shanghai began a multi-million-dollar project with the aim to remove the planted vegetation (Tang et al., 2021; X. Zhang et al., 2020).

On the Jiuduansha shoals, *Spartina* was planted in existing *Scirpus mariqueter* wetlands in 1997. The goal of this planting was to accelerate marsh formation and draw migratory birds away from a neighbouring airport (He et al., 2007). The planting led to successful colonization and rapid growth (Huang and Zhang, 2007), with predictions that the shoals will continue to rise in elevation and expand in area under all SLR scenarios (Gu et al., 2018) and there are no current plans for removal.

In addition to these two examples where vegetation planting is the primary SES, we also identify that vegetation planting is often used in conjunction with other SES (such as RNW, HKI, STW, DCP, DBP, WPS, see Table 1 and Fig. 6). For example, in the Louisiana Coastwide Vegetative Planting Project "The Jaws" (McGinnis et al., 2017). Here, ~15,000 bulrushes were planted in linear features that were intended to direct incoming Atchafalaya River water and sediment to locations where sediment accumulation was desirable. While not measured specifically, it appears the planting resulted in ~0.6 m of sediment accumulation in the target location over the course of ~5 years. The planted vegetation survived and spread broadly across the accumulated mudflat (McGinnis et al., 2017).

Some vegetation planting projects do not work as planned. In a pilot project in the Eastern Scheldt (Netherlands), planting of *Spartina anglica* onto coconut mats aimed to stabilize the coast through sedimentation and/or reduced erosion. Objectives were coastal protection and an increase in biodiversity. Plant growth and sediment deposition was low. Salt and heat stress caused plant mortality which made this strategy inefficient (EcoShape, 2021).

3. Results

3.1. Comparison of SES

When we compare 21 SES across all four SES types, we find that SES take 3 years on average to plan and implement (including stakeholder engagement). Timelines (amount of time they enhance sedimentation) vary. River sediment diversions tend to have longer lifetimes (20–100 years of repeatedly adding sediment to outflow area), some with no projected end date. Tidal flooding timelines depend on the type of land created and size of the area that is flooded. In the cases in Bangladesh (GBB, GBK, GBP, GP32) they have limited timelines (3–5 years), after which they can no longer be used to enhance sedimentation, as the newly created land changes in function. Sedimentation structures and vegetation planting have shorter lifetimes (5–10 years) before needing maintenance (which can extend viability to 25–30 years). The type of vegetation planted, and the speed and success of vegetation colonization strongly affects if vegetation planting can withstand SLR which ultimately determines its lifetime.

Most SES convert agriculture to wetlands (mangroves and marshes) and recreation areas (Fig. 4). Other common land use gains are aquaculture and flood storage, the latter of which can help alleviate flood hazard of areas close to the SES. Tidal flooding strategies can return land use to agriculture after project completion, but it can also create other land uses such as aquaculture and nature areas. The Perkpolder (WPP) is

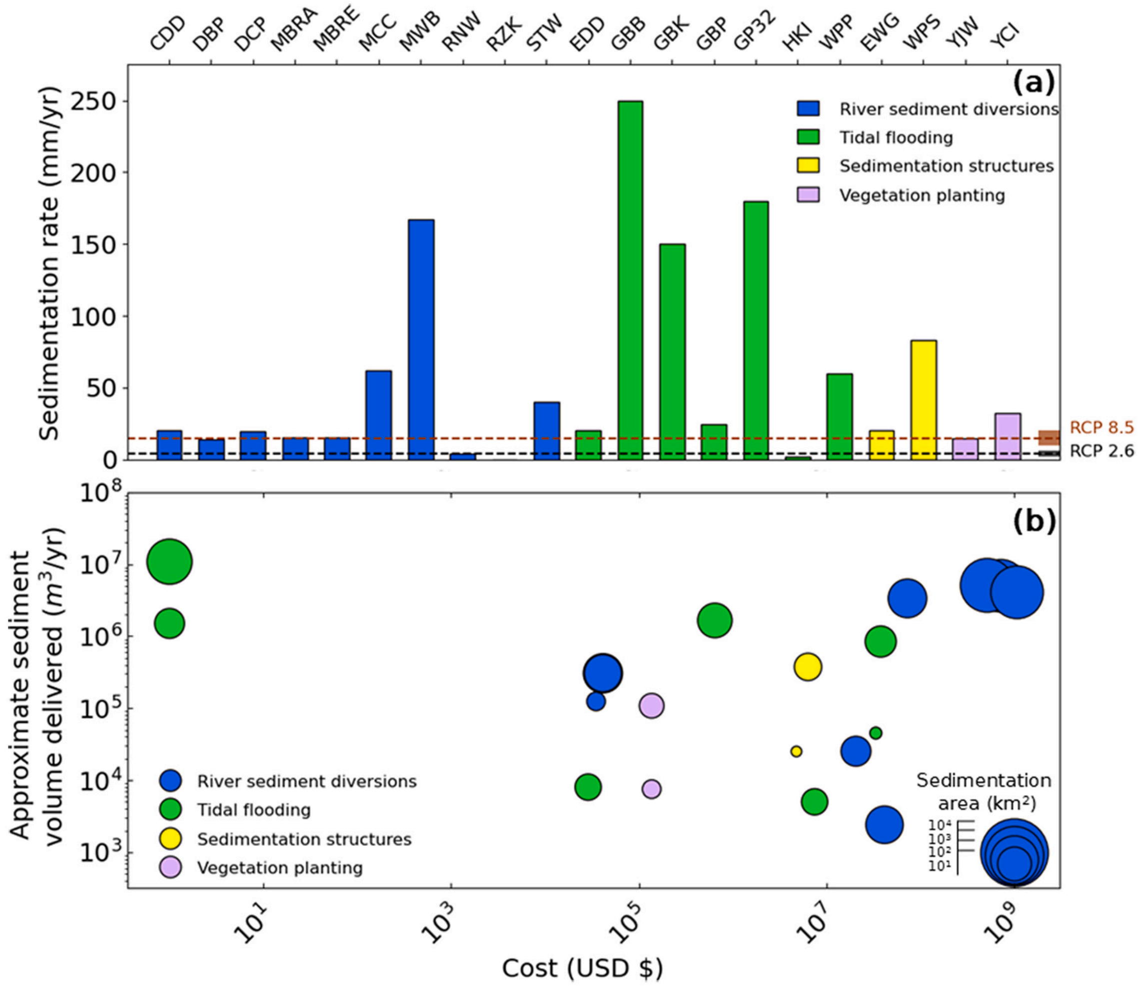


Fig. 7. a. The sedimentation rate of each strategy relative to the global sea-level rise rate for RCPs 2.6 and 8.5 in 2100 where the shaded areas on the right-hand side indicate the range of "likely" sea-level rise rates, and dashed lines are the average of these rates (Pörtner et al., 2019). b. Cost versus additional land created for each strategy with size of the circles indicating the outfall (sedimentation) area reached by each strategy, for codes/names for each strategy see Table 1.

the only strategy to create land area for housing or urban areas. Many of the projects also act as flood storage areas. Vegetation planting can change the land use by changing habitats and species diversity. In the case of Chongming Island (YCI) native mudflat fauna and migratory bird breeding habitat were lost but saltmarsh area was gained through the choice of planted vegetation.

Next, we compare vertical sediment accretion rates between all SES. We find that nearly all strategies, active and planned, keep pace with modern and future projected global mean RSLR by 2100, even for worst-case climate scenarios (RCP8.5, Fig. 5). However, accretion is mostly measured of short time horizons and may not reflect long-term average conditions. Local RSLR can also be higher or lower than the global mean. Low accretion rates are found in the Rhine-Meuse delta (RNW, RZK) and Hunter estuary (HKI) SES which do not keep pace with RSLR under RCP8.5 by 2100. For RNW and RZK, low sediment concentrations in the river (20 mg/L) make the accretion rates low (6 mm/yr). In the case of HKI, the short-term nature of the project led to low sedimentation rates as salt marsh vegetation was only beginning to establish (future accretion rates may be higher).

Cost varies tremendously between the 21 SES considered (Fig. 5). Some carry no cost (local action in Bangladesh, GBB); others are multi-million or billion USD projects (MBRA, MBRE, CDD). River sediment diversions in most cases, cost 10–1000 million USD. Tidal flooding costs range from 0–35 million USD and sedimentation structures cost 5–10 million USD. These costs are adjusted for inflation to 2021 but are not converted to local purchasing power.

Costs exclude maintenance but also any potential ecosystem service benefits. Additionally, it is important to note that the cost of doing nothing (opportunity costs), can be significant and hard engineering methods (e.g., levee construction, sea walls) can be just as expensive as these SES (Giosan et al., 2014). These elements make SES cost and benefits difficult to quantify, as it can avoid direct loss of infrastructure and land but also ecosystem and cultural loss. It is also interesting to note that while vegetation planting is relatively cheap (YJW and YCI), the cost of removal can be exceptional (hundreds of millions of US dollars) (Tang et al., 2021).

SES benefits also vary. Expressed as the delivered sediment rate, even though most sedimentation-enhancing strategies also have other objectives and benefits, we find that SES range from $\sim10^4$ m^3/yr (STW) to $\sim10^8$ m^3/yr (MBRA). Expensive strategies generally supply more sediment across a larger sedimentation area (Fig. 7). River diversions (MBRE, MBRA, CDD, RNW, RZK) cost the most to implement but reach large sedimentation areas (tens to hundreds km^2) and most are very effective at keeping pace with sea-level rise. Cheaper strategies can create similar new land areas for less cost but are generally short-term measures (Fig. 5). Sedimentation structures and vegetation planting are only suitable for smaller sedimentation areas but can deliver consistent sediment accretion.

4. Discussion

4.1. The need for multidisciplinary research

The success of SES is not only reliant on the physical setting of the delta or the strategy. SES rely heavily on socio-economic, legal and governance systems, including, but not limited to: decision making processes, stakeholder engagement, legal restrictions, land ownership, and environmental impact (including ecosystem considerations). SES are inherently local; they are fitted to suit the local environment and local knowledge is required before an SES is actualised.

Agencies involved in planning and implementation of SES vary (Table 1). Sometimes it is a top-down decision where a national government decides to target delta sedimentation and employ research institutes or private consultancies to design and test solutions (e.g., Canal del Dique, CDD (Sokolewicz et al., 2016)). In other cases (e.g., Beel Bhaina, GBB) residents implemented an SES, which was then later acknowledged and extended by the national government. In the Danube and Wulan deltas (GBP, GBP, WPS), NGOs coordinated and funded the SES with the support of local research institutes. Kooragang Island (HKI) and the Jiuduansha wetlands (YJW) projects are exceptions, as they were organised and developed by a local university (in collaboration with local authorities). Often projects are also supplemented with EU (Rhine-Meuse: RNW, RZK) or World Bank funding (Danube: DBP, DCP) and in some cases (Kooragang Island: HKI) funding from private organisations.

Planning and implementation depend on land ownership. Many SES require changes in land use. Sometimes it is permanent (e.g., Rhine-Meuse: RNW, RZK) but sometimes it is only temporary (e.g., Bangladesh: GBK, GBP) loss of agricultural land. We found that SES have been established for a mixture of state and private land and have sometimes required land purchasing with its associated legal, cultural, and ethical considerations.

All the SES listed require collaboration between several parties in planning, funding, implementation, and monitoring. Nearly all projects (aside from local actions of GBB) rely on private companies or research institutes to undertake modelling, scenario design, environmental impact assessments and design of the SES. Private contractors are often also responsible for designing and undertaking stakeholder engagement, which is pursued for most SES to bridge the physical, environmental, cultural, and governance components and allow for multidisciplinary research. The importance of including and engaging with local people is increasingly recognised in such projects, as these local and regional stakeholders have easy access to information on local issues and are aware of local environmental conditions (M. Cox et al., 2010).

The stakeholder engagement process can be undertaken at multiple steps including in the design of the project, consultation phase (adjusting the project), monitoring, and reporting. The influence and interests of stakeholders are key to how stakeholder engagement informs SES development. In most cases, and particularly if the project was not experimental (Kooragang Island, HKI and Twitchell Island, STW), stakeholder engagement was undertaken in the consultation phase and in some cases (Ems Estuary, EDD, EWG) also in the design phase. One key exception was tidal flooding in Bangladesh (GBP, GBK) where there was limited engagement. A stakeholder conflict occurred after governmental bodies took on a locally implemented idea, which has raised questions about the long-term effectiveness and acceptability of upscaling or continuation of the strategy (Gain et al., 2017). Similarly, in the Danube delta, poor communication and a lack of stakeholder engagement delayed projects and decreased their sustainability (World Bank, 2005). In the Yangtze, the earlier of the two projects had no stakeholder engagement (YJW) while the second project (YCI) had limited engagement (only the nature reserve where planting would occur) by Shanghai Municipal Government (municipal government and private partners) who are now also responsible for the removal programme of the vegetation. This is however, criticized, as often the knowledge of local people is being lost (Xie et al., 2019).

Environmental impact is also an important consideration in the planning and implementation of SES. For several of the projects (e.g., DBP, DCP, HKI, CDD, STW, RNW, RZK) the main goal is to enhance or restore wetland habitats and thus projections of habitat formation are key in decision making (Fig. 4). In nearly all cases, an environmental impact assessment is undertaken by the organising body. In most cases it is legally mandatory to identify which habitats or species will be harmed or benefit from the strategy. SES tend to have a long-term positive ecological impact, but some short-term loss of species or habitats can occur because of changes in hydroperiod and salinity (MWB, RNW). In both vegetation planning examples (YJW & YCI) there were adverse effects on habitats due to the choice of vegetation. Long-term goals in terms of ecology should also be addressed, as the example of *Spartina alterniflora* planting in China (see Section 2.1.4) indicates: while the short-term goals of soil erosion limitation were met, the invasive species led to decline of many other flora and fauna and a long-term ecological loss that extended beyond the planting area.

4.2. Prospects

The SES synthesized have are generally small footprints given the challenges faced by global deltas. Climate change driven RSLR is projected to flood 5% of global delta land by 2100 (Nienhuis and van de Wal, 2021), but all SES sedimentation areas together comprise 0.1% of global habitable delta land (Edmonds et al., 2020). Upscaling potential will be key in their implementation in deltas globally, although the suitability of local conditions presents a challenge. Sedimentation processes in river deltas are complex and success of sedimentation is closely linked to biophysical and socio-economic aspects which are case-specific. The most critical aspects in determining sedimentation rate include river sediment concentration, elevation, ecological processes (including vegetation succession, species richness, salt intrusion), biogeochemical processes and natural and human-induced subsidence (Paola et al., 2010).

Several of the projects outlined here have investigated the concept of upscaling (see Table 1) and some (STW MWB, YJW, YCI) have already been upscaled and implemented in more locations. However, it is increasingly likely that combinations of multiple, types and scales of SES will be required to offset land and elevation loss in deltas, particularly due to the varying timescales, costs, land creation and land types created. We therefore suggest that multiple strategies at various locations in deltas will be the best way for SES to be sustainable in the long-term.

An important challenge for SES in many deltas is their dependence on sufficient sediment supply (Liu et al., 2021). Reduced supply toward deltas worldwide (Dunn et al., 2019), and increased competition for sediment due to sand mining for construction (Bendixen et al., 2019), present a risk. For SES to be successful and sustainable it is imperative that sediment delivery is reliable and where necessary, maximized (Ibáñez et al., 2014). Improved regulation or even removal of hard engineering solutions such as such as dams, dikes, and seawalls, which cannot accrete sediment, is also likely to be beneficial (Bendixen et al., 2019). Other aspects of delta management can be undertaken to address the causes for elevation decline and limit the need for SES. One such example is curtailing or even ceasing groundwater withdrawal to limit subsidence (Shi et al., 2016).

Other challenges include spatial requirements of SES. They compete for space with other land use needs such as population growth, urbanisation, climate change, freshwater demand, and food security. Delta sustainability as a complex management and governance issue (Loucks, 2019; Triyanti et al., 2020). Adaptive delta management is a useful tool in tackling the issues faced by deltas and their future management (Dewulf and Termeer, 2015) and therefore in the design, implementation and funding of SES.

SES also require resources in terms of funding, technology, scientific expertise, and infrastructure which can be a challenge in “resource poor” deltas (Wesselink et al., 2020). As seen in Fig. 1, many of the SES currently implemented are in high or upper middle-income countries, in Europe, China, Colombia, Australia and the USA. Exceptions are the Wulan delta (WPS) in Indonesia where a relatively cheap project was implemented using natural materials, and tidal flooding in Bangladesh (GBB) which is a bottom-up strategy implemented by farmers at minimal cost.

5. Conclusions

SES have proven effective in many deltas globally in creating and maintaining elevation. Our synthesis of 21 strategies shows that many SES are small-scale (<20 km^2) and short-term ($<$ 20 years) because large-scale and long-term strategies are more expensive and may have more extensive impact on vested interests of stakeholders. Nevertheless, SES are effective as tools for delta sedimentation in response to high rates of SLR. Most strategies tend to create wetlands and recreation areas, opportunities for agriculture or aquaculture, and also provide flood storage. Successful SES have raised land while also managing the needs of stakeholders, displaying effective governance, minimising negative environmental impacts, and offsetting subsidence and SLR. Planning, design, and construction timelines for SES range from several years to decades, and it can take additional years to become effective in sedimentation. With accelerating SLR, the survival of densely populated and urbanized deltas depends on the timely implementation of new SES.

CRediT authorship contribution statement

Jana R. Cox: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization, Data curation, Funding acquisition. **Mandy Paauw:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Data curation. **Jaap H. Nienhuis:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Funding acquisition. **Frances E. Dunn:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Funding acquisition. **Eveline van der Deijl:** Validation, Resources, Writing – review & editing. **Christopher Esposito:** Validation, Resources, Writing – review & editing. **Marc Goichot:** Validation, Resources, Writing – review & editing. **Jasper R.F. W. Leuven:** Validation, Resources, Writing – review & editing. **Dirk S. van Maren:** Validation, Resources, Writing – review & editing. **Hans Middelkoop:** Validation, Resources, Writing – review & editing, Funding acquisition. **Safaa Naffaa:** Validation, Resources, Writing – review & editing, Funding acquisition. **Munsur Rahman:** Validation, Resources, Writing – review & editing. **Christian Schwarz:** Validation, Resources, Writing – review & editing. **Eline Sieben:** Validation, Resources, Writing – review & editing. **Annisa Triyanti:** Validation, Resources, Writing – review & editing, Funding acquisition. **Brendan Yuill:** Validation, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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