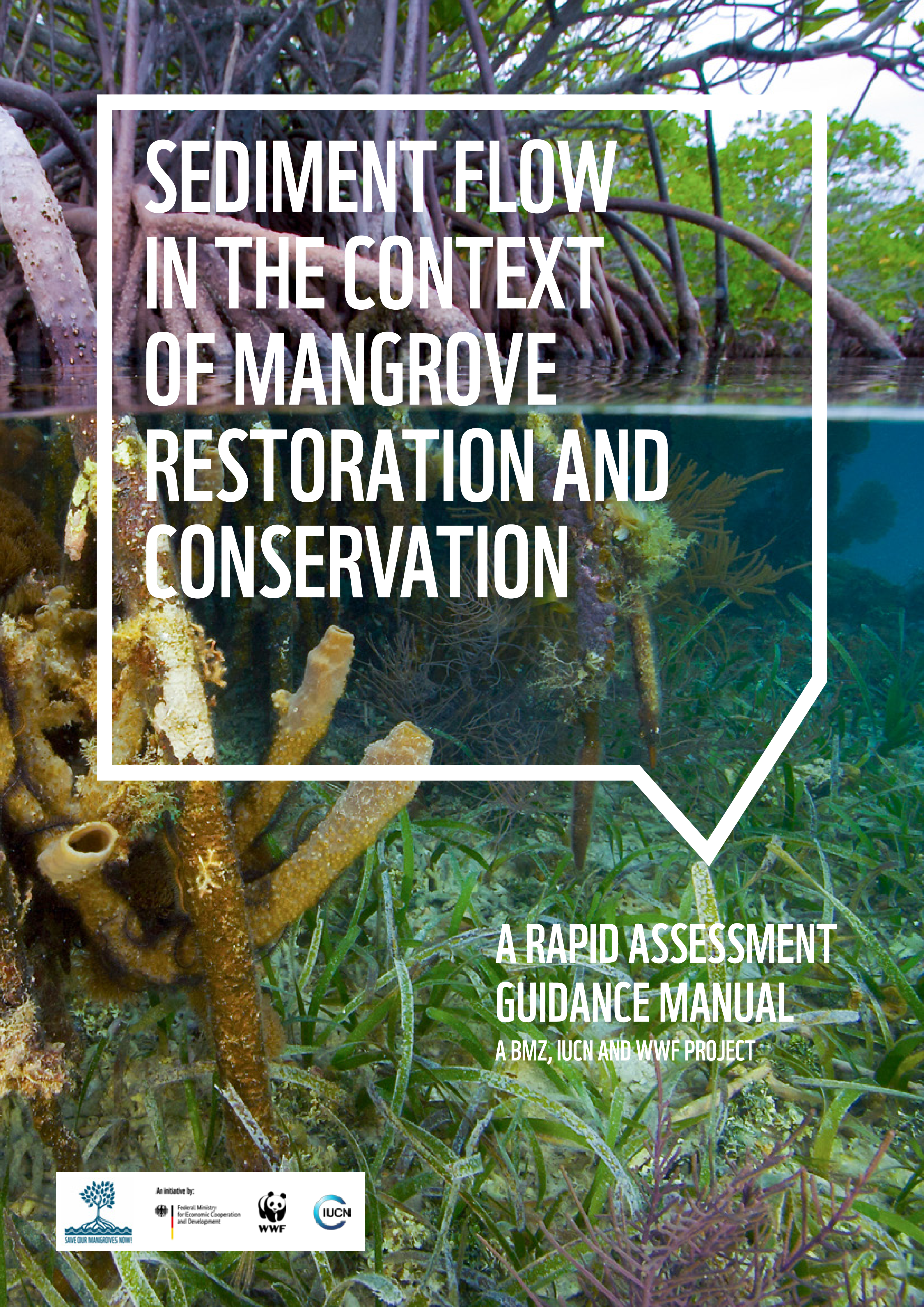

SEDIMENT FLOW IN THE CONTEXT OF MANGROVE RESTORATION AND CONSERVATION

A RAPID ASSESSMENT GUIDANCE MANUAL

A BMZ, IUCN AND WWF PROJECT

SAVE OUR MANGROVES NOW!

An initiative by:

Federal Ministry for Economic Cooperation and Development

WWF

IUCN

SAVE OUR MANGROVES NOW! - INITIATIVE

"Save Our Mangroves Now!" is an international initiative that mobilizes political decision makers and supports other actors towards halting and reversing the loss of mangroves, both globally and with a specific focus on the Western Indian Ocean. Mangroves matter to each and every one of us. They help our climate, protect our coastlines, provide us with food and support livelihoods for people living by the sea.

The initiative is led by the German Federal Ministry for Economic Cooperation and Development (BMZ), the World Wide Fund For Nature (WWF) and the International Union for Conservation of Nature (IUCN).

We join forces with other mangrove conservation stakeholders to connect the needs of nature and people by giving voice and showing solutions to the current environmental challenges. Follow and save the #humangroves.

www.SaveOurMangrovesNow.org

Lead authors: Edward Anthony (University Aix-Marseille) & Marc Goichot (WWF-Greater Mekong).

Contributors: Joerg Hartman (Consultant), Manon Besset: University of Montpellier and Aix Marseille University, Gael Chatagno: Aix Marseille University.

Thanks to the following people who contributed guidance or reviews: Andrew Wyatt (IUCN Vietnam), Dr Anurag Danda (WWF India), Emmanuel Japhet (Wetlands International Africa), Frank Van Der Valk (WWF Myanmar), Hoang Viet (WWF Vietnam), Julika Tribukait (WWF Germany), Lee Poston (WWF-Greater Mekong), Rab Navaz (WWF Pakistan), Raphaelle Flint (IUCN), Richard Lee (WWF International), Saeed Islam (WWF Pakistan), Salai Thurazaw (WWF Myanmar), Mr Siddhartha Baidya (WWF-India), Southern Institute for Water Resources Research (Vietnam), SureshBabu (WWF India), Trinh Thi Long (WWF Vietnam) and WWF Tanzania Team.

Design & Editing: Game Changer Creatives (Creative Director: Nadim Boughanmi, Art Director: H. Dennis Lee)

ISBN 2-88085-096-8

Front cover image: © *Tim Laman / WWF - Rich invertebrate life including corals, tunicates and sponges cover the underwater portions of the mangrove roots on an offshore mangrove island.*
Back cover image: © *Green Renaissance / WWF - US Pira Sulemane on patrol in a mangrove forest, he patrols for poachers and monitors wildlife in Quionga, near Palma, Mozambique, Africa.*

Supported by the

Federal Ministry
for Economic Cooperation
and Development

CONTENTS

SUMMARY		4
1.	**INTRODUCTION AND CONTEXT**	6
1.1	General overview of mangroves	6
1.2	Why is sediment supply important for mangroves?	10
1.3	What are the impacts of a diminished sediment supply on mangroves?	12
1.4	Mangrove conservation and restoration	14
2.	**REPORT OBJECTIVES**	16
3.	**SEDIMENT SUPPLY FROM RIVER BASIN TO MANGROVES: SCALES OF ANALYSIS**	17
3.1	The river basin scale	17
3.2	The delta scale	18
3.3	The coastal scale	20
3.3.1	Muddy deltaic shorelines and mud transport pathways: implications for mangroves	22
3.3.2	Sandy deltaic shorelines and sand transport pathways: implications for mangroves	23
3.4	The site scale	24
3.5	Implications of river sediment flux analysis for rehabilitation/restoration of mangroves	26
4.	**THE RAPID ASSESSMENT GUIDE ON SEDIMENT FLOW IN THE CONTEXT OF MANGROVE CONSERVATION AND RESTORATION**	28
5.	**CONCLUDING REMARKS AND PERSPECTIVES: RIVER SEDIMENT FLUX AND MANGROVES IN A CONTEXT OF CLIMATE CHANGE AND INCREASING ANTHROPOGENIC PRESSURES**	29
ANNEX: METHODOLOGY FOR RAPID ASSESSMENT		32
A.	Assessment Tables - Mangroves and sediments	33

SUMMARY

Section 1 of this report provides context on the role of mangroves, as a unique ecosystem, and their benefits to people. It also outlines why sediment supply is important for mangrove sustainability, the impacts of a diminishing sediment supply, and why one should consider sediment when undertaking mangrove conservation and restoration. Section 2 sets the objectives and frame of the rapid assessment tool. Section 3 presents method and guidance to understand and assess key processes, the impact of human interventions and how to measure this impact on sediment flows and deposition, while taking into account the state of relevant governance and policy frameworks at four spatial scales of analysis interlinked by sediment flow connectivity: (1) river basin scale, (2) delta scale, (3) coastal scale, and (4) site scale. Section 4 explains how to conduct a rapid assessment for non-experts when data is readily available – even if it is limited. Section 5 provides concluding remarks on the future of mangroves in the context of climate change and increasing anthropogenic pressures. Further guidance on how to use the tool is provided in the annex.

MANGROVES TODAY

Mangroves are found at the junction of three biomes[1]: terrestrial, marine and freshwater. They are found in the intertidal zone between high and low water on low-lying coasts, and they are one of the world's most productive ecosystems for food, notably for rice and fish. Mangrove areas are therefore often densely populated by humans, which brings them under significant and ever-increasing pressures that have resulted in the conversion of large tracts of mangrove forests to coastal developement, for exemple agriculture and aquaculture zones.

The exploitation of mangrove areas is however extremely problematic: these extraordinary trees that have the ability to thrive despite the presence of salt in water, play a unique role as biodiversity hotspots. They are also one of nature's anti-tsunami and anti-cyclone defence systems. Cyclones are becoming more intense with climate change, making the pressures on mangroves a problem that needs to be addressed with extreme vigilance.

Pressures on mangroves are often direct. These include deforestation, either related to wood-cutting – for firewood and construction – or to the conversion of mangrove areas into farmlands, aquaculture farms, and grazing pastures.

Coastal erosion and increased subsidence in river deltas – which both account for more than 40% of the world's mangrove areas – are also detrimental factors of mangrove degradation. Increased subsidence in river deltas is more difficult to ascertain, and is thus often overlooked. Coastal erosion and increased subsidence in river deltas are essentially due to insufficient river sediment supply, a phenomenon that can originate several thousand kilometres upstream in the river basins to which these deltas belong.

The net long-term sustainability of mangrove-bearing shorelines depends first and foremost on an adequate sediment supply. Mangroves – like all trees – rely on sediments, yet are at the same time, limited producers of sediments (meaning in situ organic production by mangrove roots, leaves and tree trunks.)

Mangrove populations are often found on coasts that are subjected to land subsidence and erosion processes that are in natural dynamic balance, meaning that natural forces continuously ensure that sediments are replenished. Without an adequate sediment supply, these processes become imbalanced, thus creating serious threats to the integrity of mangrove ecosystems.

MANGROVES AND SEDIMENTS

In considering the role of mangrove ecosystems, the free flow and availability of sediments constitute an overarching background factor without which (1) mangrove substrate elevations cannot be durably sustained, and (2) the commonly considered 'land-building' and 'coastal protection' roles of mangroves cannot be successful. The extent to which mangroves can be conserved, or the eventual outcome of mangrove rehabilitation or restoration projects, fundamentally depend on sediment supply. Many mangrove rehabilitation or restoration projects, often implemented at a considerable cost, unfortunately overlook this fundamental criterion, and therefore sometimes meet with failure.

[1]A biome is a community of plants and animals living together in a certain kind of climate. Scientists have classified regions of the world into different biomes. Source: NASA.

Sediment replenishment to coasts by rivers is a natural process which is greatly hindered by the trapping effect of man-made structures, such as dam reservoirs, and by sand mining. This is further aggravated by groundwater extraction and by sea-level rise induced by climate change, both of which increase the need for more sediments to balance accelerating subsidence, and to fill the 'accommodation space' created by water-level increases. This is notably the case in delta areas where natural subsidence is common, and which can exacerbate sea-level rise. Further disruptions of sediment supply and dynamics are frequently caused by the presence of harbours, ports, and coastal protection structures such as groins and dykes.

THE RAPID ASSESSMENT GUIDE

The aim of this report is to provide an assessment guidance manual for the management of mangrove conservation and restoration. This manual takes into account sediment flows and sediment deposition as crucial factors in the success of mangrove projects. This will help local decision-makers in large tropical river deltas to better plan and manage mangrove conservation and restoration programmes. Derived from background literature, workshops in Tanzania, Vietnam and Myanmar, and questionnaires on policy and field practices in connection to mangroves in the Irrawaddy, Ganges-Brahmaputra, Indus, Mekong and Rufiji river deltas, the manual has two key purposes: one, to ensure mangrove practitioners, coastal zone managers and land-use planners in delta regions are aware of, and able to address sediment issues at the various spatial and temporal scales of analysis and planning – with special attention given to mangrove resilience to environmental stressors and perturbations – and to better understand the factors that lead to the success or the failure of mangrove replanting and rehabilitation projects. Secondly, this manual aims to provide guidance on best management practices, by integrating the sediment-supply dimension in mangrove conservation, rehabilitation or restoration.

The rapid evaluation guidance manual applies a multi-scale approach to the assessment of sediment supply and availability. It guides the collection of existing information on man-made major causes of loss of sediments, and the governance frameworks relative to their management. The four embedded scales are: the river basin scale, the delta scale, the coastal scale, and the local mangrove site scale.

Crab fisherman in a mangrove forest in Thailand.

1.1 GENERAL OVERVIEW OF MANGROVES

RIVER BASIN

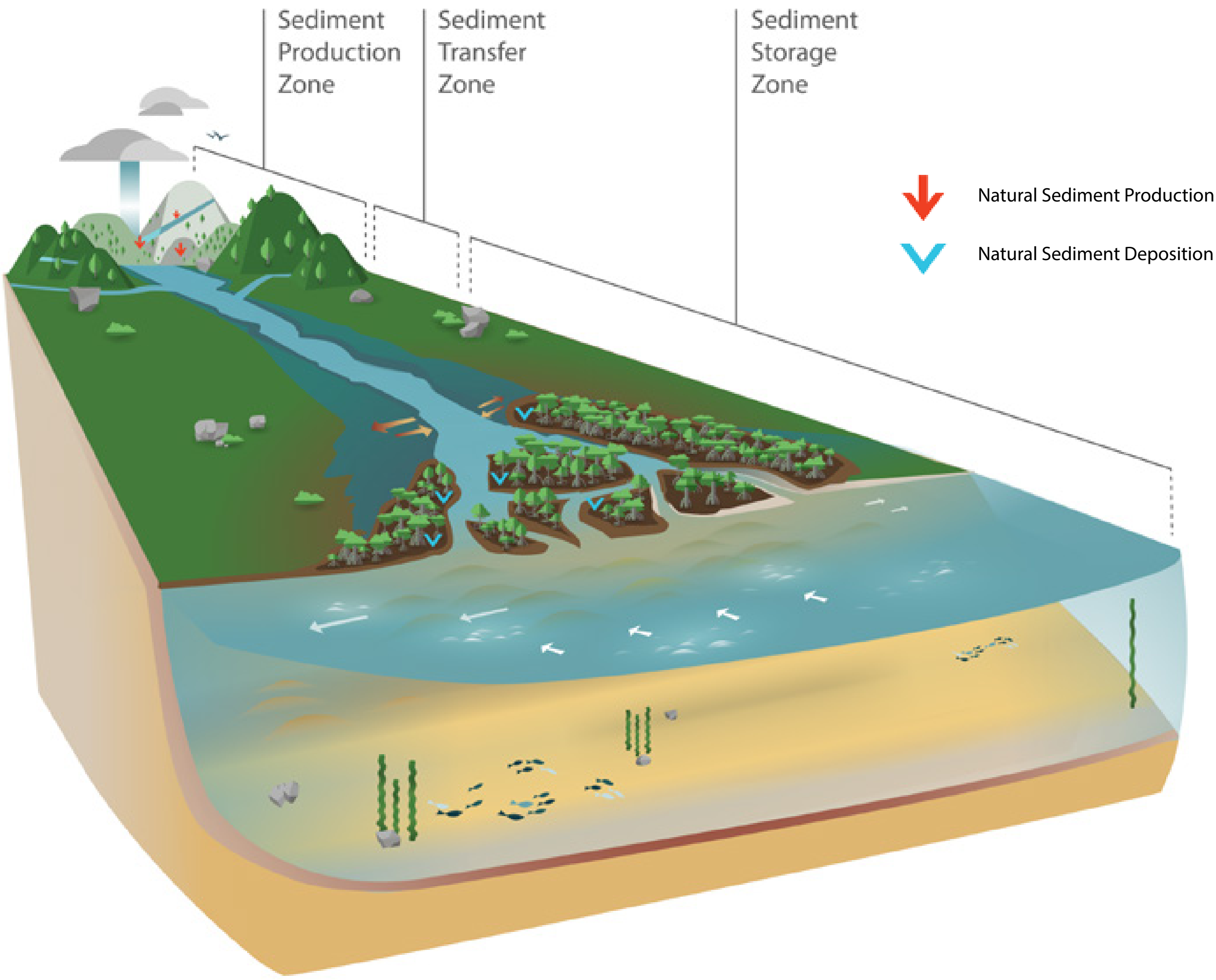

Fig 1a: Diagram of a river delta. Deltas are subaqueous and sub-aerial coastal accumulations that develop at the interface between a river catchment and a receiving basin (marine or lacustrine). They form infilled river mouths that have advanced seaward under conditions of abundant supply of sediments by the river catchment and a stable sea level. Deltas are among the largest landforms on Earth, and are usually simply classified as wave-, river- and tide-dominated. Deltas host over 40% of the world's mangroves. Mangroves are best developed in tropical, relatively wave-sheltered, tide-dominated deltas with large mud supplies, but can also be found extensively on shores and river channels and backwaters of river-dominated deltas, and in sheltered areas in wave-dominated deltas.

Fig 1a.i: Mountains and hills produce most of the sediments entering the river bed.

Fig 1a.ii: Sediments deposit in floodplains and deltas.

Mangrove colonies are halophytic[2] coastal forests that develop at the interface between muddy shores and mostly brackish waters. They are characteristic of many tropical and subtropical coastlines between 32°N and 38°S, and occur extensively within the higher part of the intertidal zone between low and high tide. The largest mangrove systems are generally associated with river deltas. Deltas are subaqueous and sub-aerial coastal accumulations of sediments supplied by a river catchment (Figure1a). The ecological status of mangroves as valuable and highly productive wetland habitats has long been recognised.

The ecosystem services provided by mangroves have been well summarized by Lee et al. (2015). Mangroves serve as nurseries for subsistence fishing and commercial fisheries, provide opportunities for green recreation, are important in assuring biodiversity, are active components of tropical coastal and estuarine food chains, act as filters of pollutants reaching estuarine and coastal waters, and act as carbon sinks that reduce greenhouse gas emissions, an important consideration in a time of climate change.

Mangroves shelter wildlife, being key for the primary production and the life cycles of many species from the terrestrial, marine, and freshwater biomes. The thriving and survival of these species are profoundly dependent on healthy mangroves. A wide and healthy belt of mangroves fringing the shoreline also plays a significant role in contributing to coastal protection by dissipating waves under normal energetic ocean-forcing conditions. Their protective role on coasts exposed to high-energy events such as cyclones and tsunami has been demonstrated in numerous scientific publications.

Mangroves are subject to continuously growing local anthropogenic pressures in the face of economic development and population growth. A number of recent global syntheses (e.g., Hamilton and Casey, 2016; Feller et al., 2017; Thomas et al., 2017; Worthington and Spalding, 2018) all document a general decrease in world mangrove coverage, albeit at a declining rate. The statistics on mangrove extent, gains and losses compiled by Worthington and Spalding (2018) show that the global extent of mangroves decreased from about 142,800 km^2 in 1996 to about 136,700 km^2 by 2016, representing a net loss of over 6,000 km^2. There are many causes for mangrove loss and these have been well documented in the literature. They include deforestation for various purposes, large-scale conversion of mangrove areas into shrimp farms

[2] Tolerant to saline waters.

AFTER HUMAN INTERVENTION

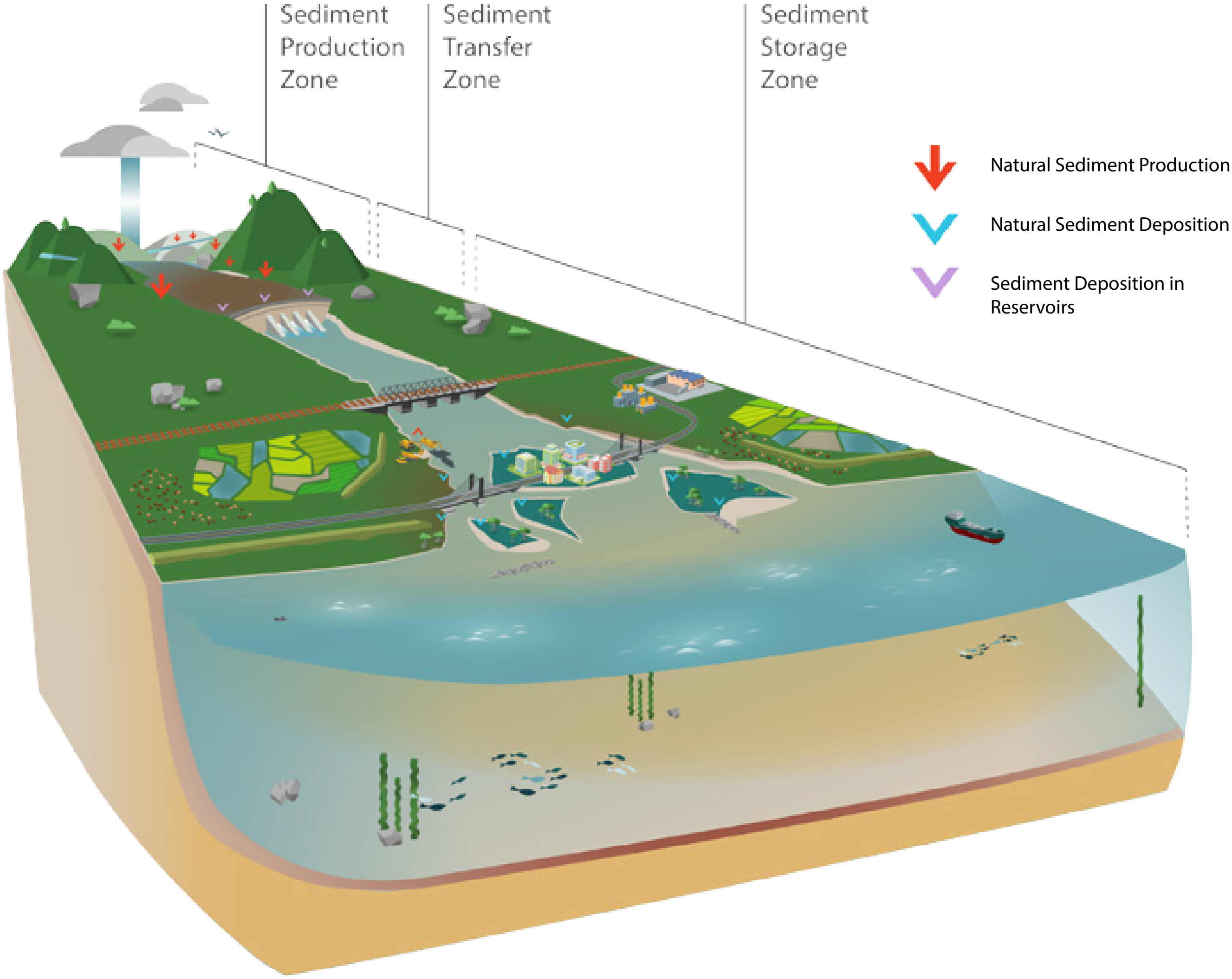

Fig 1b: Mangroves are subject to continuously growing local anthropogenic pressures in the face of economic development and population growth. They include deforestation for various purposes, large-scale conversion of mangrove areas into shrimp farms or rice fields, and the construction of roads, railways, dykes and seawalls that impair mangrove connectivity and sediment flow.

Mangroves are important coastal ecosystems that are strongly impacted by human activities, however, direct on-site alterations may not be sufficient to explain all mangrove losses, especially in large deltas which account for over 40% of the world's mangroves.

Fig 1b.i: Sand extracted from the river beds for construction and land reclamation.

Fig 1b.ii: Dam reservoirs trap sediments.

or rice fields, and the construction of roads, railways, dykes and seawalls that not only impair mangrove connectivity but also freshwater, sediment and nutrient supplies to them. In some areas, this leads to a clear mangrove 'squeeze' effect (Woodroffe et al., 2016). The literature also shows that Southeast Asia, which contains half of the entire global mangrove forests, with many large river deltas rich in mangroves, is a region of concern with mangrove loss rates ranging from 3.58% to 8.08% between 1996 and 2016 (Worthington and Spalding, 2018). Direct human impacts on mangroves may not be sufficient to explain all mangrove loss, especially in large tropical deltas where new mangrove development can be important and sediment supply a primary issue (Figure 1b).

Of the 6,000 world mangrove units identified by Worthington and Spalding (2018), only 95 are deltaic – but these cover 55,300 km² or 40.5% of global mangroves. This reflects the important spatial continuity of mangroves provided by the rich and commonly large coastal sediment repositories in river deltas (Anthony, 2013). Estuarine mangrove systems make up 27.5% of the world's mangroves scattered among 965 estuarine units (Worthington and Spalding, 2018). Together, deltas and estuaries, which are intimately linked to, and dependent on, river basins for sediment supply, account for 68% of all mangroves. Estuaries are found in drowned river valleys that are still being filled in by fluvial (and often marine) sediments. They contrast thus with deltas, which represent sediment-filled river mouths wherein the main channel generally branches out into distributaries that convey river liquid discharge and sediment loads from upstream.

1.2 WHY IS SEDIMENT SUPPLY IMPORTANT FOR MANGROVES?

Mangroves are closely linked with their physical environment, and a strong relationship exists between them and sediments. The net long-term sustainability of clastic (sedimentary) mangrove-bearing shorelines (as opposed to dominantly rocky shorelines where sparse mangroves may also subsist) depends on an adequate sediment supply. In this manual, river deltas form the essential basis for analysing sediment flows from river catchments to mangroves. Since non-deltaic clastic coasts are largely dependent on alongshore supply of sediments originating from river mouths, the status of mangroves on these coasts is also ultimately conditioned by variations in fluvial sediment supply.

Healthy and abundant mangrove colonies are found in areas with a muddy substrate that is continuously renewed in fresh water, sediments, and nutrients. A muddy substrate requires an adequate sediment supply to balance (1) the re-suspension of mud by currents and waves, (2) the sinking of the surface (subsidence) in deltaic settings under their own weight, or human activity, and (3) sea-level rise.

But this is also a two-way relationship: mangroves are not just a passive component in coastal sedimentation.

Where fine-grained sediment is available, mangroves can contribute actively to sediment accumulation (accretion) on tidal flats by slowing down sediment-charged currents (Furukawa et al., 1997; Anthony, 2004). Trapping sediment through their complex aerial root and trunk structure (Figure 2), and, in some species, their breathing apparatus, called pneumatophores, gives them the capacity to influence muddy sedimentation. This corresponds to what has been termed as their geological or 'land-building' role (Carlton, 1974), an ecological service in its own right, since it contributes to natural and active land gain.

NATURAL STATE

Fig 2: Where there is a sustained supply of mud, mangroves contribute actively to coastal accretion (their land-building role) while at the same time contributing to wave-energy dissipation (their protection role). Where there is a sustained deficit in the supply of mud, muddy substrates are eroded and the coast retreats. Light brown are recent deposits of mud, cream colour are recent deposits of sand.

Fig 2.i

Fig 2.ii

Fig 2.iii

Healthy mangroves can trap more than 80% of incoming fine-grained sediment (Furukawa et al., 1997) and contribute to sedimentation rates of the order of 1-8 mm/year.

Such rates are generally higher than current local rates of mean sea-level rise but are likely to be outstripped by sea-level rise rates within the next 35 to 50 years (Sasmito et al., 2016). Accretion cannot continue indefinitely as with time, the higher elevation reduces flooding time (hydroperiod), thus reducing the potential for fresh sediment deposition. There is a fine balance, therefore, between sediment supply and mangrove-supported accretion. Surplus sediment contributes to shoreline advancing seaward, providing a substrate for further mangrove colonization. It is worth noting here that the efficiency of sediment-trapping by mangroves depends, of course, on sediment availability.

By inducing accumulation of mud under conditions of readily available sediment, mangroves contribute to the mitigation of sea-level rise effects induced by climate change, as well as subsidence in river deltas.

River sediment supply is an overarching condition for long-term mangrove sustainability, and mangroves can, in turn, contribute actively to sediment accumulation where such sediment is available.

Fig 2.i: Where wave energy is low and mud supply high, mangroves prosper, trap mud, and there is a gain of land on the sea. Mangroves protect coastlines where cyclones and tsunamis hit.

Fig 2.ii:: Sand dunes and beach ridges create calm areas behind them that allow mud to deposit and be colonized by mangroves.

Fig 2.iii: Sand protection of mangrove coasts can also be assured by nearshore bars and banks.

1.3 WHAT ARE THE IMPACTS OF A DIMINISHED SEDIMENT SUPPLY ON MANGROVES?

Over the last few decades, human impacts, coupled with the effects of sea-level rise, have caused coasts and deltas to be economically and environmentally vulnerable – with serious repercussions on mangroves.

Ecosystem services provided by mangroves, such as coastal protection from high-energy events – tsunamis or repeated storms – and their contribution to coastal resilience, are impaired when mangrove loss has been inflicted by human activities. This can be imagined through the consideration of the concept of a 'tipping point', which corresponds to a threshold value beyond which a system cannot return to its original dynamic equilibrium (Kéfi et al., 2016).

Tipping points occur where one or more of the driving processes go beyond a threshold, resulting in destabilized dynamic feedback loops that link all processes together. This is also the case where a mangrove fringe is reduced in width by coastal 'squeeze' (Woodroffe et al., 2016) or massive deforestation (Lewis, 2005). Coastal squeeze occurs where anthropogenic (i.e. man-made) modifications on coasts lead to a significant cross-shore reduction of coastal space (Doody, 2004; Pontee, 2013).

Mangroves are not big producers of sediment (i.e. in situ organic production by mangrove roots, leaves and tree trunks). Without an adequate sediment supply, sea-level rise and subsidence are a threat to mangrove ecosystems (Woodroffe et al., 2016).

In considering the role of mangroves and their success as ecosystems, the free flow and availability of sediment constitute an overarching background factor without which (1) mangrove substrate elevations cannot be durably sustained, and (2) the commonly considered 'land-building' (or land gaining over the sea) role of mangroves cannot be successful (Figure 3). These functions cannot be maintained where the sediment supply is drastically reduced or where oceanic forcing and sea-level rise increase.

The drastic reduction of sediment replenishment to coasts by rivers due to the trapping effect of dam reservoirs and sand mining is often aggravated by

COAST

Fig 3: Sediments are carried and distributed along the coast. Nearshore sand bars and sand banks protect mangroves from erosion by dissipating waves.

groundwater extraction and sea-level rise, both of which increase the need for more sediments. The former to balance accelerated subsidence, and the latter to fill the new space (called accommodation space) created by water-level increase.

This is notably the case in delta areas where natural subsidence is common and can exacerbate relative sea-level rise. Further disruptions of the sediment supply and dynamics are frequently caused by harbours, ports and coastal protection structures.

In order to support aquaculture and agriculture, the river channels are commonly disconnected from the natural floodplain through the creation of sluice gates and dykes, resulting in significant reduction of sediment supply to the floodplain.

Mangrove degradation leads to a breakdown of the buffer effect of the mangrove forest on waves and currents – and of sediment trapping. This alteration can encourage accelerated erosion (Anthony and Gratiot, 2012; Winterwerp et al., 2013). The end-result is the deterioration and eventual disappearance of mangroves and the various ecosystem services they provide.

Mangroves are limited producers of sediment and without an adequate sediment supply, are threatened by sea-level rise, subsidence, and coastal erosion.

Aerial photo of Rufiji delta. Significant areas of mangrove have been cleared, especially in the southern part.

1.4 MANGROVE CONSERVATION AND RESTORATION

Recognition of these problems has changed approaches to mangrove conservation and restoration. In their global synthesis and review of mangrove restoration efforts, Worthington and Spalding (2018) developed data on over 160 mangrove restoration efforts worldwide covering 2,000 km².

They identified 1,389 km² of degraded mangroves and considered that about 8,120 km², or only 6%, of former mangrove area, are restorable. Using an expert-derived model for 'restorability' the authors developed, based on key environmental components that influence the ease of restoration, they considered that about 6,665 km² are highly restorable – excluding degraded areas.

Despite such models, the success of many restoration initiatives remains uncertain, and this reflects serious gaps in the integration of multi-factor physical, human, and ecological dimensions.

In addition to the deterioration of sediment supply, there are often inconsistencies in policy, as well as issues and gaps in governance and implementation capacity.

Many efforts have thus had limited success, partly due to neglect or ignorance of the wider processes at stake that cause erosion of river banks and coastlines. In considering the viability of mangrove restoration projects, the free flow and availability of sediment is a fundamental consideration.

Numerous efforts have been carried out on mangrove rehabilitation and restoration. Such projects need to take into consideration the availability of an adequate sediment supply.

Newly planted mangrove fields from Antsatrana in Ambaro Bay, Ambilobe, Madagascar (top). Kuching Wetland National Park, located near to the capital city of Sarawak, Malaysia. The habitat is mostly covered by mangrove vegetation with few local settlements within the gazetted area. (bottom).

Wood-cutter harvesting mangroves in Camau Peninsula. Mekong Delta. Southern Vietnam.

2. REPORT OBJECTIVES

The aim of this report is to develop a Rapid Assessment Guidance Manual for management of mangrove conservation and restoration that takes into account sediment flows and sediment deposition as potential factors in the success of mangrove projects, and help local decision-makers in large tropical river deltas to better plan and manage mangrove conservation and restoration. Derived from background literature, workshops, and questionnaires, the manual has two purposes: (a) it will serve to gauge the extent to which mangrove practitioners are aware of, and address sediment issues, at various spatial and temporal scales of analysis that are important to the thriving of mangroves, their resilience to environmental stressors and perturbations, and the success or failure of mangrove replanting and rehabilitation projects, and (b) it seeks to provide guidance on best management practices integrating the sediment-supply dimension in mangrove conservation, rehabilitation or restoration.

The manual adopts a multi-scale approach to evaluate sediment supply and availability, with the aim of complementing existing guidelines addressing other aspects or components that are necessary to assess success in mangrove conservation and restoration. Simply put, the manual provides initial guidance on if, where, and when to conserve or replant mangroves. It should only be seen as tool to rapidly assess existing information on natural sediment flux and its perturbation by human activities, and the governance and policy frameworks relative to the management of sediments. As an aid to rapid assessment, the manual guides the collection of existing information. Based on the outcome of the rapid assessment, if sediment starvation comes up as an important issue, a more in-depth assessment can be considered.

The manual is structured into four embedded scales of analysis interlinked by sediment flow connectivity: (1) the river basin scale, (2) the delta scale, (3) the coastal scale, and (4) the site scale. These different levels of analysis are depicted in Figure 1a and Figure 4.

Although mangroves may occur extensively along river banks, the coastal scale illustrates best the issue of sediment availability in mangrove sustainability. Sediment deficit can, however, profoundly affect the other types of mangrove loss through exacerbation of bank erosion (one consequence of reduced river sediment transport) and of subsidence and compaction which need to be balanced by sediment replenishment.

At the coast, sediment is redistributed by waves and currents, aided by wind stress. We will assume, at the site scale, that a positive sediment balance leads to accretion everywhere and a negative sediment balance results in erosion everywhere. This a gross simplification, as in reality, there may always be some local erosion or accretion resulting from sediment redistribution processes within cells.

Fig 4: From top to bottom: the delta scale, the coast scale, and the site scale.

3.1 THE RIVER BASIN SCALE

River basins are, by far, the main purveyors of sediment to the world's coasts (Figure 1a). This sediment supply thus assures mangrove sustainability at the coast. Most river basins of the world are affected in many ways by human activities (Figure 1b) and these impact the supply of sediment from the catchment to the river channel(s) (Evans, 2012; Kondolf et al., 2014; Day et al., 2016; Best, 2018; Besset et al., 2019a). Ubiquitous forms of perturbation are increasing land-use changes and mining activities in catchments, both of which contribute potentially to increased sediment loads in rivers. Enhanced sediment loads may not necessarily attain the coast, however. Locally, the river channel may not have the hydraulic capacity to mobilize the surplus sediment accumulations, and sediment may be deposited on floodplains or in natural lakes.

Irrigation, hydropower and other dams impair connectivity and significantly reduce the potential for free upstream-to-downstream water and sediment fluxes in rivers (Grill et al., 2019). As a result, in many river systems in the world, the trend is towards diminishing sediment supply due to trapping in reservoirs (Besset et al., 2019a). Reservoirs also regulate flows, and reducing peak flows can reduce downstream sediment transport. Another source of perturbation is the growing extraction of channel-bed sediments to provide aggregate for construction and land reclamation purposes, and sometimes dredging to ensure fluvial navigation. This is fast becoming an extremely serious issue in many rivers in the world (Best, 2018). Other perturbations include regulation of river flow by channelling, and building of embankments and dikes.

A SEDIMENT SUPPLY ASSESSMENT NEEDS TO BE CARRIED AT DIFFERENT GEOGRAPHIC AND TIME SCALES

Fig 1b.iii: Deforestation and other human activities increase sediment input into rivers.

Fig 1b.iv Different types of infrastructures block sediment flows in riverbeds or affect sediment deposition processes in floodplains.

3.2 THE DELTA SCALE

Deltas are dependent on fluvial sediment supply to balance marine forces of sediment dispersal, subsidence and sea-level rise. Abundant sediment supply generally leads to deltaic progradation, potentially beneficial to natural mangrove expansion (Figure 5a.i). Sediment reduction impairs the ability of deltas to balance dispersal, subsidence and sea-level rise, with aggravated sinking of the delta surface resulting in increasing areas of open water. The process can also lead to accelerated shoreline drowning. Decreasing river sediment supply to deltas can lead to a reduction in their sub-aerial area, and renders them more vulnerable to erosion, given the role sediment-charged waters play in dissipating fluvial, wave, and tidal energy (Anthony, 2015). This reduction in area can have dramatic consequences on coastal and delta populations, and on mangroves.

Further negative effects are generated by increasing urbanization of delta plains and exploitation of their resources, including mangroves (Figure 5b.i). The construction of dikes and polders for agriculture and aquaculture as well as for urban and industrial development, commonly leads to a situation where suspended sediments can no longer be deposited in delta plains by flood waters. Dikes, embankments and other structures can also prevent sediment from reaching mangroves.

The reduction of a river's sediment flux clearly diminishes, thus, a delta's resilience to change. The supply of sediment should be seen less in terms of its direct role in generating accretion, and, therefore, eventual sub-aerial delta seaward advance, and more in terms of an agent enabling deltas to keep pace with oceanic forcing and subsidence. To maintain delta resilience, mangroves are an important component and indicator of the direction of these processes.

Fig 5a

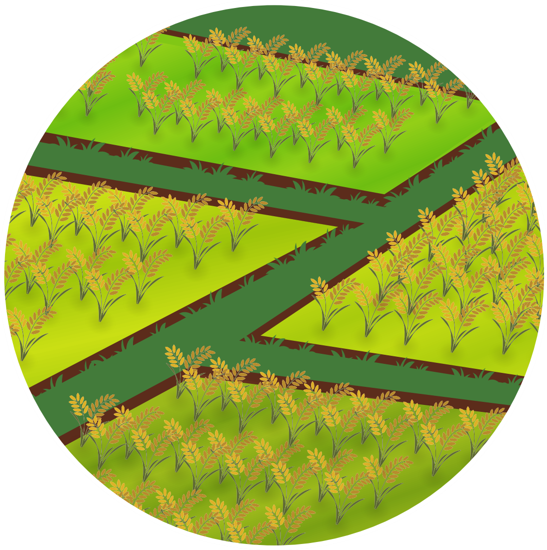

Fig 5b

Fig 5a, 5b: Subsidence increases due to pumping of groundwater to supply agriculture and urban development.

DELTA

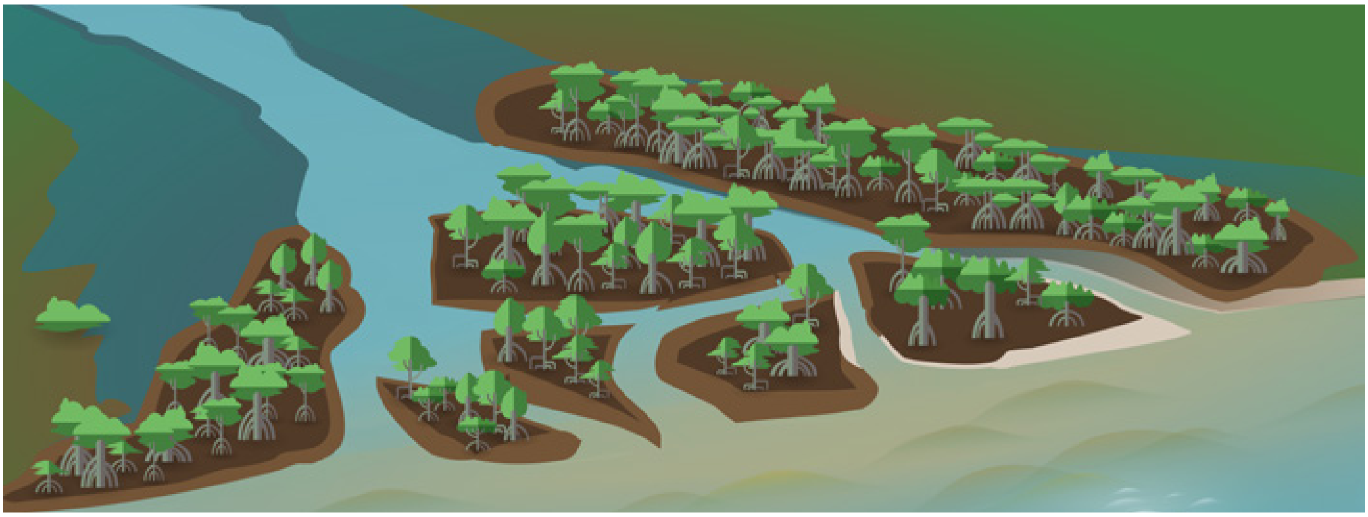

Fig 5a.i: In their natural state, deltas are in dynamic equilibrium between 3 forces: subisidence, erosion and sediment replenishment

AFTER HUMAN INTERVENTION

Fig 5b.i: Deltas after human impact: the natural equilibrium is disturbed. Sediment replenishment decreases due to dams and sand mining. Sediment movement and deposition in floodplains are affected by levees, embankments, roads and railways. Sediment replenishment further decreases due to dikes and polders.

3.3 THE COASTAL SCALE

Embedded within the scale of the delta lies the important coastal-scale component in which sediment is routed alongshore and across shore (Figure 6a). This scale addresses why erosion and accretion may prevail in different sectors of the coastline. There is no simple straightforward relationship between fluvial sediment supply and coastal mobility, since the latter can also be influenced by various other drivers acting at a variety of time scales (Besset et al., 2019a). However, fluvial sediment supply is the overarching determinant of the position of a delta's coast (stability, advance or retreat) at a multi-decadal scale and below, while sea-level change is an even longer-term determinant.

This scale focuses on the increasing impact of human activities on the world's coasts which support large concentrations of populations and a variety of socio-economic activities that impact mangroves (Figure 6b). The relationship between reduced sediment supply and retreating delta shorelines is well established. From a database of 54 of the world's deltas, (Besset et al., 2019a) showed that eroding deltas are associated with a reduction in fluvial sediment supply that is twice as large as for stable or advancing deltas. When grouped together, eroding deltas receive less than a quarter of the fluvial sediment supply of deltas with stable and advancing shorelines. However, while shoreline erosion can be used as an indicator of delta vulnerability, this metric represents only one of various indicators of delta biophysical sustainability, and cannot be used to project future rates of shoreline mobility and mangrove conservation over coming decades. River deltas are characterized by distributary networks connected to alongshore sediment transport pathways that are distinct for sand and mud. Longshore sediment transport can be hampered by multiple coastal structures (dikes, groynes, etc.), built to contain erosion or to protect humans, settlements, socio-economic activities, and infrastructure. Here, we will briefly describe the basic functioning of sedimentary coasts and sediment transport processes.

Fig 6a: The coast scale in its natural state. Sandy areas provide very effective dissipation of wave energy.

Fig 6b: The coast scale after human intervention. Coastal replenishment of sediments from rivers and sea currents is reduced. Sand transported by longshore currents is trapped behind groins and seaports. Beaches, sand bars and sand dunes erode.

The coastal zone of the southern region of Toliara, Madagascar, has long been recognized for its extraordinary beauty, and its exceptional natural ecosystems, many areas of which are still intact.

COAST

Mangroves between Anakao and Androka in the Mahafaly land- and seascape in Southwestern Madagascar.

COAST AFTER HUMAN INTERVENTION

Aerial view of fish ponds in Mai Po Nature Reserve, Hong Kong. Shenzen City in the background.

3.3.1 MUDDY DELTAIC SHORELINES AND MUD TRANSPORT PATHWAYS: IMPLICATIONS FOR MANGROVES

Most of the world's river catchments (especially those of big rivers) are characterized by the dominance of supply of mud (suspension load) which can commonly exceed 90% of the sediment load. Suspension load is also less susceptible than sand and gravel (bedload) to be sequestered in reservoirs. Mud is thus the dominant component of deltas, but it is also readily mobilized by currents. However, when mud is in abundant supply and the delta develops in a setting relatively sheltered from large ocean waves, delta growth and muddy shoreline advance can be very rapid. Where mud supplies are persistently high, the abundance of mud on the delta front can lead to damping of wave energy even when waves are high offshore. Mangroves are opportunistic plants that take advantage of calm sheltered settings where colonization and spread can be rapid, especially under such conditions of high mud supply.

Mud redistribution alongshore is conditioned by coastal currents generated jointly by tides, winds and waves, and by differences in salinity between denser seawater and lighter freshwater. This redistribution commonly has a clearly defined seasonal pattern hinged on the combination of these forcing conditions and high mud supply in the rainy season.

It is important to note that coastal currents can contribute to the distant transport of sediment to areas not directly in contact with river mouths. These include delta lobes that have been abandoned (no longer fed by rivers directly). This is the case of the largest continuous mangrove unit in the world, the Sundarbans in the Ganges-Brahmaputra delta. The sustained conservation of mangroves in this now-abandoned lobe is favoured by coastal mud supply westwards from the active mouths of the delta, which receive one of the world's largest river sediment supply.

Community mangrove restoration in Madagascar (top). Fisherman and volunteers from the Mangrove Action Project planting mangrove seedlings in abandonned shrimp ponds near Jaring Halus Village, North Sumatra (bottom).

3.3.2 SANDY DELTAIC SHORELINES AND SAND TRANSPORT PATHWAYS: IMPLICATIONS FOR MANGROVES

Sand is not commonly a substrate for mangrove colonization although mangroves can colonize sandy deposits. However, sand is indirectly important to mangrove establishment and conservation. Where sand is supplied in sufficient quantities to the coast through delta distributary mouths under conditions of net shoreline advance, beaches and dunes are constructed and protect the delta shorelines against waves and high-energy events while providing protection for back-barrier or lagoonal mangrove environments. An opposite situation, discussed below, prevails where there is a sediment deficit, and an additional case concerns occasional sand deposition in very muddy environments.

River water and sediment discharge in delta environments are typically distributed to the flood plains and coasts through one or more distributary mouths. Each of these active mouths is an area where waves and wave-induced longshore transport are dampened through both the counter-active effect of river-mouth flow on waves coming from the opposite direction, and the process called refraction, which leads to the inward bending (lengthening) of wave crests at the river mouth. This lengthening diminishes the amount of energy per metre of wave crest (the energy density decreases). The shorelines rimming the delta lobes between the distributary mouths are, thus, each characterized by individual sediment cells commonly exhibiting bi-directional longshore drift. This is a mechanism that assures the local, within-cell, retention of sand, instead of significant alongshore leakage (beyond the confines of the delta and onto adjoining non-deltaic coasts). Even though a predominant direction of longshore transport commonly prevails, the relationship between river water discharge (supplemented by tidal discharge) and the opposing wave influence leads to a system of multiple sediment cells that contributes to the local trapping of sand. Abundant sand supply has thus led to the successive formation, in advancing deltas plain, of beach ridges in each lower inter-distributary lobe of many deltas such as the Mekong, Ganges-Brahmaputra, and Irrawaddy, for instance. In the sheltered environment behind each beach ridge, muddy sedimentation occurs, sometimes accompanied by mangrove development.

Two variants of this situation are: (1) where dominantly muddy shores are episodically reworked by storms or cyclones or high seasonal waves, resulting in segregation of sand/shells from these muddy deposits to form distinct beaches called cheniers surrounded by, and resting on mud; and (2) where delta lobe abandonment leads to mud dispersal and sand reworking to form beaches and cheniers. Chenier development may be characterized by mangrove destruction as the chenier body is driven landward by waves and migrates over the muddy mangrove fringe. Commonly, however, mangrove regeneration occurs because of sustained ambient mud supply (except where the system enters a state of sustained mud deficit). The Rufiji delta provides a fine example of the second situation. Following a switch in dominant delta channel routing of river water and sediments from the southern to the northern part of the delta sometime in the 1970s, the southern delta lobe became abandoned. This has resulted in progressive erosion of the muddy mangrove shoreline in the southern sector of the delta and shoreline straightening through the formation of sandy beaches and cheniers, reflecting segregation of sand from mud in an erosional context. In contrast, the northern lobe of the delta shows active shoreline advance characterized by natural mangrove development, except where deforestation has been practised for rice-farming. Abandoned delta lobes are thus, commonly, areas of mangrove destruction as a result of shoreline retreat. An exception to this is where favourably-oriented coastal currents still supply fine-grained sediments to an abandoned lobe (case of the Sundarbans).

3.4 THE SITE SCALE

Site-scale mangrove systems interact dynamically with coastal sediment supply. The health of a mangrove system in a given site is largely in phase with the long-term (decadal to multi-decadal) pattern of local shoreline mobility (coastal scale: stability, advance or retreat), which, in turn, has been shown to be influenced by basin-scale and delta-scale sediment supply and dynamics. The overall context in which mangroves exist can be ascertained from baseline data on shoreline change, including freely-available satellite images (Google Earth and other sources), maps, and reports.

The hydrodynamic controls that determine sediment concentrations over a particular mangrove site are tidal range, tidal current velocity, tidal phase difference and asymmetry (inequality of the duration of ebb and flood flows), wave and storm wind activity and groundwater. These processes are intermeshed and invariably influenced by lower-order controls, such as the neap-spring tidal cycle, seasonal and longer-term changes in sea level and groundwater dynamics, and river discharge. The hydrodynamic controls not only govern sediment fluxes over mangroves, but modulate the duration of inundation (hydroperiod) and particle settling velocity. Flow and sediment routing patterns are, in turn, subject to strong potential influence by elevation, topography and vegetation cover.

Generally, mangroves in natural regeneration (as opposed to planted mangroves) occur in areas of shoreline advance where the sediment supply is adequate enough to assure a substrate elevation that can be colonized by the plants (Figure 7). In these situations, the new plants adapt naturally to the elevation of the substrate. The actual colonization process and spatial pattern of mangroves can be variable, depending on the criteria listed above. Exceptional growth rates can ensue in areas of very active muddy sedimentation as on the Guianas coast of South America (Proisy et al., 2008; Gensac et al., 2011) which are influenced by large mud supply from the Amazon River, where opportunistic shore-front *Avicennia germinans* deploy rapid and massive colonization tactics. A sustained erosional context implies sediment deficit, and is, evidently, deleterious to mangroves. Coastal erosion under conditions of sediment deficit likely precludes mangrove regeneration through: (1) narrowing of the mangrove fringe (consequence of erosion) which entails less dissipation of wave energy; and (2) mangrove squeeze resulting from dikes to protect rice and aquaculture farms. At this local site level, further indications of erosion can be obtained from observations of the shore: the presence of a pitted muddy foreshore, the presence of uprooted mangroves on the foreshore, shoreline erosion bluffs, etc..

Fig 7: Mangroves can be very efficient traps for mud, trapping it from floods, which allows them to gain elevation.

Replantation and growth will only be successful if sediment substrat, mud or sand, is stable (top and bottom).

3.5 IMPLICATIONS OF RIVER SEDIMENT FLUX ANALYSIS FOR REHABILITATION/RESTORATION OF MANGROVES

As described above, the extent to which mangroves can be conserved, rehabilitated or restored needs to be viewed in the context of the established (at least decadal) shoreline trend, which, in turn, is determined by sediment supply and hydrodynamic conditions. The relationship between mangroves and shoreline evolution needs to be carefully considered, taking into account antecedent and prevailing shoreline accretion or erosion. These situations of erosion or accretion are, in turn, subject to larger-scale controls exerted by alongshore adjustments between net sediment supply or availability, wave and current energy, and sediment redistribution by waves and currents. Mangrove conservation will be affected over time and the mangrove area reduced where sediment supply is in strong or persistent deficit.

This is illustrated by the mangrove-rich Guianas coast between the Amazon and Orinoco river mouths, the world's longest muddy coast (Anthony and Gratiot, 2012). Here, so-called decadal to multi-decadal 'inter-bank' phases of relative mud scarcity separating mud-rich 'bank' phases (discrete mud banks migrating alongshore from the mouths of the Amazon are separated by inter-bank zones of erosion) can be characterized by rates of mangrove shoreline erosion that can exceed 150m/year notwithstanding the presence of dense mangrove forests up to 30m high and forming stands several kilometres wide (Brunier et al., 2019). Rehabilitation or restoration projects are likely to meet with failure under such contexts of sustained sediment deficit. This reflects a tipping-point effect where once sediment supply to the coast is in chronic deficit (further aggravated by sediment trapping across the rest of the delta floodplain to compensate for accelerated subsidence induced by human activities), the vertical growth and seaward advance of shorefront mudflats that could be eventually colonized by mangroves are no longer assured. The foreshore level becomes too low to enable mangrove seedling establishment (Anthony et al., 2008; Proisy et al., 2009; Balke et al., 2011, 2013; Gensac et al., 2011).

Hence, the pertinence of a comparative analysis at different scales: delta mass as a whole representing the sediment entry zone downstream of the entire river basin, alongshore segments/cells, and local/individual zones or sites. There is no doubt that: (1) mangroves can promote coastal accretion where fine-grained sediment supply is adequate, (2) a large and healthy belt of fringing mangroves can efficiently protect a shoreline by inducing more efficient dissipation of wave energy than a narrower fringe, and (3) mangrove removal contributes to the aggravation of ongoing shoreline erosion.

In full acknowledgment of these facts, it is important to insist, however, that where mud supply is in chronic deficit, erosion becomes established, leading to sustained shoreline retreat. In these circumstances, mangroves will have little influence in containing erosion. Ignoring the basic overarching aspect of sediment availability at the local site scale may cause the failure of otherwise well planned conservation, rehabilitation or restoration initiatives. Where sediment supply is in deficit, here are some false expectations from shore-front mangroves that are doomed to meet with disappointment: (1) a large and healthy shore-front mangrove fringe is sufficient to stabilize an eroding shoreline, (2) a reduction in the width of a large mangrove fringe to the benefit of other activities, such as shrimp-farming, is not deleterious to the shoreline position, and (3) the effects of human-induced reductions in sediment supply to the coast can be offset by a large belt of fringing mangroves (Besset et al., 2019b).

Mangrove reforested area. Philippines.

Sally Lightfoot crab (Grapsus grapsus) in the mangroves in Baronesa Bay, Floreana Island, Galapagos, Ecuador.

4. THE RAPID ASSESSMENT GUIDE ON SEDIMENT FLOW IN THE CONTEXT OF MANGROVE CONSERVATION AND RESTORATION

Building on the findings presented in the previous chapters, a rapid assessment tool (see annex) is suggested to guide decision-making on mangrove restoration. The assessement is based on desk and field evaluations of (1) sediment flux continuity and quality and (2) sediment-related governance or sediment stewardship. These two assessment tables are complemented by a questionnaire on mangrove conservation, rehabilitation and restoration that takes the four scales of analysis into account. The results can range from poor (score 1) to excellent conditions (score 4).

The assessment procedure thus includes a consideration, at these various spatial scales, and in a concise format, of the parameters that determine the relationship between sediment flux and mangroves and backing policy considerations. This brings in a comprehensive set of considerations:

- the status of fluvial sediment supply over the long term, at least at a decadal scale (basin scale),
- sediment transport from the basins and its redistribution across the large delta plains (delta scale),
- sediment inputs and redistribution along the shore and subaqueous delta (coastal scale),
- the local conditions necessary to allow conservation, growth and natural regeneration of mangrove (as opposed to planted or restored mangroves) (site scale),

  and

- at each level, the degree of awareness, policy and planning frameworks and the enforcement capacities.

Tiger among mangroves in Sundarbans, a priority landscape for tiger conservation (top). Nasalis larvatus, Proboscis monkey. These monkeys are living highly specialized lives in the mangrove forest. Endangered species. South-East Asia (bottom).

5. CONCLUDING REMARKS AND PERSPECTIVES: RIVER SEDIMENT FLUX AND MANGROVES IN A CONTEXT OF CLIMATE CHANGE AND INCREASING ANTHROPOGENIC PRESSURES

A remarkable amount of grey and published literature exists on mangrove conservation and restoration. Restoration is applied at the grass-roots level (site scale in this report), and we have shown that it is important to examine the larger-scale context of river sediment and nutrient supplies and their routing in deltas and along coasts and the opportunities such fluxes provide (or not), for successful mangrove conservation and restoration. We consider this sediment-flow dimension as an important contribution to the debate on mangrove conservation and restoration. Knowledge on sediment flux should also help to predict future mangrove sustainability. Any mechanisms depriving deltas of sediment, or contributing to high subsidence rates, enhance the effects of sea-level rise in driving delta vulnerability (Syvitski, 2008), including delta shoreline retreat with repercussions on mangroves.

The erosion of river deltas and coasts and accelerated subsidence in deltas in the present context of diminishing sediment supply should be a cause for concern. Both of these processes will also determine the future of mangroves in the coming decades, given the compounding of impacts expected from climate change and sea-level rise. With few exceptions, deltas are expected to lose resilience and become more vulnerable as a result of decreasing fluvial sediment supply. This will, in turn, have a feedback effect on mangrove areas, which are likely to diminish as delta shorelines retreat. These impending pressures urgently call for sustainable management strategies for rivers, their deltas, the world's coasts and their mangroves. The proposed rapid assessment tool is contributed as an initial guidance to assess knowledge and gaps regarding sediments & nutrients management at the different relevant scales with the aim to ensure those critically important considerations are not forgotten, and decision makers are armed with the basic understanding needed to address them.

A Chital deer in the mangrove forest in the Sundarbans National Park, Bangladesh.

Anthony, E.J., 2004. Sediment dynamics and morphological stability of an estuarine mangrove complex: Sherbro Bay, West Africa. Marine Geology, 208, 207-224.

Anthony, E.J., 2013. Deltas. In: Masselink, G., Gehrels, R. (eds.), Coastal Environments: Dynamics, Climate Change and Management. Wiley-Springer, pp. 299-337.

Anthony, E.J., 2015. Wave influence in the construction, shaping and destruction of river deltas: A review. Marine Geology, 361, 53-78.

Anthony, E.J., Dolique, F., Gardel, A., Gratiot, N., Proisy, C., Polidori, L., 2008. Nearshore intertidal topography and topographic-forcing mechanisms of an Amazon-derived mud bank in French Guiana. Continental Shelf Research 28, 813-822.

Anthony, E.J., Gratiot, N., 2012. Coastal engineering and large-scale mangrove destruction in Guyana, South America: Averting an environmental catastrophe in the making. Ecological Engineering, 47, 268-273.

Balke, T., Bouma, T.J., Horstman, E.M., Webb, E.L., Erftemeijer, P.L.A., Herman, P.M.J., 2011. Windows of opportunity: thresholds to mangrove seedling establishment on tidal flats. Marine Ecological Progress Series, 440, 1–9.

Balke, T., Webb, E.L., van den Elzen, E., Galli, D., Herman, P.M.J., Bouma, T.J., 2013. Seedling establishment in a dynamic sedimentary environment: a conceptual framework using mangroves. Journal of Applied Ecology, 50, 740–747.

Besset, M., Anthony, E.J., Bouchette, F., 2019a. Multi-decadal variations in delta shorelines and their relationship to river sediment supply: An assessment and review. Earth-Science Reviews, 193-199-219.

Besset, M., Gratiot, N., Anthony, E.J., Bouchette, F., Goichot, M., Marchesiello, P., 2019b. Mangroves, mangrove squeeze, and shoreline erosion in the Mekong River delta. Estuarine, Coastal and Shelf Science, 226, https://doi.org/10.1016/j.ecss.2019.106263

Best, J., 2018. Anthropogenic stresses on the world's big rivers. Nature Geoscience, 12, 7-11.

Brunier, G., Anthony, E.J., Gratiot, N., Gardel, A., 2019. Exceptional rates and mechanisms of muddy shoreline retreat following mangrove removal. Earth Surface Processes and Landforms, 44, 1559-1571.

Carlton, J.M., 1974. Land-building and stabilization by mangroves. Environmental Conservation, 1, 4, 285-294.

Day, J.W., Agboola, J., Chen, Z., Elia, C.D., Forbes, D. L., Giosan, L., Kemp, P., Kuenzer, C., Lane, R.R., Ramachandran, R., Syvitski, J., Ya, A., 2016. Approaches to defining deltaic sustainability in the 21st century.

Estuarine, Coastal and Shelf Science, 183, B, 275–291.

Doody, J.P., 2004. 'Coastal squeeze': An historical perspective. Journal of Coastal Conservation, 10, 1-2, 129–138.

Evans, G., 2012. Deltas: the fertile dustbins of the world. Proceedings of the Geologists' Association, 123, 397–418.

Feller, I. C., Friess, D.A., Krauss, K.W., Lewis, R.R., III. The State of the World's Mangroves in the 21st Century under Climate Change. Hydrobiologia, 803, 1 12.

Furukawa, K., Wolanski, E., Mueller, H., 1997. Currents and sediment transport in mangrove forests, Estuarine, Coastal and Shelf Science, 44, 3, 301.

Gensac, E., Gardel, A., Lesourd, S., Anthony, E.J., Proisy, C., Loisel, H., 2011. Short-term prediction of the evolution of mangrove surface areas: The example of the mud banks of Kourou and Sinnamary, French Guiana. Journal of Coastal Research, Special Issue 64, 388-392.

Grill, G., Lehner, B,Thieme, M., Geenen, B.,Tickner, D.,Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Ehalt Macedo, H., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, M. E., Meng, J., Mulligan, M., Nilsson, C., Olden, J. D., Opperman, J. J., Petry, P., Reidy Liermann, C., Sáenz, L., Salinas-Rodríguez, S., Schelle, P., Schmitt, R. J. P., Snider, J.,Tan, F.,Tockner, K.,Valdujo, P. H., van Soesbergen,A., Zarfl, C., 2019. Mapping the world's free-flowing rivers. Nature, 569, https://doi.org/10.1038/s41586-019-1111-9.

Hamilton, S.E., Casey, D., 2016. Creation of a high spatio-temporal resolution global database of continuous mangrove forest cover for the 21st century (CGMFC-21). Global ecology and Biogeography, 25, 729–738.
Kéfi, S., Holmgren, M., Scheffer, M., 2016.When can positive interactions cause alternative stable states in ecosystems? Functional Ecology, 30, 1, 88-97.

Kéfi et al: Kéfi, S., Holmgren, M., Scheffer, M., 2016.When can positive interactions cause alternative stable states in ecosystems? Funct. Ecol., 30, 1, 88-97. https://doi.org/10.1111/1365-2435.12601.

Kondolf, G.M., Gao,Y.,Annandale, G.W., Morris, G.L., Jiang, E., Zhang, J., Cao,Y., Carling, P., Fu, K., Guo, Q., Hotchkiss, R., Peteuil, C., Sumi,T.,Wang, H-W,Wang, Z.,Wei, Z.,Wu, B.,Wu, C.,Yang, C.T., 2014. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. Earth's Future, 2, 256-280.

Lee,Y.P., Primavera, J.H., Dahdouh-Guebas, F., McKee, K., Bosire, J.O., Cannicci, S., Diele, K., Fromard, F., Koedam, N., Marchand, C., Mendelssohn, I., Mukherjee, N., Record, S., 2014. Ecological role and services of traopical mangrove ecosystems: a reassessment. Global ecology and Biogeography, 23, 726-743.

Lewis III, R.R., 2005. Ecological engineering for successful management and restoration of mangrove forests. Ecological Engineering, 245, 403–418.

Pontee, N., 2013. Defining coastal squeeze:A discussion. Ocean & Coastal Management, 84, 204-207.

Proisy, C., Gratiot, N.,Anthony, E.J., Gardel,A., Fromard, F., Heuret, P., 2009. Mud bank colonization by opportunistic mangroves: a case study from French Guiana using lidar data. Continental Shelf Research, 29, 632-641.

Sasmito, S.D., Murdiyarso, D., Friess, D.A. and Kurnianto, S. (2016). Can mangroves keep pace with contemporary sea level rise? A global data review.Wetlands Ecology and Management, 24, 263-278.

Syvitski, J.P.M., 2008. Deltas at risk. Sustainability Science, 3, 23–32.

Winterwerp, J.C., Erftemeijer, P.L.A., Suryadiputra, N.,Van Eijk, P., Zhang, L., 2013. Defining eco-morphodynamic requirements for rehabilitating eroding mangrove-mud coasts.Wetlands, 33, 515–526.

Thomas, N., Lucas, R., Bunting, P., Hardy,A., Rosenqvist,A., Simard, M., 2017. Distribution and drivers of global mangrove forest change, 1996–2010 ». PLOS ONE 12, 6 , e0179302.

Woodroffe, C., Rogers, K., McKee, K., Lovelock, C., Mendelssohn, I., and Saintilan, N., 2016. Mangrove sedimentation and response to relative sea-level rise.Annual Review of Marine Science, 8, 243-266.

Wodehouse, Dominic C. J., et Mark B. Rayment. « Mangrove area and propagule number planting targets produce sub-optimal rehabilitation and afforestation outcomes ». Estuarine, Coastal and Shelf Science 222, 91 102.

Worthington,T., Spalding, M., 2018. Mangrove Restoration Potential:A global map highlighting a critical opportunity. https://doi.org/10.17863/CAM.39153

© Green Renaissance / WWF US A boat patrols through mangroves as part of the monitoring program in Quionga, near Palma, Mozambique, Africa.

ANNEX: METHODOLOGY FOR RAPID ASSESSMENT GUIDANCE

This task concerns the methodology for the rapid assessment guidance for management of mangrove conservation and restoration. The assessment is based on four scales (basin, delta, coast, site) and two perspectives for each scale (physical state and governance), resulting in eight topics. For each topic, there are several criteria and indicators to differentiate between four levels of conditions or performances (excellent, good, problematic, poor).

In many cases, users will find that some information may not be available, reliable, or consistent. Because the assessment tool is explicitly designed for rapid evaluations based on easily accessible information, this should simply be noted as an indicator of potential underlying problems. Also, for the same topic, some criteria may show different results (for example, some could meet the definition of 'excellent' but others could appear as 'problematic'). In these cases, the lowest scoring criteria should generally be used, instead of an average, because even missing one out of several criteria can be enough to indicate significant risks.

The results of the assessment will be eight individual scores ranging from 1-4, which can be presented, for example, in a table or spider diagram. Again, it is recommended not to average the scores but to keep them separate for each topic, to allow the user to quickly see the positive and negative aspects of the assessment ('strengths and weaknesses').

This is a rapid assessment with the objective to identify areas that need more attention, either by compiling or conducting more research or filling data gaps; or fostering more awareness amongst certain stakeholder groups, improve policies, governance frameworks or enforcement measures.

A. ASSESSMENT TABLES - MANGROVES AND SEDIMENTS

RIVER BASIN - PHYSICAL STATE

Score	Criteria and Indicators
4 Excellent	a. River is entirely free-flowing (according to the definition in Grill et al. Nature, 2019) b. No dams with limited ability to pass sediments (e.g. without low-level outlets or with large storage-to-inflow ratios) exist or are under construction in the basin (longitudinal connectivity) c. No sand mining (e.g. for aggregates) and silt/clay mining (e.g. for bricks production) from river bottom, banks or islands in the basin d. No obstruction of natural exchanges between river bed and floodplains (lateral connectivity) e. Limited river bank erosion/river bed incision, which can be attributed to natural processes f. At least the natural sediment load is delivered to the delta
3 Good	a. More than 75% of river reaches in basin are free-flowing b. Few dams with limited ability to pass sediments exist or are under construction, but not on the mainstem and on the tributaries with high sediment contributions c. Only minor sand and silt/clay mining in the basin (equivalent to less than 10% of bedload and suspended load transport) d. Only minor obstructions of natural exchanges between river bed and floodplains (e.g. embankments around cities) e. Most river bank erosion/river bed incision can be attributed to natural processes f. Sediment load delivered to the delta is close to natural (>80%)
2 Problematic	a. More than 50% of river reaches in basin are free-flowing b. A moderate number of dams with limited ability to pass sediments exist or are under construction in the basin, including on the mainstem or on the tributaries with high sediment contributions c. Significant sand and silt/clay mining in the basin (equivalent to less than 30% of bedload and suspended load transport) d. Natural exchanges with river bed are possible along some of the floodplain e. River bank erosion/river bed incision is significantly elevated above natural levels f. Sediment load delivered to the delta is significantly reduced (>60%)
1 Poor	a. More than 50% of river reaches in basin are free-flowing b. A moderate number of dams with limited ability to pass sediments exist or are under construction in the basin, including on the mainstem or on the tributaries with high sediment contributions c. Significant sand and silt/clay mining in the basin (equivalent to less than 30% of bedload and suspended load transport) d. Natural exchanges with river bed are possible along some of the floodplain e. River bank erosion/river bed incision is significantly elevated above natural levels f. Sediment load delivered to the delta is significantly reduced (>60%)

POTENTIAL SOURCES

- Free-flowing river assessments
- Maps and records of dams, embankments, sand mining activities and bank erosion
- Bathymetry records for reservoirs and river bed
- Bedload and suspended sediment monitoring data at delta apex and river mouth
- Interviews with technical experts

RIVER BASIN - GOVERNANCE

Score	Criteria and Indicators
4 Excellent	a. Public and private actors such as river basin organizations, water resources agencies, and dam operators (if any) have clear mandates and are functional, well-resourced, operating according to comprehensive plans based on sediment budgets, and coordinated b. Sediment management operations at dams (e.g. flushing) are making regular and effective use of available facilities c. Sediment-related regulations (e.g. permitting of sand mining and dredging) are comprehensive and well-enforced d. Sediment-related baseline data on natural conditions are available, and monitoring includes correct parameters, locations and frequency e. Effective public participation in basin management, as well as public confidence in and access to sediment-related plans and data
3 Good	a. Public and private actors have some gaps regarding capacity, planning and coordination b. Sediment management operations at dams have some gaps c. Sediment-related regulations and their enforcement have some gaps d. Sediment-related baseline and monitoring data have some gaps e. Some gaps regarding public participation, confidence and access
2 Problematic	a. Public and private actors have significant gaps regarding capacity, planning and coordination b. Sediment management operations at dams have significant gaps c. Sediment-related regulations and their enforcement have significant gaps d. Sediment-related baseline and monitoring data have significant gaps e. Significant gaps regarding public participation, confidence and access
1 Poor	a. No public organization with an awareness of and authority over sediment issues, and other actors such as dam operators are poorly resourced and coordinated b. No effective sediment management operations at dams c. Sediment-related regulations are lacking or not enforced (e.g. significant unregulated and illegal sand mining) d. No reliable sediment-related baseline and monitoring data e. No public participation, confidence or access

POTENTIAL SOURCES

- River basin plans
- Institutional and legal assessments
- Data on dams' operations, sediment monitoring, regulations and enforcement
- Interviews with officials and stakeholders

DELTA - PHYSICAL STATE

Score	Criteria and Indicators
4 Excellent	a. Delta is in near-natural state with low population density and no net conversion of natural vegetation such as mangroves, wetlands, and grasslands to settlements, agriculture, aquaculture or other land uses b. Mangrove ecosystems are in healthy state, with no degradation from wood harvesting, fishing, droughts, fires, increased salinity or other pressures c. Sediment and associated nutrient transport through the distributaries and onto floodplains are not affected by, among other things, river incision/dredging, regulation of natural flood patterns by upstream dams, and infrastructure such as barrages that cut off distributaries, roads without culverts, dikes without sluice gates to allow temporary flooding, etc.. d. There is a balance between sediment deposition, subsidence and sea-level rise along nearly the entire length of river bank and coast, with an overall result of at least maintaining the delta land area
3 Good	a. Some population pressure and local conversion of natural vegetation to other land uses (<10% over past 5 years) b. Some local degradation of mangroves (<10% of biomass loss over past 5 years) c. Some local interruptions of sediment transport and deposition (resulting in <15% of delta area cut off from sediment replenishment through annual floods) d. Net loss of delta area (<2% over past 5 years)
2 Problematic	a. Significant population pressure and conversion of natural vegetation to other land uses (<20% over past 5 years) b. Significant degradation of mangroves (<20% of biomass loss over past 5 years) c. Significant interruptions of sediment transport and deposition (resulting in <30% of delta area cut off from sediment replenishment) d. Net loss of delta area (<5% over past 5 years)
1 Poor	a. Strong population pressure and widespread conversion of natural vegetation to other land uses (>20% over past 5 years) b. Widespread degradation of mangroves (>20% of biomass loss over past 5 years) c. Widespread interruptions of sediment transport and deposition (resulting in >30% of delta area cut off from sediment replenishment) d. Net loss of delta area (>5% over past 5 years), along nearly the entire length of river bank and coast

POTENTIAL SOURCES

- Maps and satellite images of topography/bathymetry, land use, and infrastructure (barrages and linear infrastructure such as dikes and roads, including design features such as culverts, bridges, sluice gates, structure raised on stilts etc..)
- Records of population, land use, mangrove health, river flows, sediment deposition, subsidence, sea level rise, salinity, and river bank and shoreline erosion/accretion

DELTA - GOVERNANCE

Score	Criteria and Indicators
4 Excellent	a. There is a long-term delta-wide vision that is shared by government agencies at different levels and from different sectors, based on a scientific understanding of processes (such as groundwater budgets), expressed in clear policies and plans, and implemented effectively b. Infrastructure is well mapped, and its locations, designs and operations (e.g. regular opening of sluice gates) allow effective sediment transport and deposition (e.g. by opening large polders to store floodwaters) c. Regulations (e.g. regarding sustainable groundwater extraction and protected mangrove zones) are comprehensive and well-enforced d. Baseline data on natural conditions such as topography and bathymetry, flows, sediment, nutrients, groundwater levels, and vegetation are available, and monitoring includes correct parameters, locations and frequency There is effective public participation in delta management, as well as public confidence in and access to relevant plans and data
3 Good	a. Some gaps regarding a consistent delta-wide vision, policies, plans, and implementation capacity b. Some gaps regarding infrastructure mapping, locations, design and operations c. Some gaps regarding regulations and their enforcement d. Some gaps regarding baseline data and monitoring e. Some gaps regarding public participation, confidence and access
2 Problematic	a. Significant gaps regarding a consistent delta-wide vision, policies, plans, and implementation capacity b. Significant gaps regarding infrastructure mapping, locations, design and operations c. Significant gaps regarding regulations and their enforcement d. Significant gaps regarding baseline data and monitoring e. Significant gaps regarding public participation, confidence and access
1 Poor	a. No consistent delta-wide visions, policies or plans, and agencies are poorly resourced and coordinated b. Infrastructure is not mapped and is not located, design and operated with a view towards sediment management c. Regulations are lacking or not enforced (e.g. significant unregulated and illegal extraction of groundwater) d. No reliable baseline and monitoring data e. No public participation, confidence and access

POTENTIAL SOURCES

- Delta-wide documents such as development visions, land-use plans, infrastructure maps and masterplans
- Institutional and legal assessments
- Data on infrastructure, mining and dredging operations, groundwater extraction, sediment-related monitoring, regulations and enforcement
  Interviews with officials and stakeholders

COAST - PHYSICAL STATE

Score	Criteria and Indicators
4 Excellent	a. Population pressure and economic activity along the 200m coastal fringe is low, and the entire coast consists of healthy natural ecosystems including beaches, sand dunes, mangroves and sea grass b. There are no engineered structures such as groins, harbours etc.. impeding the longshore movement of sediment c. There are no engineered structures such as sea dikes, roads and land use changes leading to 'mangrove squeeze' d. Shoreline is in net progradation or stability
3 Good	a. Some population pressure and economic activity along the coastal fringe, but most of the coastal fringe (>80%) still consists of healthy natural ecosystems b. Some engineered structures such as groins, harbours etc.., generally located and designed to minimize impeding the longshore movement of sediment d. Some engineered structures such as sea dikes and land use changes leading to 'mangrove squeeze' e. Some shoreline stretches affected by erosion, with some local artificial sand nourishment and protection activities
2 Problematic	a. Significant population pressure and economic activity along the coastal fringe, with natural vegetation converted in many places and significant degradation of natural ecosystems b. Significant numbers of engineered structures such as groins, harbours etc.. impeding the longshore movement of sediment c. Significant numbers of engineered structures such as sea dikes and land use changes leading to 'mangrove squeeze' A majority of the shoreline affected by erosion, with some local artificial sand nourishment and protection activities
1 Poor	a. Strong population pressure and economic activity along the coastal fringe, with natural vegetation converted in most places and widespread degradation and destabilization of natural ecosystems b. Large numbers of engineered structures such as groins, harbours etc.. impeding the longshore movement of sediment c. Large numbers of engineered structures such as sea dikes and land use changes leading to 'mangrove squeeze' d. All of the shoreline affected by erosion

POTENTIAL SOURCES

- Maps and satellite images of topography/bathymetry, land cover, and infrastructure along the coastal fringe
- Records of population, land use, ecosystem health, sediment movements, subsidence, sea level rise, and shoreline erosion/accretion

COAST - GOVERNANCE

Score	Criteria and Indicators
4 Excellent	a. There is political leadership and there are capable, well-resourced and -coordinated agencies at different government levels responsible for coastal management and monitoring (e.g. local and provincial government, agencies for protected areas, shipping, fishing, coastal protection, and tourism, coastal observatories) b. Coastal infrastructure is well mapped, and facilities for transport, protection, recreation etc.. are located and designed with a view to allowing sediment movement c. Regulations (e.g. regarding setbacks for seawalls, protected mangrove zones) are comprehensive and well-enforced d. Baseline data on natural conditions such as topography and bathymetry, currents, sea levels, shoreline erosion/accretion, and vegetation are available, and monitoring includes correct parameters, locations and frequency e. There is effective public participation in coastal management, as well as public confidence in and access to relevant plans and data
3 Good	a. Some gaps regarding coastal-wide management capacity b. Some gaps regarding infrastructure mapping, locations, and design c. Some gaps regarding regulations and their enforcement d. Some gaps regarding baseline data and monitoring e. Some gaps regarding public participation, confidence and access
2 Problematic	a. Significant gaps regarding coastal-wide management capacity b. Significant gaps regarding infrastructure mapping, locations and design c. Significant gaps regarding regulations and their enforcement d. Significant gaps regarding baseline data and monitoring e. Significant gaps regarding public participation, confidence and access
1 Poor	a. No consistent coastal-wide plans, and agencies are poorly resourced and coordinated b. Infrastructure is not mapped and is not located and designed with a view towards sediment management c. Regulations are lacking or not enforced (e.g. uncontrolled mangrove degradation) d. No reliable baseline and monitoring data e. No public participation, confidence and access

POTENTIAL SOURCES

- Coastal scale visions, policies, plans and maps
- Institutional and legal assessments
- Data on protected areas, infrastructure, sediment-related monitoring, regulations and enforcement
- Interviews with officials and stakeholders

SITE - FIELD CONDITIONS

Score	Criteria and Indicators
4 Excellent	a. Healthy mangrove stands at the site, with varied composition and including young and pioneer growth stages, and evidence of wildlife b. No infrastructure such as groynes or seawalls impeding longshore and cross-shore sediment deposition, and restricting mangrove habitat c. No human use of mangroves at site (e.g. for wood harvesting, fishing, sediment extraction etc..) Locally sufficient sediment supply and stable shoreline or active shoreline accretion with mangrove colonization
3 Good	a. Partially converted and degraded mangrove stands at the site (>30%) b. Some infrastructure, although at some distance from the site d. Limited human use of mangroves at site e. Less than sufficient sediment supply and beginning shoreline erosion
2 Problematic	a. Heavily converted and degraded mangrove stands at the site (>60%) b. Infrastructure close to the site c. Heavy human use of remaining mangroves d. Active shoreline erosion
1 Poor	a. Scattered and dying mangrove trees at the site, no natural regeneration b. Infrastructure directly impeding sediment deposition and restricting mangrove habitat c. Heavy human use of remaining mangroves d. Rapidly advancing shoreline erosion

POTENTIAL SOURCES

- Site assessment reports (geomorphology and ecology at site level)
- High resolution maps and aerial pictures

SITE - GOVERNANCE

Score	Criteria and Indicators
4 Excellent	a. The site is managed (including protection, sustainable use and rehabilitation) with clear responsibilities, suitable plans, and sufficient resources b. Baseline data on natural conditions at the site such as topography and bathymetry, currents, tides and waves, substrate and vegetation, and shoreline erosion/accretion are available, and monitoring includes correct parameters, locations and frequency c. There is community awareness and effective participation in site management, as well as community confidence in and access to relevant plans and data
3 Good	a. Some gaps regarding site management b. Some gaps regarding baseline data and monitoring c. Some gaps regarding community awareness, participation, confidence and access
2 Problematic	a. Significant gaps regarding site management b. Significant gaps regarding baseline data and monitoring c. Significant gaps regarding community awareness, participation, confidence and access
1 Poor	a. No effective site management b. No reliable baseline and monitoring data c. No community awareness, participation, confidence and access

POTENTIAL SOURCES

- Site plans and maps
- Data on protected zones, infrastructure, sediment-related monitoring, regulations and enforcement
- Interviews with officials and stakeholders

SCORING TABLE

	Score	Key Issues
River Basin - Physical State	/4	
River Basin - Governance	/4	
Delta - Physical State	/4	
Delta - Governance	/4	
Coastal - Physical State	/4	
Coastal - Governance	/4	
Site - Physical State	/4	
Site - Governance	/4	

@mangrovesNow

www.SaveOurMangrovesNow.org

Contact: Marc Goichot
Greater Mekong Programme Office
marc.goichot@wwfgreatermekong.org