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Sustainable Deltas in the Anthropocene

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11.1 Introduction

This book examines the recent development of selected populous deltas from a variety of perspectives—sediment budgets, vulnerability hotspots, settlement and migration, the delta economy, household adaptation and delta-level adaptation. Building on these analyses, this chapter extracts key lessons for delta development and management through the early twenty-first century and beyond. Some of the emerging trends seem almost inevitable, such as declining sediment supplies, while others will

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R. J. Nicholls et al. (eds.), *Deltas in the Anthropocene*,
https://doi.org/10.1007/978-3-030-23517-8_11

depend strongly on the choices that are made, such as how delta populations are enabled to adapt. Hence, what are the possible trajectories for delta development and how can the more desirable ones be achieved?

Deltas are home to 1 in 14 of the global population: hence a key issue is the implications of delta science for the sustainability and persistence of deltas as geomorphic, ecological, economic and social systems. Many chapters in this book highlight how deltas are dynamic in all these aspects today and change seems inevitable. As deltas are fundamentally geomorphic features, their geomorphic persistence is a core prerequisite for delta sustainability in the long-term (Syvitski et al. 2009; Giosan et al. 2014; Day et al. 2016). Rapid socio-economic changes are also a feature of

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Anthropocene deltas. What are the implications of these different types of change and their different timescales? Economic development gives the opportunity for deltas to prosper and increase the welfare of their whole population over the coming few decades. Given current low levels of income of populations in many agriculture-dominated delta regions, such development is essential. However, in the decade to century time-scale, how will the bio-geomorphic constraints operate and can populations adapt to them? The evidence in this book shows that the twenty-first century will continue to transform landscapes as deltas become more engineered, urbanised and more central to economic activity in their wider regions. Yet the decisions taken in the next decade will set in train pathways that are potentially irreversible. The benefits are increasingly clear of conserving natural capital and conserving ecosystem services in the present day to keep options open for nature-based adaptation into a sustainable and good Anthropocene for deltas (Bennett et al. 2016).

The chapter is structured around the three specific questions asked above. First, the Anthropocene transition in deltas is synthesised. This, second, forms the basis of the review of implications for management and adaptation. Third, the chapter then considers dimensions of sustainability and the wider lessons of this analysis beyond deltas. As examples, Boxes 11.1, 11.2 and 11.3 synthesise current knowledge for three archetypal deltas in Asia and Africa (see Chapters 2–4) to provide a plausible set of futures to 2050 and beyond.

Box 11.1 Ganges-Brahmaputra-Meghna Delta: Realistic and plausible trends to 2050

Change in economic structure and implications for land use

The GBM Delta will continue to see significant urbanisation with a focus in and around Kolkata and Dhaka, and a corresponding stabilisation or probable decline in rural populations. Greater Dhaka may reach a size bigger than any city existing today. At the same time, the economy will continue to transform and grow rapidly: by 2050 the GDP per capita in the Indian part of the GBM Delta could be seven times larger than today and five times larger in the Bangladeshi part, with major expansion of sectors such as industry and services, and a continued decoupling from agriculture (Chapter 8). Agriculture will decline significantly as a proportion of the economy with intensification of rice (and aquaculture). As a result, labour will leave agriculture in search of higher wages in other sectors. This will be particularly true of smallholders and landless labourers who will find it harder to benefit from the growing service economy and agricultural intensification. This is one key driver of rural to urban migration. Further, agriculture may become more intensive with more mechanisation and larger farm sizes, although no evidence of such trends is yet apparent.

Implications of policies and plans

The Bangladesh Delta Plan 2100 (BDP2100) will trigger more coordinated top-down adaptation and development across Bangladesh, while new infrastructure provision such as the Padma Bridge (scheduled opening 2020) will transform how Bangladesh develops. The Indian portion of the delta would also benefit from its own delta plan, but there is no obvious impetus for this today. The renegotiation of the Ganges Water Treaty from 2026 will have a significant impact on both the Bangladeshi and Indian parts of the delta, though national and state governance frameworks may struggle to adapt to these changes initially.

Biophysical changes and implications for inhabitants and livelihoods

Deltaic accretion is likely to continue in Bangladesh, particularly around the Meghna Estuary, although this may slow, while the Indian part of the GBM Delta will continue to erode (Chapter 5). To 2050, climate change will be a challenge, even with business-as-usual adaptation (Chapter 8). Modelling suggests that wild fisheries are more of a concern, and continued regulation is important to maintain catches. In the short-term (next 10 years) growth in aquaculture looks likely. Beyond this, changes are less certain and over intense aquaculture can lead to abandonment of fish ponds that are difficult to convert to other uses, blighting areas: mixed culture is becoming more popular to overcome this issue. The Sundarbans mangrove forest can persist under expected sea-level rise scenarios to 2100, but has many other threats such as pollution. Beyond 2050, climate change and sea-level rise become a bigger concern, while the expected decline of sediment supply from the rivers will hinder the application of sediment-based and working with nature approaches (Chapters 9 and 10). The wild card of major cyclone landfall remains and this could have severe and disruptive impacts.

Role of adaptation

Under plausible improved adaptation measures, agriculture can continue to prosper and flourish and the delta will remain habitable and productive (Chapter 10). Innovative adaptation approaches such as build elevation via controlled sedimentation (Chapter 5) could be widely implemented across the delta, but this must also address the social issues that it raises. Recent improvements in flood/storm surge warnings and cyclone shelters have greatly improved responses to cyclone, and dikes—if well maintained—are generally considered adequate. The post-2050 challenges require significant preparation which should be integral to today's delta planning. The BDP2100 is arguably transformative and supportive in this regard. It also creates a platform for other transformative adaptation, such as what to do about abandoned fishponds as one example.

11.2 The Anthropocene Transition in Deltas

A key message of the preceding chapters is that deltas are highly dynamic systems in multiple biophysical and socio-economic ways and they are evolving rapidly. Table 11.1 summarises the key observed trends and drivers in deltas. These trends are diverse and linked either directly or indirectly to human activities, consistent with the concept of the Anthropocene. While humans have been influencing deltas for thousands of years in some cases (Bianchi 2016; Welch et al. 2017), these type of changes are now pervasive in low and mid-latitude populated deltas and dominate their evolution. Table 11.2 summarises some potential indicators of the Anthropocene transition in deltas from the analysis discussed in previous chapters.

While within any single discipline the individual trends in Table 11.1 and indicators in Table 11.2 might be unsurprising, the trends are usually seen and managed in isolation. However, in deltas these trends are occurring in the same location and interacting in complex ways. As a result, deltas today are quite different to deltas 30 years ago, reflecting the growing importance of cities, agricultural intensification and the changing structure of the economy. The continuation of human activities means that deltas in 2050 will be different to what is seen today. This evolving inter-relationship of trends contrasts with the common narrative about deltas in a changing world, which often narrowly focuses on just one threat—that of relative sea-level rise—while ignoring the implications of other factors, both singly and in

Table 11.1 Key observed trends in deltas in the late 20th/early 21st century highlighted in this book

Key trends	Drivers	Comments	Chapter
Threatened ecosystems	Human pressures, climate change	Longstanding problem, which is still intensifying, but growing interest in working with nature may indicate a new direction (linked to adaptation)	2, 3, 4
Sediment starvation and relative sea-level rise	Dams, natural subsidence, human-enhanced subsidence, climate-induced sea-level rise	Leads to erosion, loss of elevation and growing flood hazard unless there is significant adaptation	5
Changing risks due to changing hazard, exposure and vulnerability	Growing population and economy, adverse environmental and climate change	Growth in risk is almost inevitable without significant adaptation	6
Growing urban populations/stable or declining and ageing rural populations	Livelihood threats and opportunities, economic/education opportunities, better infrastructure and health facilities in cities, demographic transition, increasing life expectancy	Details depend on fertility, the demographic transition is stronger in Asia than Africa	7

(continued)

Table 11.1 (continued)

Key trends	Drivers	Comments	Chapter
Larger economies: major growth in industry and services and relative decline in agriculture and fisheries	Economic growth, agricultural intensification	Growth in climate and other risks can threaten this trend, so the economic development of deltas is strongly linked to adaptation	8
A growing need for adaptation, especially large scale, planned adaptation	Multiple issues galvanising action such as: climate change, growing numbers of receptors, changing attitudes and a more risk-adverse population	The Bangladesh Delta Plan 2100 illustrates the scale and intervention that is needed: transformative adaptation. What are the best strategic options for such transformation?	9
A recognition that adaptation trade-offs and choices have major influence on future delta evolution		Retreat, protect, build elevation or whatever? The linkages to catchments and neighbouring seas must also be considered	10

Table 11.2 Potential indicators of Anthropocene conditions in deltas

Factor	Anthropocene indicators
Sediment supply	Declining trend in sediment supply, with sometimes catastrophic decline compared to pre-Anthropocene conditions, mainly reflecting dam construction
Subsidence	Often enhanced subsidence due to ground fluid withdrawal and drainage, sometimes very rapid (>10 cm/yr) most especially within urban areas on deltas
Land use and land management	Intensification/higher yields to feed the growing delta and associated populations; More diverse, higher value agriculture and aquaculture production (e.g., growth in brackish shrimp aquaculture for export); Move from a subsistence to cash economy and globalisation; Declining agricultural employment
Population/migration	Urbanisation and stable/falling rural populations. Active migration systems, within or adjacent to the delta
Economy	Growing and diversified economy
Natural ecosystems	Decline in biodiversity and natural systems preserved in reserves and protect refuges
Delta-level adaptation	Growing dependence on engineered flood protection (dikes, polders, etc.) as in the Netherlands, leading to lock-in where the choice is between higher defences or major retreat/abandonment; Large-scale integrated and adaptive management up to the whole delta scale (e.g. Bangladesh Delta Plan 2100)

combination. For example, migration from deltas is widely discussed in the climate narrative as being solely a response to sea-level rise, while research summarised in Chapter 7 shows that sea-level rise and environmental degradation more widely is perturbing well-established migration systems, reflecting more general and systemic social trends. Hence sea-level rise and its impacts are only one of many drivers and effects that should be considered when analysing delta evolution and development policies.

The role of adaptation in general and protection through infrastructure in particular is also key to the Anthropocene in deltas. Many deltas could not support their large populations without significant hard adaptation in the form of defence infrastructure. For example, in Bangladesh alone there are more than 6000 km of dikes and embankments around coastal polders and over 2500 cyclone shelters (multi-storey robust buildings) which are a key element in the agricultural and disaster management systems.

These cyclone shelters have been demonstrated to be highly effective to reduce mortality for exposed populations during cyclones (Faruk et al. 2018). They have been transferred to the Mahanadi Delta (Fig. 11.1) where they have similarly been effective (Box 11.2). Significant enhancement of this infrastructure, and its implications for a diverse profile of livelihoods, is ongoing and will continue under the BDP2100 which covers all of Bangladesh (BDP2100 2018). This is discussed more in Sect. 11.3.

11.3 Management and Adaptation of Deltas in the Anthropocene

People living in deltas have long adapted to the changing conditions and situations that characterise the systems, including the seasonal cycles that shape delta life. However, it would seem that the multiple stresses apparent under Anthropocene conditions mean that historic approaches to adaptation and management will not be enough in the future. This mandates an intensification and transformation

Fig. 11.1 Effective local adaptation infrastructure: Cyclone shelter in the Mahanadi Delta, India (Photo: Amit Ghosh/Shouvik Das)

of adaptation in terms of technical approach, scale and governance arrangements.

The emergence of delta-scale plans (Seijger et al. 2017) would seem to be one appropriate response to modifying the approach to adaptation in deltas. Being in many ways a response to the flooding of New Orleans in Hurricane Katrina in 2005, these started in the Netherlands with the Delta Plan in 2008 (Deltacommissie 2008; Kabat et al. 2009; Stive et al. 2011). This approach to delta planning has been exported to the Mekong Delta, Vietnam (Mekong Delta Consortium 2013) and Bangladesh (BDP2100 2018), with other deltas considering similar plans. The Mississippi Delta also has a major delta planning process (CPRAL 2017).

All these deltas plans and planning processes stress the importance of governance and integration and a long-term commitment to adaptation. For example, the Netherlands has created a Delta Commission and a Delta Commissioner role with long-term (20 year) financial commitments and new institutions/governance approaches to manage the delta; a structure which has the potential to be translated to other deltas. However, it is important not to see delta governance approaches in isolation, as they are heavily influenced and directed by governance frameworks across multiple administrative and hydrological scales. The Dutch system, for example, operates within the confines of the river basin management planning framework under the Water Framework, Floods and Environmental Impact Assessment Directives (among others), but also under international legal arrangements for the Meuse, Rhine and Scheldt Rivers. Likewise, the implementation of the Mekong Delta Plan is dependent to some extent on the Mekong River Convention and on relevant (though not delta-specific) national policy and legal contexts.

Such delta plans promote a systems view of adaptation which allows important changes in adaptation and management to be incorporated. For example, there is growing interest in soft infrastructure and "building with nature" approaches (van Wesenbeeck et al. 2014) and hybrid approaches that combine soft and hard adaptation (Smajgl et al. 2015); these can include maintaining or recreating mangrove and forest belts and controlled sedimentation within polders to raise land levels. Natural system approaches are most strongly developed in the Mississippi Delta, USA (Costanza et al. 2006; Day et al. 2007; Paola et al. 2010), reflecting a desire to counter massive historic losses of wetland since the 1950s. Further innovation in delta adaptation is anticipated over the next few decades and working with nature to the maximum degree possible, especially for sediment management, is one guiding principle of these efforts.

An important issue when considering future adaptation is the notion of "lock-in". Lock-in occurs when any decisions limit or curtail future options. Building embankments and dikes with polders in a delta with relative sea-level rise, and growing economic value behind the defences leads to choice between raising these defences or a major abandonment/retreat. This dilemma epitomises much of today's Netherlands and other wealthy developed countries. Thus, defences can lock the delta into a pathway that is unsustainable in the long-term and can only be reversed with great efforts and significant resources. Seijger et al. (2018) conceptualise that the delta pathway lock-in can occur for technological and institutional reasons that co-evolve. Skills, relations and interests of an institution can limit their willingness to take up a new technology. On the other hand, if a technology is widely deployed, it is easier and cheaper to maintain and improve than replace with a completely new approach affecting assets and way of living. This is what Seijger et al. (2018) call the dual lock-in of deltas. However, environmental concerns of societies, especially in wealthy countries, can also have a bearing on delta development and planning (van Staveren and van Tatenhove 2016; Welch et al. 2017). In such cases, the competing interests between hazard exposure, economic development, social welfare and environmental protection make delta planning more complex, and a clear understanding of trends, threats and trade-offs is essential (Suckall et al. 2018; Chapter 9).

As an alternative adaptation pathway, controlled sedimentation and building elevation may create a pathway where the land surface can keep relative pace with sea level—the sediment that allows this strategy has been characterised as "brown gold" (Darby et al., 2018). This is a more sustainable adaptation strategy in deltas if sufficient sediment is available. However, to be sustainable, land raising will need to be an ongoing process and the effects on society during the time that the land is in the process of being raised needs to be considered; this requires a strategic approach. More broadly, questions of equity and how the poorest and politically-underrepresented are treated in such processes, especially the possibility of being displaced from their land, must be addressed.

As noted in Boxes 11.1–11.3, the commitment and interest in delta planning in the Mahanadi, Volta and Indian portion of the GBM Delta is currently lower than in Bangladesh. Would they benefit from their own delta plan? Or should they be managed together with the neighbouring non-deltaic coasts? In the Mahanadi context, there may be good reasons for the development of a delta plan by the state of Odisha, if only in order to inform the current controversy over water use in the upstream state of Chhattisgarh and where, although legal frameworks on coastal zone management are actively enforced, broader water resource management legislation across the basin is much less effective.

In other cases, this question needs to be explored further. As part of these discussions, two additional questions also need to be considered: how should this management be conducted, and what is a sustainable delta?

Box 11.2 Mahanadi Delta: Realistic and plausible trends to 2050

Change in economic structure and implications for land use
The Mahanadi Delta will see many trends similar to the GBM delta. There will be significant urbanisation with a particular focus in and around Bhubaneswar, and a continued decline in rural populations (Chapter 7). However, the scale of these cities is small compared to Dhaka and Kolkata in the GBM Delta. Again, the economy will continue to transform and grow rapidly: by 2050 the GDP per capita could be 5.4 times larger than today, with major expansion of sectors such as industry and services, and a decline in the relative size and employment in agriculture (Chapter 8).

Implications of policies and plans
Separate delta level efforts need to be initiated to counter the decline of forest and biodiversity and combat increasing pollution load in the ecosystem. In governance terms, increasing conflict between the Indian states of Chhattisgarh and Odisha may prompt the determination of state water allocations, but the delta is unlikely to feature strongly in this process and may suffer from increasing water scarcity in future. This creates little impetus for the development of strategic delta planning (Chapter 9).

Biophysical changes and implications for inhabitants and livelihoods
Erosion is already widespread in the delta and this is likely to continue and may trigger hard or soft (working with nature) engineering responses (Chapter 5). The wild card of a major cyclone landfall remains a concern and this could have severe impacts as in the 1999 Super Cyclone. Beyond 2050, climate change and sea-level rise become a bigger concern, and sediment supply from the rivers is expected to decline, hindering working with nature approaches (Chapter 5). These upcoming challenges require preparation now and should be integral to delta planning today, but the institutional framework and willingness to facilitate this do not exist.

Role of adaptation
Adaptation by individual households is likely to continue as is, without a larger development plan for the delta. This is likely to continue to be driven by the need to reduce vulnerability, e.g. migration, loans and improving individual homes. Hence, the emergence of women headed

household as a separate vulnerable group within the delta is likely to persist. While this may improve the opportunities for those able to afford adaptation, those unable to find the resources to adapt are likely to remain in poverty and fall further behind. However, recent improvements in disaster risk management, including flood warnings, evacuations and the provision of cyclone shelters have greatly improved responses—Cyclone Phailin in 2013, while causing widespread damage, had hardly any casualties. Such planned delta level adaptation would be increasingly useful beyond 2050.

11.4 Deltas and Sustainability

The idea of sustainability is key to the concept of the Anthropocene. The analysis in this book shows that sustainability has multiple dimensions and timescales. Day et al. (2016) consider delta sustainability within the context of global biophysical and socio-economic constraints, recognising geomorphic, ecological and economic aspects of delta sustainability. However, a narrow focus on the physical processes that underpin delta functioning tends to underemphasise the influence of maintaining a sustainable delta society, which includes livelihood sustainability, demography and well-being. The following therefore highlight trade-offs inherent in the concept of adaptation when considered in relation to the different aspects of delta sustainability, focussing on the examples raised in the detailed delta studies.

Geomorphic Sustainability

Geomorphic sustainability links sediment budgets and resulting land elevation (see Chapter 5). Sediment flux to the deltas from the catchment is often significantly reduced by upstream dams, but even within deltas, sediment movement is widely restricted by engineering interventions such as dikes for urbanisation and flood defence. Subsidence in deltas is a naturally occurring process due to sediment compaction (Meckel et al. 2007; Syvitski 2008) that can be greatly accelerated by groundwater abstraction (e.g. for irrigation or for drinking water). The mean subsidence of 46 major deltas is 3.6 mm/yr, but can reach at least 22 mm/yr in extreme cases such as the Indus Delta in Pakistan (Tessler et al. 2018), and even more in urban areas on deltas (Nicholls 2018). This, combined with one metre or more sea-level rise, will result in significant land areas in deltas being below sea level by the end of this century (Syvitski et al. 2009; Brown et al. 2018); land which will either be submerged or dependent on major defences and drainage systems (as in the Netherlands) (Fig. 11.2).

The benefits of regular flooding and sedimentation for deltas is highlighted by Auerbach et al. (2015). They estimated that poldered areas in coastal Bangladesh have lost 1.0–1.5 m land elevation since the 1960s compared to the neighbouring Sundarbans mangrove forest whose land elevation has remained stable relative to sea level. However, if such subsided lands are reconnected with tidal inundation as a result of a natural disaster, or through controlled flooding, rapid sedimentation of around tens of centimetres of elevation increase in months can occur (Auerbach et al. 2015). There are examples of small-scale controlled inundation practices to locally raise land levels, such as the Tidal River

Fig. 11.2 Erosion and flooding are both indicative of sediment supply and sea-level rise issues (Photo: Mousuni Island, GBM Delta—Shouvik Das)

Management (TRM) in Bangladesh (Chapter 2; Box 11.1), aiming to ensure long-term geomorphic and ecological sustainability. Even though such interventions provide long-term benefits of reduced flooding and waterlogging, TRM remains controversial as it results in the temporary loss of productive land and hence livelihoods. Without addressing the short-term institutional limitations and providing compensation, many communities are therefore reluctant to implement it (Gain et al. 2017). Future plans for TRM are consequently limited, and it is not included within more than 100 proposals contained within the BDP2100. A more ambitious plan in Bangladesh could aim to raise larger areas of land and try to keep pace with relative sea-level rise, but a change in mindset will be required.

Eliminating the sediment retention of upstream dams is similarly problematic as many of these dams are located in a different country, and they serve multiple economic purposes such as providing irrigation water, producing electricity and ensuring navigation. Even if sediment can bypass the dam, the regulation of flow greatly reduces downstream sediment transport to the delta. Thus, competing economic interests often cause sediment starvation of the coastal areas even without the negative effect of embankments and water abstraction. The widespread erosion of the Volta Delta due to sediment starvation from upstream dams is well known (Chapter 4).

As noted earlier, long-term adaptation and planning in deltas are becoming more widespread around the world, aiming to balance the geomorphic and societal needs of the delta (MDP 2013; BDP2100 2018; DP 2018). However, there are ultimately three policy choices in the face of the long-term (i.e. 2100 and beyond) sea-level rise and subsidence: (i) abandon the coastal zone; (ii) protect the population of the coastal zone with ever-higher defences, including pumping; or (iii) build land elevation by controlled sedimentation (Nicholls et al. 2018a). Assuming climate stabilisation and sufficient sediment supply can be maintained from upstream catchments, innovative solutions for sediment management are proposed, but their long-term feasibility and social acceptability need further trials (Day et al. 2014; Gain et al. 2017; also Chapter 5).

Ecological Sustainability

The ecology of populated deltas is highly modified and agriculture and aquaculture have largely replaced natural systems, except for protected areas like the Sundarbans. Day et al. (2016) argued that river inputs regulate soil processes thus enabling better accretion rates, soil formation and resistance to erosion and sea-level rise. But ecological sustainability should be viewed more broadly. Saline intrusion in rivers and groundwater results in soil salinisation (Fan et al. 2012) and the degradation of aquatic and terrestrial biodiversity (Goss 2003). Salinisation also requires radically altered agriculture practices (Rahman et al. 2011; Renaud et al. 2015). However, soil salinisation and biodiversity degradation is also driven by economic transformations of land use that can be highly detrimental to the agricultural yields and may encourage maladaptive processes (Fig. 11.3). An example of such a maladaptation, from a sustainability point of view, is the large-scale

Fig. 11.3 Extensive shrimp farming replaces traditional agricultural practices and local ecosystems in the GBM Delta (Photo: Attila Lázár)

high intensity brackish shrimp cultivation in Bangladesh, which increases soil salinity, acidity, degrades soil quality and can also result in soil toxicity and mangrove destruction (Ali 2006; Azad et al. 2009). While unplanned and uncoordinated shrimp cultivation creates short term export value, it also creates social conflicts, as it negatively impacts traditional agriculture and has significant negative ecological consequences (Flaherty et al. 1999; Hossain et al. 2013; Paul and Røskaft 2013). For example, the collection of shrimp larvae is an important informal livelihood, and one that is accessible for women (Ahmed et al. 2010), but the systematic removal of larvae from coastal waters has significant negative impacts on ecosystem services and aquatic ecology (Hoq 2007; Azad et al. 2009). Also, even though shrimp cultivation is lucrative for the private interests involved, the realised benefits of the shrimp production to delta residents is small due to the outflow of profit to the investors (Swapan and Gavin 2011). Virtually all shrimp produced in the GBM Delta in Bangladesh is exported (Quassem et al. 2003), and hence does not support local food security and availability.

In natural areas such as the Sundarbans—the world's largest mangrove forest (Chapter 2)—major land losses are widely expected due to sea-level rise. However, there is good evidence that these systems are more resilience and can persist, even under high rates of sea-level rise and subsidence, although this is dependent on the availability of sediment and does not mean that the current species composition is conserved. In the Sundarbans, there is a change to more salt-tolerant mangroves (Payo et al. 2016; Mukhopadhyay et al. 2018). Other non-climate risks are noteworthy such as oil spills and pollution—the Sundarbans contain major shipping routes.

Thus, ecological sustainability partially depends on geomorphological processes, but can also be heavily impacted by human activities in the short-term. In the long-run, ecological sustainability must be linked to geomorphic sustainability.

Economic Sustainability

From the economic perspective, the future sustainability of deltas will depend on their capacity to provide the goods and services required to ensure the well-being of their population and contribute to the achievement of the Sustainable Development Goals (SDGs) (Nicholls et al. 2018b). But there are significant potential trade-offs involved when some elements of the sustainability are prioritised. For example, shrimp farming is very lucrative and contributes to economic growth (SDG8), being the fifth largest export commodity of Bangladesh at about US$500 million in 2016–2017 (BBS 2017) while simultaneously damaging water quality and affecting biodiversity conservation (SGDG15). Similarly, coastal protection protects economic activities from extreme events, but this threatens geomorphic sustainability.

Economic sustainability can, in theory, be steered through policies, research and development and investment. However, stark dilemmas exist between seeking the benefits of industrialisation and protection of the environment, biodiversity and the traditional way of living. The sustainability dilemmas highlight issues of reversibility, the potential for technology, and the inertia in policy focussed on economic growth. A planned Indian-Bangladeshi cross-border coal power plant, for example, endangers the Sundarbans mangrove forest and the wider region through water and air pollution (Ghosh 2018). Yet India is rapidly moving away from coal power as a redundant resource, seeking to implement solar and other renewable energy technologies that are less polluting for climate and local environments (Mehra and Bhattacharya 2019).

The drive for economic growth is acute in delta regions, because of their role as growth poles of population and economic activity in virtually all deltas (Chapter 8). In effect, natural capital in deltas is being converted to physical and financial capital. Principles of sustainability suggest that such a strategy can be sustained as long as natural capital thresholds are not exceeded. Without knowledge of where many thresholds and tipping points for natural systems are in deltas, there is a significant priority to conserve natural systems and processes to keep future development options open and to ensure the avoidance of overall loss of sustainability potential.

Social Sustainability

Economic sustainability does not necessarily mean that the delta can equitably provide livelihoods and well-being. An increasing GDP or an increase in average living standards does not mean that poverty is reduced for everyone (Ravallion 2001). The poor typically benefit from economic growth, but they are also disproportionally hurt from economic contraction or hazard events. Indeed, increased economic growth can drive inequality, where poorer sectors of society are left out of growth or are driven from areas of development as land values rise (Amoako-Johnson et al. 2016). Unequal benefits of farming technologies are also highlighted by Chapman and Darby (2016) in the Mekong Delta, Vietnam. They showed that the current triple-cropping strategy with protection from dikes only benefits the wealthier farmers with a limited 10-year maximum benefit window as soil nutrients are depleted. However, taking a more sustainable view and leave the sluice gates open, agriculture could become more equitable although the net economic benefits would become smaller.

If rural delta regions do not prioritise liveability and livelihood security, such regions will inevitably lose populations to cities. Environmental dimensions of migration in deltas include land grabbing for agricultural intensification, land degradation and marginalised livelihoods. These exacerbate existing migration trends relating to family obligations, seeking better education and infrastructure (Chapter 7). In addition, exposure to climate shocks often displaces populations temporarily but changes the long term attractiveness of permanent moves, almost invariably to urban settlements (Fig. 11.4). Rural coastal communities are exposed to environmental stress and hazards, and often lack education and health infrastructure that can be a serious motivation for migration. Societal sustainability therefore incorporates the spatial distribution of populations, the links between cities and rural hinterlands and liveable environments where inequality and poverty and minimised.

Deltas and the Sustainable Development Goals

The 17 SDGs express aspirations for human development that require the realisation of a universal, but diverse set of ethical principles, such

Fig. 11.4 Displacement of populations by floods can lead to permanent migration (Photo: A. K. M. Saiful Islam)

as inclusion, justice, equality, dignity, well-being, global solidarity, sharing, sustainability and public participation (United Nations 2015; Szabo et al. 2016; Hutton et al. 2018). As with all coupled human-environment systems, the issues that impact deltas in the Anthropocene are both diverse and complex (Young et al. 2006). It is for this reason that the SDGs are extensive and comprehensive in their approach to capturing the biophysical and socio-economic context for development, as well as the inherent trade-offs associated with this development (Hutton et al. 2018). Economic growth, poverty, environmental degradation, and inequality as well as food production are recurrent issues. As such, of particular interest within delta systems is the relationship between the SDG goals in Table 11.3, although all the SDGs are linked.

These goals can, and do, directly compete with each other through the sustainability of food production processes and the demands of urbanisation (Machingura and Lally 2017). Decision makers are

Table 11.3 Selected SDG goals of particular relevance in the future management of deltas

SDG	Aim
1	(No poverty) Eradicating poverty in all its forms by 2030
2	(No hunger) End all forms of hunger and malnutrition by 2030
8	(Decent work and economic growth) Promote sustained economic growth and higher levels of productivity
10	(Reduced inequalities) Reduce inequality within and among countries
14	(Life below water) To sustainably manage and protect marine and coastal ecosystems
15	(Life on land) To conserve and restore the use of terrestrial ecosystems

therefore faced with choices regarding the intensification of agriculture that, while enhancing food production, may also reduce the demand for labour, increase inequalities, undermine subsistence and small holding livelihoods as well as causing damage to the terrestrial and aquatic ecosystems. Similarly, the development of infrastructure, so important for reducing rural poverty, can also lead to highly destructive environmental practices. Such insight is extremely relevant for policy development, as it calls for processes of trade-off decisions, compromise and planning of strategic development pathways. The recognition of this raises critical ethical questions about potential pathways and compromises to achieve a balance between the SDGs, and demands transparent scrutiny of priorities and motivations for sustainable development, as well as the identification of winners and losers (Hutton et al., 2018).

Box 11.3 Volta Delta: Realistic and plausible trends to 2050

Biophysical changes and implications for inhabitants and livelihoods

The Volta Delta differs from the GBM and Mahanadi Deltas in that the main marine hazard is erosion and flooding at the immediate coast—tides and surges are small and penetrate relatively small distances inland compared to the other deltas. Other delta processes have been removed for 50 years or more by upstream dams so river floods and a new sediment supply are almost totally absent (Chapter 5). These trends are likely to continue and accelerate, as are the engineered protection responses of breakwaters, groynes and nourishment in developed areas.

This protection is certainly buying time in the more critical locations on the open coast like Keta, but could exacerbate erosion to the east, causing potential conflict with Togo. Beyond 2050, climate change and sea-level rise become a bigger concern for the delta with a growing flood plain and the potential for more widespread impacts.

Change in economic structure and implications for land use
There will be significant rural to urban outmigration to Accra, Tema, Lomé (Togo) and other urban areas mainly due to livelihood decisions (Chapter 7). Looking to 2050 and beyond, the urban footprint of Greater Accra and Greater Lomé may significantly expand on to the Volta Delta. As the total fertility rate is higher in West Africa than in Asia, the rural population may be stable or even rise rather than decline as in the Asian deltas. This in turn is likely to drive land cover change towards agriculture and more intense agriculture, although urbanisation may become a feature in a few decades as the neighbouring cities grow. Similarly aquaculture on the Keta Lagoon is expected to intensify greatly. Inland, climate variability and change may be manifest by drought and its impact on agriculture, with the impacts beyond the delta (Chapter 6). As with the other deltas, the delta economy will continue to transform and grow rapidly: by 2050 the GDP per capita in the delta could be 4.5 times larger than today, with major expansion of sectors such as industry and services, and a decline in the relative size and employment in agriculture (Chapter 8).

Implications of policies and plans
In governance terms, the specific needs of the delta are not well recognised as a distinct feature, but the erosion of the coast is widely recognised as a problem, as demonstrated by the government-funded adaptation projects. As with the Mahanadi, this creates little impetus for the development of strategic delta planning. Upcoming challenges require preparation now and should be integral to delta planning today, but the institutions for this to happen do not seem to exist. In the absence of delta planning, climate change is likely to increase migration away from the delta.

Role of adaptation
While more adaptation is to be expected due to ongoing erosion, climate and other changes, this is likely to be more of the same (Chapter 9). A key innovation would be the development of more integrated beach and erosion management and recognising the value of beach sand. With the absence of cyclones and local storms, erosion will continue to displace people where there is no protection, but this will be small compared to other drivers of migration. However, the images of these impacts are evocative and will continue to draw significant attention.

11.5 Insights on the Anthropocene Transition and Its Management

Beyond deltas, these analyses provide an important and useful perspective on the Anthropocene in general that are applicable for other coupled human-environment systems. In deltas, geomorphic, ecological, economic and social processes coexist in the same space and interact in multiple ways. They show that multiple drivers are in operation today and these are linked, directly or indirectly, to human agency. Importantly, this includes adaptation that, while a response to these drivers, also potentially has an important feedback on the future evolution of deltas (Welch et al. 2017; Seijger et al. 2018). This brings out the complexity of these systems and their evolution is difficult to predict with confidence—different possible trajectories are apparent and policy can steer change towards desirable outcomes. Similar processes are operating in other coupled human-environment systems, such as river catchments (upstream of the deltas considered here), drylands or coastal lowlands. In all cases, this suggests that a systems analysis is useful and instructive to analyse the current status of these areas, and to consider possible future trajectories and inform policy.

It is also important to recognise the complementary role of bottom-up and top-down approaches in such analyses (Conway et al. 2019). Climate science often takes a "global" view, but this can miss important social and economic changes that manifest at more local levels. Integrating these approaches leads to a more complete analysis and recognition of both the broad-scale and more local drivers of change and sets the global driver of climate change (and other broad-scale drivers) into an appropriate context. This means engaging with stakeholders in a participatory manner is a key component of success in managing and developing coupled human-environment systems in the Anthropocene (e.g. Nicholls et al. 2018b).

11.6 Key Lessons

This book identifies a number of important dimensions of sustainability for deltas in the Anthropocene. Firstly, it demonstrates that deltas are hotspots in the Anthropocene transition and exemplify many of the diverse social and environmental changes that are occurring across the planet. The range of biophysical and socio-economic processes interacting in deltas, including migration flows and adaptation choices, are shaping their future development and sustainability or persistence. Deltas are, therefore, about more than sediment supply and geomorphic change, but sediment availability and sedimentation emerge as key factors influencing long-term delta survivability. Over the next 30 years, all the deltas considered here have potential to develop in ways that will deliver great benefits for their populations (Boxes 11.1–11.3). Economic development can create significant adaptive capacity to address the challenges that lie beyond this time frame, especially if the framework for such responses is planned now rather than delayed.

Strategic adaptation and consideration of delta development trajectories can help to avoid lock-in and other irreversible decisions—strategic raising of agricultural and natural areas with controlled sedimentation should be encouraged and become the norm where possible. However, it is unclear if sufficient sediment will be available in all cases, and this does not address urban areas where more traditional flood defence is likely to remain the key form of risk management. The prospect of occasional large floods in delta cities is a significant concern (cf. Hallegatte et al. 2013). This raises the question about the trade-off between elevation and wealth. For example, Day et al. (2016) and many other sources see elevation in deltas as fundamental. Yet the Netherlands presently copes with such conditions of lost elevation, reflecting its high wealth, access to technology and good governance. Hence, while the long term health of deltas is dependent on sediment supply, wealthy societies in deltas can, in effect, buy time and adapt with technology, and economic growth greatly increases the capacity of these options.

Long-term adaptation and planning is becoming more common in deltas around the world aiming to balance the biophysical and societal needs. However, as we look to the long-term (i.e. 2100 and beyond), there are ultimately three policy choices for deltas in the face of sea-level rise and subsidence: (i) abandon the coastal zone; (ii) protect the population of the coastal zone with ever-higher defences, including pumping, and consideration of residual risk; or (iii) raise land elevation by controlled sedimentation. As noted, this dilemma can be dodged in the short-term, but as time goes on this stark choice will become clearer and clearer. In populated deltas, building elevation is an attractive option if sufficient sediment is available and it can be delivered to the delta surface in a manner that is socially acceptable. The absence of such proposals in the current BDP2100 is noteworthy and much work remains to be done in promoting this approach. However, the BDP2100 will be regularly updated allowing such innovation. In contrast, in the Volta Delta controlled sedimentation does not seem to be an option as there is no sediment supply and other approaches are required.

Many earlier analyses paint a negative picture of the future of deltas and suggest that, without radical transformation, disaster lies ahead (e.g. Syvitski et al. 2009; Day et al. 2016). This book recognises those major challenges, but it also highlights opportunities and possible trajectories where these deltas will prosper, in some senses the potential for a good Anthropocene (Bennett et al. 2016). These futures depend on significant adaptation, be it working with nature to build elevation via controlled sedimentation, or more traditional hard adaptation approaches such as building and improving dikes and embankments and moving towards a situation resembling the Netherlands. Bennett et al. (2016) define "seeds" of a good Anthropocene, and in deltas this would seem to include working with natural approaches to maximise geomorphic sustainability. Importantly, delta scale simulations, including human agency, are becoming feasible (Angamuthu et al. 2018), facilitating this approach. Equally, there are trajectories where collapse may occur especially under scenarios of degraded livelihoods and extreme events. To a great extent, the future effectiveness of delta-specific approaches will be tempered by the overall quality of governance in basins as a whole. It is important to recognise that not all deltas will behave or respond in the same ways, and success stories in some deltas may be offset by failure in others.

References

Ahmed, N., Troell, M., Allison, E. H., & Muir, J. F. (2010). Prawn postlarvae fishing in coastal Bangladesh: Challenges for sustainable livelihoods. *Marine Policy, 34*(2), 218–227. https://doi.org/10.1016/j.marpol.2009.06.008.

Ali, A. M. S. (2006). Rice to shrimp: Land use/land cover changes and soil degradation in southwestern Bangladesh. *Land Use Policy, 23*(4), 421–435. https://doi.org/10.1016/j.landusepol.2005.02.001.

Amoako-Johnson, F., Hutton, C. W., Hornby, D., Lázár, A. N., & Mukhopadhyay, A. (2016). Is shrimp farming a successful adaptation to salinity intrusion? A geospatial associative analysis of poverty in the populous Ganges–Brahmaputra–Meghna Delta of Bangladesh. *Sustainability Science, 11*(3), 423–439. https://doi.org/10.1007/s11625-016-0356-6.

Angamuthu, B., Darby, S. E., & Nicholls, R. J. (2018). Impacts of natural and human drivers on the multi-decadal morphological evolution of tidally-influenced deltas. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science, 474,* 2219. https://doi.org/10.1098/rspa.2018.0396.

Auerbach, L. W., Goodbred, S. L., Jr., Mondal, D. R., Wilson, C. A., Ahmed, K. R., Roy, K., et al. (2015). Flood risk of natural and embanked landscapes on the Ganges-Brahmaputra tidal delta plain. *Nature Climate Change, 5,* 153–157. https://doi.org/10.1038/nclimate2472.

Azad, A. K., Jensen, K. R., & Lin, C. K. (2009). Coastal aquaculture development in Bangladesh: Unsustainable and sustainable experiences. *Environmental Management, 44*(4), 800–809. https://doi.org/10.1007/s00267-009-9356-y.

BBS. (2017). *Bangladesh statistics 2017*. Bangladesh Bureau of Statistics, Statistics and Informatics Division (SID), Ministry of Planning, Bangladesh. http://bbs.portal.gov.bd/sites/default/files/files/bbs.portal.gov.bd/page/a1d32f13_8553_44f1_92e6_8ff80a4ff82e/Bangladesh%20%20Statistics-2017.pdf.

BDP2100. (2018). *Bangladesh delta plan 2100. Volumes 1-Strategy and 2-Investment plan*. General Economics Division (GED), Bangladesh Planning Commission, Government of the People's Republic of Bangladesh, Dhaka, Bangladesh. https://www.bangladeshdeltaplan2100.org/. Last accessed 8 October 2018.

Bennett, E. M., Solan, M., Biggs, R., McPhearson, T., Norström, A. V., Olsson, P., et al. (2016). Bright spots: Seeds of a good Anthropocene. *Frontiers in Ecology and the Environment, 14*(8), 441–448. https://doi.org/10.1002/fee.1309.

Bianchi, T. S. (2016). *Deltas and humans: A long relationship now threatened by global change*. Oxford, UK: Oxford University Press.

Brown, S., Nicholls, R. J., Lázár, A. N., Hornby, D. D., Hill, C., Hazra, S., et al. (2018). What are the implications of sea-level rise for a 1.5, 2 and 3 °C rise in global mean temperatures in the Ganges-Brahmaputra-Meghna and other vulnerable deltas? *Regional Environmental Change, 18*(6), 1829–1842. http://dx.doi.org/10.1007/s10113-018-1311-0.

Chapman, A., & Darby, S. (2016). Evaluating sustainable adaptation strategies for vulnerable mega-deltas using system dynamics modelling: Rice agriculture in the Mekong Delta's An Giang Province, Vietnam. *Science of the Total Environment, 559*, 326–338. https://doi.org/10.1016/j.scitotenv.2016.02.162.

Conway, D., Nicholls, R. J., Brown, S., Tebboth, M., Adger, W. N., Bashir, A., et al. (2019). The need for bottom-up assessments of climate risks and adaptation in climate-sensitive regions. *Nature Climate Change, 9*, 503–511. https://doi.org/10.1038/s41558-019-0502-0.

Costanza, R., Mitsch, W. J., & Day, J. W., Jr. (2006). A new vision for New Orleans and the Mississippi Delta: Applying ecological economics and ecological engineering. *Frontiers in Ecology and the Environment, 4*(9), 465–472. http://dx.doi.org/10.1890/1540-9295(2006)4[465:ANVFNO]2.0.CO;2.

CPRAL. (2017). *Louisiana's comprehensive master plan for a sustainable coast: Commited to our coast*. Baton Rouge, LA: Coastal Protection and Restoration Authority of Louisiana. http://coastal.la.gov/wp-content/uploads/2017/04/2017-Coastal-Master-Plan_Web-Single-Page_CFinal-with-Effective-Date-06092017.pdf. Last accessed 20 December 2018.

Darby, S. E., Nicholls, R. J., Rahman, M. M., Brown, S., & Karim, R. (2018). A sustainable future supply of fluvial sediment for the Ganges-Brahmaputra Delta. In R. J. Nicholls, C. W. Hutton, W. N. Adger, S. E. Hanson, M. M. Rahman, & M. Salehin (Eds.), *Ecosystem services for well-being in deltas: Integrated assessment for policy analysis* (pp. 277–291). Cham: Springer. http://dx.doi.org/10.1007/978-3-319-71093-8_15.

Day, J. W., Agboola, J., Chen, Z., D'Elia, C., Forbes, D. L., Giosan, L., et al. (2016). Approaches to defining deltaic sustainability in the 21st century. *Estuarine, Coastal and Shelf Science, 183*, 275–291. http://dx.doi.org/10.1016/j.ecss.2016.06.018.

Day, J. W., Boesch, D. F., Clairain, E. J., Kemp, G. P., Laska, S. B., Mitsch, W. J., et al. (2007). Restoration of the Mississippi Delta: Lessons from hurricanes Katrina and Rita. *Science, 315*(5819), 1679. http://dx.doi.org/10.1126/science.1137030.

Day, J. W., Kemp, G. P., Freeman, A., & Muth, D. P. (2014). *Perspectives on the restoration of the Mississippi Delta: The once and future delta*. Netherlands: Springer.

Deltacommissie. (2008). Working together with water. A living land builds for its future. *Findings of the Delta Commissie*. The Netherlands: Delta Commissie. http://www.deltacommissie.com/doc/deltareport_full.pdf. Last accessed 28 August 2017.

DP. (2018). *Delta programme 2018—Continuing the work on a sustainable and safe delta*. The Netherlands: Delta programme. https://deltaprogramma2018.deltacommissaris.nl/viewer/publication/1/2-delta-programme.

Fan, X., Pedroli, B., Liu, G., Liu, Q., Liu, H., & Shu, L. (2012). Soil salinity development in the yellow river delta in relation to groundwater dynamics. *Land Degradation & Development, 23*(2), 175–189. http://dx.doi.org/10.1002/ldr.1071.

Faruk, M., Ashraf, S. A., & Ferdaus, M. (2018). An analysis of inclusiveness and accessibility of cyclone shelters, Bangladesh. *Procedia Engineering, 212*, 1099–1106. https://doi.org/10.1016/j.proeng.2018.01.142.

Flaherty, M., Vandergeest, P., & Miller, P. (1999). Rice paddy or shrimp pond: Tough decisions in rural Thailand. *World Development, 27*(12), 2045–2060. https://doi.org/10.1016/S0305-750X(99)00100-X.

Gain, A. K., Benson, D., Rahman, R., Datta, D. K., & Rouillard, J. J. (2017). Tidal river management in the south west Ganges-Brahmaputra Delta in Bangladesh: Moving towards a transdisciplinary approach? *Environmental Science & Policy, 75,* 111–120. https://doi.org/10.1016/j.envsci.2017.05.020.

Ghosh, S. (2018). A cross-border coal power plant could put Sundarbans at risk. *The Wire*.

Giosan, L., Syvitksi, J. P. M., Constantinescu, S., & Day, J. (2014). Climate change: Protect the world's deltas. *Nature, 516,* 31–33. https://doi.org/10.1038/516031a.

Goss, K. F. (2003). Environmental flows, river salinity and biodiversity conservation: Managing trade-offs in the Murray–Darling basin. *Australian Journal of Botany, 51*(6), 619–625. https://doi.org/10.1071/BT03003.

Hallegatte, S., Green, C., Nicholls, R. J., & Corfee-Morlot, J. (2013). Future flood losses in major coastal cities. *Nature Climate Change, 3*, 802. http://dx.doi.org/10.1038/nclimate1979.

Hoq, M. E. (2007). An analysis of fisheries exploitation and management practices in Sundarbans mangrove ecosystem, Bangladesh. *Ocean*

& Coastal Management, 50(5), 411–427. https://doi.org/10.1016/j.ocecoaman.2006.11.001.

Hossain, M. S., Uddin, M. J., & Fakhruddin, A. N. M. (2013). Impacts of shrimp farming on the coastal environment of Bangladesh and approach for management. *Reviews in Environmental Science and Bio/Technology, 12*(3), 313–332. https://doi.org/10.1007/s11157-013-9311-5.

Hutton, C. W., Nicholls, R. J., Lázár, A. N., Chapman, A., Schaafsma, M., & Salehin, M. (2018). Potential trade-offs between the Sustainable Development Goals in coastal Bangladesh. *Sustainability, 10*(4), 1008. http://dx.doi.org/10.3390/su10041108.

Kabat, P., Fresco, L. O., Stive, M. J. F., Veerman, C. P., van Alphen, J. S. L. J., Parmet, B. W. A. H., et al. (2009). Dutch coasts in transition. *Nature Geoscience, 2*, 450. http://dx.doi.org/10.1038/ngeo572.

Machingura, F., & Lally, S. (2017). *The Sustainable Development Goals and their trade-offs* (ODI Development Progress, Case Study Report). London, UK: Overseas Development Institute (ODI). https://www.odi.org/publications/10726-sustainable-development-goals-and-their-trade-offs. Last accessed 4 April 2019.

MDP. (2013). *Mekong Delta plan: Long-term vision and strategy for a safe, prosperous and sustainable delta* (pp. 126 p.). https://www.wur.nl/upload_mm/2/c/3/b5f2e669-cb48-4ed7-afb6-682f5216fe7d_mekong.pdf.

Meckel, T. A., Ten Brink, U. S., & Williams, S. J. (2007). Sediment compaction rates and subsidence in deltaic plains: Numerical constraints and stratigraphic influences. *Basin Research, 19*(1), 19–31. https://doi.org/10.1111/j.1365-2117.2006.00310.x.

Mehra, M., & Bhattacharya, G. (2019). Energy transitions in India: Implications for energy access, greener energy, and energy security. *Georgetown Journal of Asian Affairs*. http://hdl.handle.net/10822/1053156.

Mekong Delta Consortium. (2013). *Mekong Delta plan: Long-term vision and strategy for a safe, prosperous and sustainable delta*. Partners for Water, Netherlands. Ministry of Infrastructure and Environment, Embassy of the Kingdom of the Netherlands, Hanoi Ministry of Natural Resources and Environment, Ministry of Agriculture and Rural Development Consortium, Royal HaskoningDHV, WUR, Deltares, Amersfoort, Netherlands. https://www.mekongdeltaplan.com/storage/files/files/mekong-delta-plan.pdf?1. Last accessed 10 April 2019.

Mukhopadhyay, A., Payo, A., Chanda, A., Ghosh, T., Chowdhury, S. M., & Hazra, S. (2018). Dynamics of the Sundarbans mangroves in Bangladesh under climate change. In R. J. Nicholls, C. W. Hutton, W. N. Adger,

S. E. Hanson, M. M. Rahman, & M. Salehin (Eds.), *Ecosystem services for well-being in deltas: Integrated assessment for policy analysis* (pp. 489–503). Cham: Springer. http://dx.doi.org/10.1007/978-3-319-71093-8_26.

Nicholls, R. J. (2018). Adapting to sea-level rise. In Z. Zommers & K. Alverson (Eds.), *Resilience: The science of adaptation to climate change* (pp. 14–29). Oxford, UK: Elsevier.

Nicholls, R. J., Brown, S., Goodwin, P., Wahl, T., Lowe, J., Solan, M., et al. (2018a). Stabilization of global temperature at 1.5°C and 2.0°C: Implications for coastal areas. *Philosophical Transactions of the Royal Society, 376*(2119). http://dx.doi.org/10.1098/rsta.2016.0448.

Nicholls, R. J., Hutton, C., Adger, W. N., Hanson, S. E., Rahman, M. M., & Salehin, M. (Eds.). (2018b). *Ecosystem services for well-being in deltas: Integrated assessment for policy analysis*. London, UK: Palgrave Macmillan.

Paola, C., Twilley, R. R., Edmonds, D. A., Kim, W., Mohrig, D., Parker, G., et al. (2010). Natural processes in delta restoration: Application to the Mississippi Delta. *Annual Review of Marine Science, 3*(1), 67–91. https://doi.org/10.1146/annurev-marine-120709-142856.

Paul, A. K., & Røskaft, E. (2013). Environmental degradation and loss of traditional agriculture as two causes of conflicts in shrimp farming in the southwestern coastal Bangladesh: Present status and probable solutions. *Ocean and Coastal Management, 85,* 19–28. https://doi.org/10.1016/j.ocecoaman.2013.08.015.

Payo, A., Mukhopadhyay, A., Hazra, S., Ghosh, T., Ghosh, S., Brown, S., et al. (2016). Projected changes in area of the Sundarban mangrove forest in Bangladesh due to SLR by 2100. *Climatic Change, 139*(2), 279–291. https://doi.org/10.1007/s10584-016-1769-z.

Quassem, M. A., Khan, B. U., Uddin, A. M. K., Ahmad, M., & Koudstaal, R. (2003). *A systems analysis of shrimp production* (Working Paper WP014). Program Development Office for Integrated Coastal Zone Management Plan (PDO-ICZMP).

Rahman, M. H., Lund, T., & Bryceson, I. (2011). Salinity impacts on agro-biodiversity in three coastal, rural villages of Bangladesh. *Ocean and Coastal Management, 54*(6), 455–468. https://doi.org/10.1016/j.ocecoaman.2011.03.003.

Ravallion, M. (2001). Growth, inequality and poverty: Looking beyond averages. *World Development, 29*(11), 1803–1815. https://doi.org/10.1016/S0305-750X(01)00072-9.

Renaud, F. G., Le, T. T. H., Lindener, C., Guong, V. T., & Sebesvari, Z. (2015). Resilience and shifts in agro-ecosystems facing increasing sea-level

rise and salinity intrusion in Ben Tre Province, Mekong Delta. *Climatic Change, 133*(1), 69–84. https://doi.org/10.1007/s10584-014-1113-4.
Seijger, C., Douven, W., van Halsema, G., Hermans, L., Evers, J., Phi, H. L., et al. (2017). An analytical framework for strategic delta planning: Negotiating consent for long-term sustainable delta development. *Journal of Environmental Planning and Management, 60*(8), 1485–1509. https://doi.org/10.1080/09640568.2016.1231667.
Seijger, C., Ellen, G. J., Janssen, S., Verheijen, E., & Erkens, G. (2018). Sinking deltas: Trapped in a dual lock-in of technology and institutions. *Prometheus*, 1–21. http://dx.doi.org/10.1080/08109028.2018.1504867.
Smajgl, A., Toan, T. Q., Nhan, D. K., Ward, J., Trung, N. H., Tri, L. Q., et al. (2015). Responding to rising sea levels in the Mekong Delta. *Nature Climate Change, 5,* 167–174. https://doi.org/10.1038/nclimate2469.
Stive, M. J. F., Fresco, L. O., Kabat, P., Parmet, B. W. A. H., & Veerman, C. P. (2011). How the Dutch plan to stay dry over the next century. *Proceedings of the Institution of Civil Engineers—Civil Engineering, 164*(3), 114–121. https://doi.org/10.1680/cien.2011.164.3.114.
Suckall, N., Tompkins, E. L., Nicholls, R. J., Kebede, A. S., Lázár, A. N., Hutton, C., et al. (2018). A framework for identifying and selecting long term adaptation policy directions for deltas. *Science of the Total Environment, 633,* 946–957. https://doi.org/10.1016/j.scitotenv.2018.03.234.
Swapan, M. S. H., & Gavin, M. (2011). A desert in the delta: Participatory assessment of changing livelihoods induced by commercial shrimp farming in southwest Bangladesh. *Ocean and Coastal Management, 54*(1), 45–54. https://doi.org/10.1016/j.ocecoaman.2010.10.011.
Syvitski, J. P. M. (2008). Deltas at risk. *Sustainability Science, 3*(1), 23–32. https://doi.org/10.1007/s11625-008-0043-3.
Syvitski, J. P. M., Kettner, A. J., Overeem, I., Hutton, E. W. H., Hannon, M. T., Brakenridge, G. R., et al. (2009). Sinking deltas due to human activities. *Nature Geoscience, 2*(10), 681–686. https://doi.org/10.1038/ngeo629.
Szabo, S., Nicholls, R. J., Neumann, B., Renaud, F. G., Matthews, Z., Sebesvari, Z., et al. (2016). Making SDGs work for climate change hotspots. *Environment: Science and Policy for Sustainable Development, 58*(6), 24–33. http://dx.doi.org/10.1080/00139157.2016.1209016.
Tessler, Z. D., Vörösmarty, C. J., Overeem, I., & Syvitski, J. P. M. (2018). A model of water and sediment balance as determinants of relative sea level rise in contemporary and future deltas. *Geomorphology, 305,* 209–220. https://doi.org/10.1016/j.geomorph.2017.09.040.

United Nations. (2015). *Seventieth session agenda items 15 and 116 resolution adopted by the General Assembly on 25 September 2015*. Transforming Our World: The 2030 Agenda for Sustainable Development. New York, NY: UN General Assembly.

van Staveren, M. F., & van Tatenhove, J. P. M. (2016). Hydraulic engineering in the social-ecological delta: Understanding the interplay between social, ecological, and technological systems in the Dutch delta by means of "delta trajectories". *Ecology and Society, 21,* 1. https://doi.org/10.5751/ES-08168-210108.

van Wesenbeeck, B. K., Mulder, J. P. M., Marchand, M., Reed, D. J., de Vries, M. B., de Vriend, H. J., et al. (2014). Damming deltas: A practice of the past? Towards nature-based flood defenses. *Estuarine, Coastal and Shelf Science, 140*, 1–6. https://doi.org/10.1016/j.ecss.2013.12.031.

Welch, A. C., Nicholls, R. J., & Lázár, A. N. (2017). Evolving deltas: Co-evolution with engineered interventions. *Elementa Science of the Anthropocene, 5*, 49. http://dx.doi.org/10.1525/elementa.128.

Young, O. R., Berkhout, F., Gallopin, G. C., Janssen, M. A., Ostrom, E., & van der Leeuw, S. (2006). The globalization of socio-ecological systems: An agenda for scientific research. *Global Environmental Change, 16*(3), 304–316. https://doi.org/10.1016/j.gloenvcha.2006.03.004.