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Building resilience in Asian mega-deltas

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Abstract

The five Asian mega-deltas (Yangtze, Pearl, Chao Phraya, Mekong and Ganges-Brahmaputra-Meghna (GBM)) are home to approximately 80% of the global deltaic population and the region experiences 90% of global flood exposure. In this Review, we investigate the similarities and differences between the Asian mega-deltas to identify transferable lessons to improve climate resilience. The deltas are increasingly threatened by coastal flooding, saline intrusion and erosion caused by climate change and human activities such as groundwater extraction and dam construction. Owing to differences in the stages of their development, various resilience measures have been implemented. For example, the GBM and Mekong deltas use strategic delta plans to identify risk hotspots and guide decision-making. These deltas also increase resilience at a community level by supporting communities to diversify their livelihoods to respond to changing risks and land conditions. Meanwhile, the Yangtze and Pearl deltas have developed forecasting and sensing technologies to allow them to prepare for and respond to hazards effectively. Therefore, the Asian mega-deltas must learn from one another to integrate effective resilience plans across regional, delta and community levels. Future cross-delta collaborations and knowledge transfer, for example through the formation of a regional Delta Resilience Alliance, could help to achieve long-term sustainable delta management.

[H1] Introduction

Anthropogenic interventions[1,2], combined with the growing impacts of climate change, are exacerbating the exposure of coastal deltaic populations to natural hazards. At present, the surface areas of approximately 85% of the world's largest deltas are diminishing owing to reduced sediment supplies caused by upstream dams, channel diversions, and sand mining. These changes undermine the natural ability of the deltas to persist above sea level[3] and can lead to an increase in coastal flooding, river and pluvial (especially monsoonal) flooding, and riverbank and coastal erosion, causing setbacks in development across exposed deltaic populations. For example, 90% of the world's exposure to flooding is experienced in South and Southeast Asia[4,5]. The Yangtze, Pearl, Chao Phraya, Mekong and Ganges-Brahmaputra-Meghna (GBM) deltas, hereafter referred to as the five Asian mega-deltas (5AMDs)— are the largest and most populous of these deltas, housing over 400 million people[7] (**Figure 1**), which equates to approximately 80% of the global deltaic population[6].

Despite experiencing similar natural hazards, the 5AMDs use different disaster management approaches, owing to variations in the development stage and institutional contexts of the deltas. The Yangtze and Pearl deltas have densely populated urban centres, which use well-maintained engineered structures such as embankments, flood gates and channelised river networks to mitigate flood risk[8,9]. Conversely, agriculture and aquaculture continue to dominate the landscapes of the GBM and Mekong deltas, although urban centres, such as Dhaka in Bangladesh, are rapidly developing[10,11]. In these deltas, engineered structures are being increasingly used for disaster risk management, although traditional measures such as earthen embankments and bamboo riverbank protection structures continue to prevail. The Chao Phraya Delta in Thailand is roughly in the middle of this development spectrum. All five deltas are developing and implementing long-term solutions to mitigate and adapt to climate change; therefore, it is important to share experience on building flood resilience to support decision and policy making.

In this Review, we illustrate the common challenges and transferable lessons for adapting to natural hazards across the 5AMDs. First, we investigate the distinct managerial practices to determine the efficacy of different approaches to climate change adaptation. Next, we identify transferable solutions, focusing on the national and municipal levels of current flood resilience and climate policies. Finally, we recommend practices to improve coastal climate resilience in these globally important mega-deltas. This Review provides an initial exchange of knowledge and practices for delta management at a regional scale. The lessons and recommendations made are not only relevant to the 5AMDs but also to other deltas facing similar challenges.

[H1] Current hazards in the 5AMDs

The 5AMDs all drain different parts of the Himalayas and are located within the South and Southeast Asian Monsoonal Climate Zone. Consequently, the 5AMDs have highly seasonal climates, with up to 90% of the annual rainfall occurring within the monsoon months of June to September[12]. Monsoon, fluvial and coastal processes, combined with increasingly complex interactions between humans and nature, impact the sustainability of the deltas. This section describes the dominant processes in each delta, and how they influence deltaic vulnerability to different coastal hazards.

[H2] Ganges-Brahmaputra-Meghna Delta

Located in Bangladesh and West Bengal, India, the GBM is the world's largest delta system, draining 75% of the Himalayan mountain range[10,13]. Up to 90% of water and 95% of sediment discharge to the delta occurs during the monsoonal months of June to September[14,15]. This flood pulse is fundamental to the existence of the GBM delta, but can also damage the livelihoods of the 140–190 million inhabitants[6,10,16-19] (Bangladesh Bureau of Statistics), owing to the low-lying and flat topography of the delta. Additionally, the GBM delta is situated in a global hotspot of cyclonic activity. On average, there is at least one cyclone on the GBM delta coastline each year, and a severe cyclone strikes every three years[20]. The storm surges accompanying these cyclones can have heights of 1.5–10 m(ref.[20]), causing widespread destruction. Around 53% of global cyclone-induced deaths occur in Bangladesh[21], despite only 1% of tropical cyclones making landfall there.

Human interventions have been used in the GBM delta since the 1960s to protect the coastline and boost agricultural production and economic growth. For instance, the Farakka barrage was constructed in India in 1975 to improve the navigability of the Ganges mainstem by diverting around 60% of the dry-season flow towards the Kolkata Port [10,22,23]. Additionally, between the 1960s and 1980s 139 polders (embankments enclosing low-lying floodplain land) were constructed across the whole coastal region of Bangladesh[24] to protect the land from coastal flooding and saline intrusion. The polders separated rivers from their floodplains, leading to reduced deposition of sediment on the embanked floodplain land and increased siltation of channel beds [16,22,25,26]. Consequently, subsidence has been observed on the floodplains behind the embankments and water levels in the channels have risen from siltation[27,28]. Although the polders have reduced flooding caused by storm surges in Bangladesh's coastal areas, they have increased the exposure to pluvial flooding, extending the duration of inundation owing to drainage congestion[27,29]. Thus, the vulnerability of the GBM delta is influenced by complex interactions between natural processes and anthropogenic activities at the landscape scale.

[H2] Yangtze Delta

The Yangtze River delta (YRD)—located in an alluvial fan on the east coast of China[30]—is affected by monsoonal flooding and typhoons. Over 70% of the annual precipitation (1,700 mm) in the YRD falls between May and October[31], owing to the subtropical monsoon climate system of the West Pacific[32,33]. The YRD has a high population density (approximately 656 people km^{-2}) and one of the most developed regional economies in China[34,35], including the mega-city of Shanghai, and parts of Jiangsu and Zhejiang Provinces. Therefore, monsoonal flooding can cause catastrophic damages. For example, monsoon-induced flooding in 1991 and 1999 caused economic losses of approximately 11 billion and 14.1 billion Yuan (RMB) (US$1.52 billion and US$1.94 billion), respectively[36]. The YRD is also prone to typhoons and an average of five typhoons affected the delta each year between 1950 and 2010 (ref.[36]). Combined with the intensive summer monsoon rainfall, these typhoons and their associated storm surges can cause severe fluvial, pluvial and coastal floods, leading to widespread socio-economic losses, such as during Typhoon Fitow (2013) and Typhoon In-Fa (2021)[37], where economic losses of 2.03 billion RMB and 0.19 billion RMB (US$280 million and US$26 million) were observed.

Given its economic importance and urbanised nature, the YRD has relied on engineered infrastructures for protection from coastal flooding for centuries. Seawalls line the coast, and levees are used to maintain navigational waterways[38,39]. In addition, land reclamation has increased the land area of the YRD by approximately 1,500 km^2 since 1950 and lengthened the shoreline by nearly 26%

(ref. [38,40,41]). Despite these infrastructures, coastal flood risk is increasing owing to the increase in population and assets in exposed areas and changes in the sediment discharge of the Yangtze River, which has decreased by 75% since 1950, leading to increased subsidence and relative sea-level rise[38,42,43].

[H2] Mekong Delta

The Mekong Delta is the world's third largest delta and is considered one of the most important agricultural (predominantly rice) and aqua-cultural areas in Southeast Asia[44]. Situated in Vietnam and Cambodia, the Mekong Delta is home to approximately 30 million people, of which nearly 20 million are in Vietnam[45,46]. Most of this population (~80%) is rural with highly resource-dependent livelihoods (for example, fish-farming and paddy rice farming); therefore, irrigation canals and water distribution channels have been constructed across the delta. This irrigation and drainage system has increased agricultural production in the delta, which now produces 7–10% of all internationally-traded rice[47].

The main challenges in the Mekong Delta are associated with reduced sediment influx and the unsustainable mining of sand in the riverbeds of deltaic channels. Over 50% of the annual sediment supply from the Mekong River basin is already trapped behind upstream dams[47,48], and approximately 54 Mt of sand – or one-third of the pre-dam sediment influx – has been removed from river channels for construction, land reclamation and land infilling[47]. In addition, coastal sediment influx from tropical cyclones, which deliver approximately 32% of the suspended sediment load, is also decreasing because cyclone tracks have moved further north[47,49]. This sediment starvation has resulted in widespread subsidence, saline intrusion, and coastal erosion of over 50% of the delta's shoreline[48,50].

Since the 1980s, management measures in the Mekong Delta have used hard infrastructure and irrigation structures to protect the delta from flooding and boost socio-economic outputs, as in the GBM and Yangtze deltas[51-53]. However, since the early 2000s, more flexible irrigation systems (for example, seasonally adjusting to saline or brackish environments) have been used to accommodate diverse agricultural and aquacultural production activities, aiming to better align with the underlying dynamics of the Mekong Delta[52,54,55].

[H2] Pearl Delta

The Pearl River Delta (PRD) consists of 42,800 km^2 of low-lying floodplain lands with a population of approximately 50 million[56] and is located in the Guangdong Province of southern China[57]. Owing to the monsoonal climate zone, the PRD receives about 80% of its annual rainfall (2,600–2,800 mm) from April to September[9]. Typhoons are also common in the PRD and occur between June and September, often coinciding with the monsoon[58]. Monsoonal rains bring nutrient-rich sediment to the PRD, creating an alluvial sediment layer that consists of organic-rich mollisol soils[59,60].

The PRD is primarily threatened by increasing subsidence and saline intrusion. Subsidence rates are increasing across the PRD[61] owing to the natural compaction of organic-rich soils over time[60] combined with the over-extraction of groundwater resources[62]. For example, land elevation is now over 1 m below mean sea level in the west of the PRD[56]. Such subsidence is particularly concerning in the face of rising sea levels. According to the Hong Kong Observatory, sea levels in Victoria Harbour have risen by approximately 2.6 $mm\ yr^{-1}$ (during 1954–2009), resulting in a 14 cm relative elevation change.

Therefore, the PRD, particularly the western area, is increasingly exposed to coastal flooding [3], and the saltwater front is gradually shifting further inland. This saline intrusion during the dry season is the most pressing hazard in the PRD, because it threatens the freshwater supplies for 15 million people across Zhuhai, Zhongshan, and Macao[63].

Dykes have been used for millennia to protect the PRD from flooding, thereby accelerating agricultural and economic development[64]. Dykes and reclamation projects have also created new land for further development, but have simultaneously led to the over-exploitation of shoals and beaches, threatening coastal environments by increasing the risk of flooding and causing drainage congestion[9,64]. The dense population of the PRD has led to the continued use of engineering approaches to manage flood risk, such as building breakwaters, installing flood gates, channelising river networks, and constructing embankments. These infrastructures have not been regularly updated despite increasing flood magnitudes owing to the lack of available space and the growth of cities and other human developments [9,65].

[H2] Chao Phraya Delta

The Chao Phraya Delta is home to Bangkok—one of the major financial and logistical hubs of Southeast Asia. Bangkok has expanded rapidly from 50 km^2 and a population of 1.3 million in the 1950s to more than 550 km^2 and 10.5 million people in the 2020s (ref.[66-68]). This growth has been accompanied by large extractions of groundwater resources, leading to land subsidence rates of up to 120 $mm\ yr^{-1}$ during the 1980s–1990s (ref.[69]). However, strict controls on groundwater extraction and the dredging of sediments from river channels have now reduced subsidence to approximately 20 $mm\ yr^{-1}$ (ref.[70]). Despite this reduction, subsidence in the Chao Phraya delta remains a concern, owing to the flat and low-lying topography with average elevations of 1 m above mean sea level[71].

The flood-prone areas of the Chao Phraya Delta rely heavily on engineering practices, such as channelisation and embankments to protect infrastructure networks such as roads and railways, as well as properties and assets (households and commercial infrastructures, as well as livestock and agricultural fields). Despite these protective infrastructures, flooding still causes substantial damage. For example, during the 2011 Chao Phraya flood, an extreme rainfall event resulted in flood depths reaching 10.5 m (500-year return period level) and 18.6% of the basin area, including Bangkok, was inundated[72]. This inundation lasted 198 days in parts of Thailand, making it the longest rainfall-induced flood on record[73]. Therefore, the key challenges for the Chao Phraya Delta are the growing population and economic base at risk of flooding (pluvial and coastal), which is exacerbated by the decreasing elevation and the growing threat of relative sea-level rise.

[H1] Future challenges

Climate change and anthropogenic activities threaten the 5AMDs. Monsoonal climates are expected to become more extreme and less predictable, leading to increased fluvial and pluvial flooding. Meanwhile, relative sea-level rise and more frequent cyclones will exacerbate coastal and tidal flood risks[6,56,74]. Combined with increasing anthropogenic pressures associated with socio-economic growth, these increased flood hazards, are expected to impact water resources, food security and human and environmental well-being. The impact of future human activities and increases in flood risk and saline intrusion are discussed here.

[H2] Flood risk

Climate change is expected to impact monsoonal and cyclonic patterns across the 5AMDs. The timing and duration of monsoonal rains is already becoming less predictable and more intense and these trends are likely to continue and worsen in the future [75-77]. Rainfall in the South and Southeast Asian monsoonal region is expected to increase by 0.29–1.5 mm day^{-1}, exacerbating fluvial and pluvial flood risks[75-77]. Cyclonic activity is also anticipated to become more frequent and intense[78]. By the end of the 21st century, the annual mean frequency of tropical cyclones on the east coast of China is anticipated to increase by 16% compared to the present day[79].

Increases in monsoonal and cyclonic activity could lead to substantial economic losses across the 5AMDs. For example, a 1 in 100-year storm surge in the PRD could inundate 80% of the delta[80], leading to economic losses exceeding 232 billion RMB (excluding inflation), equivalent to US$32 billion. Similarly, in Bangladesh, a conservative scenario of a 10% intensification of wind speeds and a 27 cm sea level rise by 2050 could increase the area exposed to more than 3 m of inundation from cyclonic storm surges by 69%, and increase the area exposed to greater than 1 m storm surge depths by 14% (ref.[20]). Investments in protection to minimise this damage, such as cyclone shelters, cyclone-resistant housing, strengthening of polders, foreshore afforestation, and improved early warning and evacuation systems could cost over US$50 million a year[20].

Future sea level rise could also increase flood risks. Across the 5AMDs, sea-levels are rising, with rates ranging from 0.24–2.5 mm yr^{-1} in the PRD delta to as high as 3–7.8 mm yr^{-1} in the GBM delta (**Figure 1**). The Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR)5[81], and the latest AR6 report, project that sea levels will rise by 0.6–1.2 m by the end of the century (or higher under some scenarios and climate actions in the 2015 Paris Agreement)[82]. Given the flat topographies of the 5AMDs, such increases could cause vast coastal flood inundation. For example, a moderate sea-level rise of 40 cm by the end of the century in the Mekong Delta could result in 25% of the delta falling below sea level. If a 1 m sea-level rise occurred, land that is currently home to over 12 million people (approximately 70% of the total population of the Mekong delta in Vietnam) would be below sea level[83].

These different flood risks frequently coincide to generate compound flood events. For instance, coastal or tidal flooding in urban centres within deltas, such as the Pearl or the Yangtze deltas, can submerge urban drainage outlets and reduce the ability to drain surface floodwaters from rain, rivers, and/or the sea. During Typhoon Utor in the PRD in July 2001, for instance, surge heights reached 4 m above mean sea level, which coincided with an intensive rainstorm of 166 mm day^{-1}, inundating the major Central Business District of Hong Kong [57,84]. Such compound events are likely to become more frequent and intense in the future. Similarly, in the GBM delta compound events – particularly between coastal storm surge flooding and fluvial flooding – are likely to become more common[85], threatening the productivity of agricultural and aquacultural lands in Bangladesh and West Bengal[86]. It has been estimated that the impacts of sea-level rise and changes in upstream river flows could increase the inundated areas by approximately 231% relative to current inundation events[87]. Such increases are particularly concerning because management approaches typically only focus on protecting populations and assets to a particular event level (for example, a 1 in 30-year coastal flood level) and ignore the possible threats from compound flood events. Therefore, compound events could put even the most advanced management strategies under stress.

[H2] Human activities

There is growing evidence that human activities, such as dam construction and upstream diversions, are already increasing the flood exposure of deltas, and will continue to do so in the immediate term (over the next decades)[11,88]. For example, there are plans to build 414 dams in the GBM river catchment (285 in Nepal, 108 in India, 12 in Bhutan, 8 in China and 1 in Bangladesh), as well as a large-scale diversion of the Brahmaputra river to the Yellow River in China and interlink 44 rivers in India (the National River Linking Project)[10]. India's National River Linking Project alone would divert 9–75% of the water and sediment load of the Ganges and Brahmaputra rivers before they enter Bangladesh[10,88-91]. Additionally, the planned dams are expected to reduce sediment supplied to the GBM delta by up to 88% by the end of the century [88]. Similarly, dams on the Mekong mainstem in China and Laos, as well as on important tributaries in Laos, Cambodia, Thailand and Vietnam have already reduced water and sediment delivery to the Mekong delta by over 50%[92] . The Chinese Manwan and Dachaoshan dams alone have reduced the sediment budget in the Mekong delta by 38% (ref.[93]). There are also plans to build over 220 additional dams within the Mekong catchment[94], which, if constructed, could reduce sediment delivery to 4% of pre-dam levels[95].

Despite increasing climatic hazards, sediment starvation, and risk of inundation, the population within all of the 5AMDs is likely to continue to increase. By the end of the century, it is expected that 500 million people will be living in the 5AMDs, compared to just over 400 million in 2024, (World Population Review)[96-98]. The greatest relative population increase is expected to occur in the PRD where the population is expected to double to 120 million by 2050 (ref.[99,100]). This increase in population will add pressure to coastal systems, and will likely lead to the formation of risk hotspots, particularly in urban centres [74]. In the PRD, municipal governments are already reclaiming land to meet the huge demands for urban coastal development, which will impact the water and sediment processes of the delta.

Growing urban centres are also expected to cause localised subsidence, impacting relative rates of sea-level rise (**Figure 1**). Natural background subsidence processes (such as sediment compaction and seasonal flood-induced subsidence[102]) are likely to continue, irrespective of human activities[103]. Meanwhile, groundwater and resource (over)extraction accelerate sediment compaction and therefore subsidence [104]. For example, continued groundwater extraction in the Mekong delta, could cause 43–68% of the delta to sink below sea level by the end of the century, depending on the rate of extraction [105]. Even if all extraction ceased, approximately 15% of the delta would still be below sea level by the end of the century, owing to decades of past over extraction[105]. Moreover, the reduction in sediment delivery to the Mekong Delta, due to the construction of upstream dams and diversions, combined with sand mining in Cambodia and Vietnam[47], will impact the delta's overall stability and potential to prograde (grow horizontally) or aggrade (grow vertically) in the future. These changes will also further exacerbate channel incision, coastal erosion and salinity intrusion[106]. Similar trends are expected across all 5AMDs.

[H2] Saline intrusion

Saline intrusion is already undermining agricultural livelihoods in the Mekong and GBM deltas. In the Mekong Delta, extensive sand mining and the reduced influx of sediment and freshwater through the Mekong River system has caused the saltwater front to move further inland during the dry season.

This intrusion increases the salinity of cultivated land, forcing farmers to further exploit groundwater resources. Increased groundwater extraction can accelerate land subsidence and exacerbate salinisation[107], trapping deltas in vicious cycles. In the coastal zone of the Mekong Delta and the south-west of the GBM Delta, many farmers have converted to brackish and saline fish and shrimp farming in response to widespread saline intrusion in the dry season. However, these aquaculture livelihoods bring saline water further inland, which decreases the quality of surrounding soil and groundwater, increases water scarcity, and exacerbates social inequality[108,109].

In all 5AMDs, saline intrusion has, and is likely to continue to have, negative impacts on drinking water resources. Saline water intrudes into natural and piped drainage networks, contaminating freshwater and groundwater sources and reducing the quality of drinking water, particularly in the dry season[110]. Most cities in the PRD, for example, face severe water shortages, with annual per capita water resources often reaching the threshold for severe water scarcity (500 m^3 per capita)[111]. Additionally, the demand for public and domestic water will inevitably rise because the population of the PRD is expected to double by 2050, placing further pressure on the water supply system, especially during the dry season[112].

[H1] Resilience

The 5AMDs are each responding differently to the threats from climate change and anthropogenic activities and thus have different trajectories towards resilience. The IPCC's AR6 defines resilience as "the capacity of social, economic and ecological systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure […] while also maintaining the capacity for adaptation, learning and transformation"[113]. Therefore, to build resilience, the capacity to absorb (cope with hazards), adapt (incrementally adjust to hazards) and transform (change livelihood or location) must be strengthened, through improved preparation, response, recovery, and preventative measures[114,115] (United Nations disaster risk reduction terminology). This section discusses three levels of delta management: the strategic policy level, the delta-wide implementation level, and the community level, and how these strategies can be integrated through top-down and bottom-up approaches to improve delta resilience (**Figure 2**).

[H2] Strategic delta planning

Strategic plans and policies are needed to address the multitude of challenges facing the 5AMDs. Delta plans can identify key hotspots of risk, provide guidelines and practices to decide where interventions are most urgently required, and lay out a landscape-wide vision for a sustainable future for deltas. All 5AMDs have some form of strategic policy or plan (**Box 1**). The Mekong Delta has the Mekong Delta Plan (MDP) and the subsequent Mekong Delta Regional Masterplan (MDRMP) and the Bangladesh portion of the GBM, which makes up 80% of the delta, has the Bangladesh Delta Plan 2100 (BDP2100). There is currently no strategic delta plan for West Bengal, India. The other three deltas have national, municipal or provincial development plans, but they lack delta-wide plans that systematically zone land and prioritise investments within one unified hydrological system. Municipal or provincial plans often omit interactions with other deltaic provinces or municipalities, which can lead to isolated measues generating unintended regional consequences.

The BDP2100 assesses the threats to the GBM Delta now and in the future and identifies strategic measures for six key hotspot areas. Similarly, the MDRMP outlines future delta conditions, identifying regions that will become more saline in the future where transitions to brackish livelihoods are recommended to align with these inevitable changes. Both delta-wide plans extend beyond sub-national jurisdictions and identify a way forward for the whole deltaic system.

[H2] Technological advances

Rapid technological advances across the 5AMDs have improved the forecasting and monitoring of disasters to support disaster preparation. The largest technological advances have occurred in heavily urbanised deltas. For instance, in the PRD, residents are provided with a free-of-charge and open system that combines the latest meteorological information (including satellite images, radar data, and real-time rainfall data for the last 72, 48, 24 and 6 hours), storm surge and wave data, temperature changes, and natural hazard warnings (floods, droughts, typhoons or storms), enabling the public to be better prepared for such hazards[9]. Similar services are used in the major cities of the YRD [116,117]. This real-time information is typically provided by internet webpages, mobile apps, radio and TV channels, and includes hazard announcements in low-lying flood-prone areas based on predicted tides or rainstorm warnings. Social media platforms have increasingly been used to inform the public about flood hotspots and erosion locations[9], as well as to communicate the locations of shelters and access to medical and emergency services. This timely and accessible information has reduced the impacts of disasters by ensuring the safety of the population.

[H2] Nature-based solutions

Nature-Based solutions (NbS)—referred to as green and blue infrastructure solutions in urban settings—leverage nature to protect people, optimise grey infrastructure, and safeguard a stable and biodiverse future. These solutions use and align with natural processes to provide flexibility, adaptability, and various co-benefits that are typically absent from grey infrastructure. Combining grey, green, and blue infrastructure in interconnected networks of natural and designed landscape components, including water bodies and green and open spaces[118], can help to achieve resilient delta systems.

Although engineered coastal defences, such as dykes, embankments, breakwaters, and sea walls are effective, they are extremely expensive to construct and maintain. Thus, such defences are generally more viable in high-income countries with the financial resources to maintain and update them[119]. For example, the Central National Government and the Guangdong Provincial Government have invested more than 820 billion RMB (US$115 billion) to increase flood and climate resilience in the major districts of the PRD[120]. In contrast, the effectiveness of the protection provided by 139 polders (approximately 6,000 km of embankments) constructed in the coastal region of Bangladesh in the GBM delta has declined owing to a lack of financial capacity and human resources to maintain this infrastructure. In some parts of the GBM, these poorly maintained polders have now exacerbated the risk of flooding[10,27].

Integrating grey and nature-based solutions would help to address such problems. For instance, an embankment maintenance system that includes foreshore afforestation, aquaculture and fisheries, and diversified agricultural development has been proposed in Bangladesh[27]. Natural habitats in deltas can store water, enhance biodiversity, protect against hazards, and provide substantial ecosystem services for local populations. Freshwater swamps, mangroves along coastlines and river mouths, and wetlands all help to mitigate disaster risks. Examples of such ecosystems include the Chongming Island wetland in Shanghai (Yangtze)[121], the Futian and Mai Po wetlands in Shenzhen Bay (Pearl)[122], the Bay of Bangkok Wetland (Chao Phraya)[67], the Mekong Delta Wetland[123], and the Sundarban mangrove forest (GBM)[124]. As well as being invaluable ecological habitats, foreshore mangroves and sea grass reduce wave energy and coastal erosion rates[125] by providing a buffer for tidal and storm surges (such as typhoons from the South China Sea or cyclones in the Bay of Bengal)[1]. For example, around 76,000 ha of mangrove forests and salt marshes at the mouth of the Dong Nai River in the Mekong Delta reduce wave energy by 20% for every 100 m of mangroves and provide substantial flood protection[126].

Delta plans and climate action plans across the 5AMDs include the protection and restoration of natural ecosystems. For example, the Regional Masterplan issued by the Vietnamese Government recognises the importance of mangrove and wetland protection[127] in addressing coastal erosion and subsidence and reducing disaster risk[128]. Similarly, the Chinese Government recognises the importance of integrated grey-green-blue infrastructure to reduce urban flood risk. For example, Sponge Cities have been implemented in urban centres across China, including in cities of the PRD and YRD (**Box 2**). Despite its limitations, such as only focusing on urban stormwater management[129] and only being able to absorb up to a 1-in-30-year flood event, the Sponge City Programme (SCP) has reduced urban stormwater flooding across selected flood-prone cities in China by absorbing up to 150–180 mm day^{-1} of rainfall[130-132]. As well as providing a multitude of co-benefits, these integrated approaches require less initial investment and maintenance expenditure than traditional grey infrastructure, but they take more time and space to be effective.

[H2] Community-level initiatives

Rural communities, particularly those with highly resource-dependent livelihoods, are often disproportionately impacted by natural hazards due to the sensitivity of their livelihoods to fluctuations in the environment [10,133,134]. Thus, community-scale resilience initiatives, such as community support groups or small-scale flood management measures using sand bags or raising homesteads, are fundamental to building resilience at the local level. Although there are many examples of effective community activities in urban deltaic settings [9], such as the neighbourhood emergency service group in Tai O town in Hong Kong (PRD), this section focuses on community initiatives in rural communities of the Bangladeshi part of the GBM Delta, because these settings have been identified as some of the most vulnerable [144].

Communities in Bangladesh have led many adaptation projects to reduce the damage caused by natural hazards. Prior to the large-scale polderisation of coastal Bangladesh in the 1960s–80s, communities built small-scale temporary earthen embankments to prevent saline intrusion. These temporary embankments were washed away during the flood season to enable the deposition and vertical aggradation of nutrient-rich sediments from monsoonal freshwater onto the floodplains, maintaining the elevation of the floodplains above sea level[27,135]. Since the deterioration of the polder infrastructure, communities have begun to deliberately breach embankments to relieve waterlogging inside the polders[135]. This method is now recognised by the Government of Bangladesh as an adaptive approach, known as 'Tidal River Management' and is also applied to encourage sediment deposition on subsiding embanked lands[27,136]. However, the large-scale application of this approach remains problematic because it involves deliberately flooding large areas, potentially displacing or otherwise impacting vast populations.

Community-level practices to diversify livelihoods have also been implemented to increase resilience. For example, coastal communities in the GBM delta have adopted practices of sharecropping and shared ownership of livestock, which require less upfront investment and encourage households to diversify their livelihoods, increasing their resilience should one livelihood be affected by a climatic shock[137]. Similar strategies are also observed in the Mekong Delta, where rice cropping for part of the year is combined with farming of fruit trees, fish, shrimp, and/or vegetables for other parts of the year[138].

[H2] Integrated activities across governance levels

To achieve long-term delta resilience, activities across the three key governance levels must be coordinated at every stage of the resilience-building process (that is, preparation, response, recovery, and prevention) (**Figure 3**). For example, at the preparation stage, improvements in data collection and monitoring systems by central governments will strengthen early warning systems and real-time communication, which can inform local authorities where short-term (for example, evacuation sites) and longer-term emergency measures (for example, shelters) are required. The locations of these sites must then be communicated to affected communities. These preparation activities must also occur in the reverse order whereby community experiences of evacuation can inform where emergency infrastructure is required, which can provide improved and updated information on vulnerability hotspots. Similarly, in the prevention stage, government adaptation plans must direct and prioritise adaptive and flexible risk reduction measures, with input from community leadership and initiatives. These activities should also occur in reverse order with communities suggesting measures that are most urgently needed, which should be incorporated into delta-wide adaptation plans.

[H1] Transferable lessons

Although the 5AMDs experience similar climatic hazards (**Figure 1**)[6,84,139], each delta faces unique challenges owing to differences in the stages of development, socio-political settings, physiologies, and the levels of anthropogenic influence. These differences provide an opportunity to share past experiences and existing knowledge on managing similar climate hazards, enabling the 5AMDs, as well as other deltas, to improve their long-term climate resilience.

[H2] Management challenges

During the Anthropocene, coastal management approaches have generally involved low-risk tolerance in areas of high economic value[140], resulting in hotspots of protective adaptation, which encourages further development in these exposed areas. For example, historical land reclamation, port development, and river mouth and inland river channelisation in the Pearl, Yangtze and Chao Phraya deltas have led to rapid population growth and socio-economic development[141]. Once engineered solutions have been introduced to control dynamic delta systems, it is extremely difficult to reverse or veer away from engineered approaches. Such development trajectories often generate lock-in effects for future delta management, which can be very expensive to maintain because the infrastructures must be continuously updated to adapt to changing conditions in the delta [18]. The YRD and the PRD are both on highly engineered trajectories and it is estimated that up to US$44 billion (312.9 billion RMB) is needed to maintain water infrastructures in the YRD between 2023 and 2027 (ref.[142]).

The effective protection provided by engineered solutions can also create a false sense of security, encouraging more people (and assets) to move to these high-risk areas. The resulting increase in population and development in these areas can subsequently lead to an increase in the level of defences required— this cycle is known as the levee effect[143]. The levee effect is a key challenge in the Yangtze, Pearl and the Chao Phraya deltas, where populations are rapidly growing, leading to a large increase in the number of exposed people and assets that require ever-increasing levels of protection.

Contrastingly, rural resource-dependent populations are typically less protected than urban communities, and past approaches to reduce risk can sometimes have unintended negative consequences[144-147]. Repeated damages to livelihoods can have chronic economic, social, and psychological costs and can further restrict recovery and regrowth capacity [144,148]. Moreover, previous management measures, such as the polderisation of the coastal zone in Bangladesh, have exacerbated the multi-hazard risks experienced by some rural communities, due to increased drainage congestion, waterlogging, and greater risk of pluvial flooding and storm surge overtopping[134,29]. The negative impacts of past measures must therefore be understood to guide future management.

In the GBM and Mekong deltas, the implementation of the ambitious strategic delta plans involves huge upfront costs and requires continuous annual investments. Thus, large-scale infrastructure to reduce disaster risk often relies on financial support from foreign donors. However, such construction investments can fail to provide sufficient support for the long-term operation and maintenance of infrastructures, leaving deltaic nations, such as Bangladesh and Vietnam, with outdated and poorly maintained infrastructure and high levels of debt.

Unlike the Chao Phraya, YRD and PRD, which are national-scale river systems, the GBM and Mekong deltas are part of vast transboundary river systems and are therefore affected by decisions made outside of their national borders. The Ganges and Brahmaputra rivers flow through China, Bhutan, Nepal, India, and Bangladesh, and the Mekong River flows from China to Myanmar, Laos, Thailand, Cambodia and Vietnam. The planned construction of around 414 dams, diversions, and reservoirs in upstream nations in the GBM catchment and 220 dams in the Mekong catchment [88,94], will test any delta management approach, no matter how resilient or sustainable.

[H2] Lessons from urbanised deltas

[H3] NbS for urban resilience

The use of NbS in urbanised deltas has improved flood resilience by alleviating flooding induced by urban stormwater[149] and reducing urban water demand and freshwater scarcity through improved retention, purification, water storage and water-reuse (for example, for irrigation)[150]. For instance, sponge cities in Shanghai and Ningbo (YRD), as well as in Guangzhou, Shenzhen, and Zhuhai (PRD) (Box 2), have managed to absorb stormwater runoff for up to a 1-in-30 year flood event. The implementation of the SCP required substantial economic investment from the Chinese National

Government (1.5–1.8 billion RMB (US$200–250 million) between 2015 and 2018 for the first set of Sponge Cities)[130], and efficient and coordinated action by the central, provincial, and city governments.

Despite the urban environments of the Chao Phraya, Mekong, and GBM deltas having different institutional and socio-economic contexts to those of the YRD and PRD, lessons can be learnt from the SCP. Owing to their monsoonal climates, urban environments in the Chao Phraya (for example, Bangkok), Mekong (for example, Can Tho, Rach Gia, or Long Xuyen), and GBM (for example, Kolkata, Khulna, or Dhaka) Deltas are prone to seasonal flooding, resulting in excess urban runoff. Therefore, the SCP approach of making space for seasonal flood water and reusing it for other purposes, such as irrigation, could be used to manage localised urban flooding.

For instance, in Can Tho—the fastest-growing city in the Mekong Delta—the socio-political setting is ready to incorporate lessons from the SCP to address flood risks. Between 2010 and 2012, the local authorities of Can Tho issued the first phase of an 'action plan to respond to climate change during the period 2015–2030', which aims to protect the city and establish an environmentally-friendly economy[151,152]. This plan specifies that NbS will be needed to limit flood impacts and sustain livelihoods. Subsequent surveys with local residents revealed that out of a list of suggested projects to address flood challenges, local people would choose to prioritise NbS that minimise flood impacts and enhance local communities' engagement, such as building sponge parks along the Rach Ba Bo and Rach Tu Ho Canals, as well as converting the existing An Khanh Park and the Rach Ngong Canal park into sponge parks[152]. These suggested projects would apply similar concepts to the SCP in China to alleviate flood risk. Thus, by building on the Sponge City concept, learning from the experiences in China, and incorporating the critical lessons, the sponge city projects proposed for Can Tho could be even more effective in flood alleviation.

[H3] **Forecasting and monitoring systems**

To effectively reduce the impacts of disasters on lives and property, accurate flood and climate forecasts are needed alongside real-time information on hazard conditions. Additionally, appropriate emergency support must be provided, such as medical support and emergency services, as well as information about rescue services, the locations of shelters, food and water supplies, and road blockages. In China, CCTV cameras and mobile devices are used alongside early warning systems (based on meteorological and hydrological forecasts) to provide real-time hazard updates for roads and railways with high spatial and temporal resolution [153]. Such data allow emergency and support systems to provide rapid rescue services, because they can be informed of the safest and quickest route to provide aid[154]. The use of these practices in the YRD and PRD have reduced casualties, injuries and economic losses from hazard events, such as Typhoon In-Fa in 2021 (ref.[37]), Typhoon Hato in 2017, and Typhoon Mangkhut in 2018 (ref.[155]).

However, such technological services require substantial financial support, coordination between institutions, and time to develop the necessary analytical capabilities to process the data collected. In countries and districts with limited financial resources, costs can be reduced by initially applying systems at smaller scales (for example, district or province)[156]. However, it is important to ensure that communities in rural areas with reduced digital connectivity are not disadvantaged and left behind.

[H3] Recovery practices and flood insurance

Following Typhoon Fitow (2013) and In-Fa (2021)[37,157] the YRD and PRD demonstrated strong recovery practices, which other deltas could learn from. For example, after Typhoon Fitow, the Ningbo Municipal Government established a local flood insurance programme that aimed to provide affordable flood insurance for coastal communities. Communities that joined this insurance plan experienced an overall reduction in the financial risk associated with flooding[37]. Additionally, an improved online documentation process (using mobile apps) used during Typhoon In-Fa allowed effected communities to access financial compensation to rebuild and recover through insurance claims within as little as 20 minutes[37]. The government is also continuously enhancing other recovery processes, such as restoring public infrastructure (for example, rapidly repairing road damage, pumping floodwater away from road surfaces and restoring public transport)[153] and ensuring adequate food and clean water, electricity, and sanitation services are available as quickly as possible after a disaster, by improving co-ordination and communication between stakeholders and communities [158,159]. Such transparent and accessible insurance schemes and the efficient recovery practices evident in the Pearl and Yangtze deltas can act as a guide for the future development of hazard response schemes in the Chao Phraya, Mekong, and GBM deltas.

[H2] Lessons from resource-dependent deltas

[H3] Delta-wide plans

Lessons from the plans outlined for the Mekong Delta (MDP and the subsequent MDRMP) and the GBM Delta (BDP2100) can be applied in other deltas to develop long-term plans that effectively integrate climate adaptation and hazard mitigation. The goals of both the MDP (and MDRMP) and the BDP2100 are achieved through collaborative governance, capacity building (for example, developing technical skills for forecasting systems or infrastructure operation and maintenance), public engagement, local and indigenous knowledge transfer and by raising public (local communities) and private (stakeholders) awareness of the plans[128,161]. Such delta-wide policies guide urban and rural settings towards sustainable socio-economic growth and have supported the planning and development of infrastructure that particularly benefits poor communities, such as the effective provision of cyclone shelters in poor, remote and rural parts of the GBM delta[162,163].

The Yangtze, Pearl, and Chao Phraya deltas currently lack such high-level strategic management plans at the delta scale. The upstream catchments of these three deltas are within their national borders; therefore, the Chinese and Thai governments could consider establishing catchment-wide management plans, extending beyond just the deltas. Such plans could avoid one of the key drawbacks of the Mekong plans and the BDP2100, which is that the delta plans are largely disconnected from upstream interventions.

[H3] Aligning with delta dynamics

Livelihoods in the GBM and Mekong deltas rely heavily on the ecosystem services provided by the deltas. For instance, in the GBM delta, the Sundarbans—the world's largest mangrove forest— supports ecosystem-based livelihoods, provides socio-economic benefits, and protects coastal populations from cyclonic storm surges, coastal erosion, tidal flooding and sea-level rise[124,164]. Therefore, the Government of Bangladesh is discussing where further mangrove afforestation could occur (including a 'green belt' along the coastline)[124,164,165]. Additionally, the Government of India classes the Sundarbans as a national park, a tiger reserve, and a biosphere reserve in West Bengal, strengthening conservation regulations. Planting mangroves at smaller scales along coastlines in the Mekong Delta has been demonstrated to be an effective and cheaper alternative to alleviate erosion[46,125]; coastal protection through wetland and mangrove conservation for the Mekong and GBM deltas, only costs 8–11% of the investments required for conventional engineering practices (such as seawalls, breakwaters and sea dykes), and even less in terms of maintenance costs[166].

Moreover, delta management approaches for the GBM and Mekong deltas aim to become increasingly aligned with the underlying biophysical changes in the systems. For example, the Governments of India and Bangladesh are exploring ways to use natural sediment processes to create more land and accelerate vertical land aggradation (for example, through Tidal River Management). This availability of sediment is no longer evident in the Mekong Delta, thus the Government of Vietnam has acknowledged that some subsidence and saline intrusion is likely to be inevitable. Thus, the MDRMP outlines ecological zones (freshwater, saline, and brackish or intermittent) for 2030 and 2050 and encourages provinces to begin facilitating transitions in livelihood activities to align with these changing environmental conditions[167]. For example, planned development of water and agricultural infrastructure should help communities to transition to farming coconuts, fish, or shrimp in the brackish areas, as these livelihood activities are more resilient to brackish water environments than rice or other fruit and vegetable crops.

Despite the increasing impacts of climate change and changing environmental conditions, the Regional Plans of the Chinese Government up to 2050(ref.[168]) do not prioritise aligning with changing conditions as an approach to building resilience. Therefore, the YRD and PRD could learn from the GBM and Mekong deltas to improve their responses to regional challenges (such as subsidence and erosion) by utilising and aligning with the underlying dynamics of the deltas.

[H3] ***Empowering local communities***

Local populations in developed and highly engineered areas often expect risk management to be dealt with by local authorities or central governments. Although communities must feel supported by good governance, some risk ownership enables local populations to decide how to manage their livelihoods. For example, the GBM and Mekong deltas are changing dramatically from being regions dominated by rice farming into areas with diverse livelihoods (fruit, vegetable, shrimp, and fish, amongst others), as well as urban centres. Good governance and infrastructure investments are needed to support such transitions, but the changes are primarily led by individuals. Such empowerment can enhance perceptions of hazards, and consequently the level of preparedness[144,169].

[H2] Integrating lessons across the 5AMDs

Many lessons can be integrated to achieve increased resilience across the 5AMDs (**Figure 4**). The deltas in China and Thailand could aim to develop strategic delta (or catchment) plans, increase the alignment of future development and livelihoods with the underlying biophysical dynamics of the delta systems, and empower local populations to respond to risks. Conversely, the GBM and Mekong deltas could aim to develop improved information databases, forecasting technologies and immediate response strategies, as well as learning from NbS applications in urban centres, such as from the SCP.

To improve long-term resilience across all deltas, top-down approaches (such as the development of technologies, policies, and large-scale infrastructure) must be merged with bottom-up approaches (such as empowering community initiatives). Additionally, data and critical information should be shared not only within deltas and their catchments but also across different deltas. All 5AMDS are rapidly developing and implementing long-term solutions to mitigate and adapt to climate change; therefore, it is critical that information and lessons are shared now to support the use of targeted and effective solutions.

[H1] Summary and future perspectives

Despite facing similar climatic hazards, the challenges of the 5AMDs are unique because each delta is at a different stage of development. In the highly developed urbanised deltas of China (YRD and PRD) and Thailand (Chao Phraya Delta), the key challenges include high levels of subsidence, the substantial exposure of financial and logistical hubs to natural hazards, and the high costs associated with engineered management approaches. Conversely, the resilience of the GBM and Mekong deltas is primarily threatened by upstream interventions, increasing groundwater and resource extraction within the deltas, poorly maintained infrastructure, and inefficient communication systems. Delta management in each delta could be refined by exploring the different resilience approaches implemented across the 5AMDs, and the lessons that can be learnt from them.

Several areas of further research are required to refine future deltaic management approaches. First, various trajectories for future development must be examined for the Yangtze, Pearl and Chao Phraya deltas that account for the effects of climate change and growing anthropogenic pressures. Such trajectories should be used to ensure future development is aligned with expected changes in socio-environmental conditions and can withstand multi-hazard events. Second, the suitability of NbS, such as mangrove afforestation, for supporting rural areas in adapting to climatic hazards must be explored, as well as the suitability of blue-green infrastructure (such as Sponge Cities) for urban areas. Third, it is important to assess how information from satellite imagery and mobile phone technologies can be combined with data from in-situ monitoring stations to improve early warning systems. Last, widespread and frequent community-based research must be undertaken to better understand local disaster risk reduction strategies and identify what communities actually need to build greater resilience.

This Review facilitates the exchange of knowledge on delta management practices at a regional scale, with the hope of strengthening collaboration between the 5AMDs. The formation of an Asian Delta Resilience Alliance, where knowledge, data, and information could be shared across the 5AMDs, as well as other Asian deltas, could encourage cross-collaboration and stimulate innovation to develop sustainable delta management approaches that are also relevant for deltas worldwide.

Related links

Bangladesh Bureau of Statistics. http://www.bbs.gov.bd/
Bangladesh Delta Plan(BDP)2100 https://www.bdp2100kp.gov.bd/
Hong Kong Observatory https://www.hko.gov.hk/en/wservice/tsheet/pms/stormsurgedb.htm
Nature-Based Solutions https://www.iucn.org/our-work/nature-based-solutions
Mekong Delta Regional Masterplan https://www.royalhaskoningdhv.com/en/projects/driving-resilience-for-vietnams-mekong-delta
World Population Review https://worldpopulationreview.com

Mekong Delta Plan https://www.mekongdeltaplan.com/
United Nations disaster risk reduction terminology https://www.undrr.org/drr-glossary/terminology
Predicted tides http://www.weather.gov.hk/tide/estation_select.htm
Rainstorm warnings http://www.hko.gov.hk/wservice/warning/rainstor.htm

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Figure legends

Figure 1 Coastal hazards across the five Asian mega-deltas. The boundaries (solid blue lines)[18], catchment boundaries (dashed blue lines), rivers (white lines), population density in 2020(ref.[170]) and the key coastal hazards associated with each delta. The population count is calculated based on the population density within each delta, and the stated area is the area within each delta boundary. Inset graphs illustrate the minimum and maximum annual observed sea-level rise and land subsidence rates reported in each delta[171],[17],[172],[173],[174],[175]. GBM, Ganges-Brahamputra-Meghna. The five Asian mega-deltas are densely populated hotspots of coastal hazards, with relative sea-level rise becoming a ever-growing threat.

Figure 2: Disaster risk management approaches. Examples of regional and national policies, delta-wide management approaches, and community-level actions for managing disaster risk. The arrows indicate strategies for top-down (regional and national policies and plans informing delta management to support community initiatives) and bottom-up (community-level activities contributing to the wide-scale implementation of policies and plans) integration of these measures. Deltaic risk management is an iterative and dynamic process spanning the high-level policy landscape, on-the-ground implementation across the delta, and community-level initiatives.

Figure 3: Building resilience in the five Asian mega-deltas. Example approaches that can be applied by central governments, local authorities and communities at each stage of the resilience-building process: preparation, response, recovery, and prevention. To achieve resilience, coordinated actions from across the three governance levels will be needed.

Figure 4: Transferable lessons across the five Asian mega-deltas. The resilience measures (bold text) that each delta can apply in the different stages of resilience-building (preparation, response, recovery, and prevention) and which deltas they can learn from (in brackets). For example, the GBM delta can improve its hazard

preparation by learning from the forecasting methods applied in the Yangtze and Pearl river deltas. These transferable lessons can guide future resilience building measures in each of the five Asian mega-deltas (and beyond), by highlighting similar approaches applied in other deltas that can be learnt from. NbS, Nature-based solutions.

Box 1: Climate adaptation plans

The five Asian mega-deltas each have different national or regional scale plans for climate adaptation, as outlined here.

[bH1] Ganges-Brahmaputra-Meghna Delta

The Bangladesh Delta Plan (BDP) 2100 aims to use adaptive long-term measures to reduce climate change risks and deliver a vision for sustainable water, ecology, and land use. The BPD2100 emphasises that achieving food security and long-term agricultural production will require the use of more efficient irrigation systems and less water-intensive cropping strategies. The plan aims to reduce urban migration by about 60%, by encouraging farmers to stay in rural areas by supporting agricultural and aquacultural livelihoods via 65 infrastructure projects. Support for such development from public and private institutions (such as, the World Bank or South Asia Water Initiative) is estimated to reach US$ 38 billion[176]. This plan only covers the Bangladeshi part of the delta, which makes up 80% of the deltaic land area.

[bH1] Yangtze River Delta

Although not at the delta-wide scale, the city-wide Climate Adaptation plan established by the Shanghai Municipality focuses on carbon reduction[116]. The plan aims to achieve 18% forest coverage in Shanghai by 2030, which will have a carbon storage capacity of 3 million tonnes, acting as a carbon sink to 600,000 tonnes of carbon dioxide per year[177]. The plan will also support the formation of ecological networks, comprising wetlands, forest belts, nature reserves, waterfront green corridors, large parks and country parks. Under this plan, 71,300 ha of degraded wetland and farmland within the Yangtze River Delta have already been restored. These activities align with the National Government's goal of achieving carbon neutrality by 2050 (ref.[178]).

[bH1] Mekong Delta

The Vietnamese Government established the Mekong Delta Plan (MDP) in 2011 and the legislation was finalised in 2013. The plan develops a long-term strategic vision towards a safe, prosperous and sustainable delta, including policy recommendations and solutions. The MDP aims to increase green space coverage and improve flood prevention and water resilience by calling for specific flood protection measures (for example, dykes) and water supply systems (waterways and irrigation systems). Such developments must also support current plans for socio-economic development and the future goals of the Mekong Delta towards 2100(ref.[179]). The Mekong Delta Regional Masterplan was subsequently approved in April 2022 and provides spatially-explicit guidelines and trajectories for future development in line with expected changes in environmental and socio-economic conditions until 2050.

[bH1] Pearl River Delta

The climate adaptation strategy of the Guangdong Provincial Government primarily focuses on protecting and restoring forests, marine and wetland ecosystems (especially coral reefs, seagrass beds and mangroves), to protect coasts from natural hazards[179]. In December 2020, the Shenzhen Municipal Government implemented the Shenzhen Natural Disaster Prevention and Control Capacity Enhancement Action Plan[155], to promote practices to reduce disaster risk. Similarly, Hong Kong's Climate Action Plan 2050 outlines strategies to combat climate change[180].

[bH1] Chao Phraya Delta

The Thai National Government[181] has initiated a Climate Change Master Plan for the Chao Phraya Delta, which presents a long-term vision for achieving sustainable low-carbon growth and climate resilience by 2050. This plan promotes carbon reduction via reduced emissions, as well as carbon capture and storage at the national level. Additionally, the National Disaster Prevention and Mitigation Plan targets improvements in disaster risk reduction; multi-sectoral cooperation for emergency management; recovery, rehabilitation, and reconstruction measures; and international cooperation for disaster risk management[182].

Box 2: Sponge Cities

Sponge cities (shown in the figure) were introduced by The Chinese National Government in 2014 (ref.)[183] and are designed to withstand a 1-in-30-year flood event. Rather than rapidly discharging stormwater runoff, the Sponge City approach encourages the reuse of stormwater. The goal is that by 2030 sponge cities will collect, store, purify and utilise 70% of rainwater across 80% of their urban areas[131,184,185] using combined grey, green and blue infrastructure. This target will be achieved by controlling urban peak runoff, and temporarily storing, recycling and purifying stormwater; developing more flood-resilient drainage systems and increasing discharge protection standards to offset peak discharge and reduce excess stormwater; and enhancing ecosystem services that improve drainage by integrating natural water-bodies and adding blue and green spaces [130,186].

The Chinese National Government has been funding the development of sponge cities in 30 pilot cities. The Sponge City Programme has been implemented in two cities in the Pearl River Delta (Zhuhai and Shenzhen) and in two cities in the Yangtze River Delta (Ningbo and Shanghai)[130]. In addition, Guangzhou – in the Pearl River Delta – has voluntarily joined the sponge city programme.

Image courtesy of Sitong Liu.

Toc blurb

Climate change and human activities are increasing exposure of deltaic communities to natural hazards. This Review discusses lessons that Asian mega-deltas can learn from one another to develop long-term resilience strategies.