TOPICAL REVIEW

Developed river deltas: are they sustainable?

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Keywords: river deltas, delta sustainability, delta vulnerability, delta resilience, delta ecology, delta urbanization, delta flooding

Abstract

Background. Coastal river deltas provide multiple ecosystem services. Many deltas serve as major centers of agriculture, industry and commerce. The annual economic benefits derived from major deltas are often a substantial fraction of a country’s GDP. Yet, many deltas are losing land due to erosion, subsidence and subsequent flooding. Such vulnerabilities are often increased due to local land and water management decisions, relative sea-level rise, and increases in climate extremes. Aim of this review. Considerable literature exists addressing the formation of deltas and the effects of increasing urbanization, industrialization and crop and fish production, increases in relative sea level rise, and decreasing sediment deposition. This leads to the question: are the economic, environmental, ecological and social benefits derived from developed river deltas sustainable? This review focuses on this question. Methods/Design. Over 180 published documents were identified and reviewed using various search engines and key words. These key words included river deltas; delta sustainability, vulnerability, resilience, coasts, ecology, hazards, erosion, water management, urbanization, reclamation, agriculture, governance, pollution, geomorphology, economic development, socio-economic changes, and delta wetlands; relative sea level change; sediment trapping; sand mining; salinity intrusion; coastal restoration; estuarine engineering; shoreline evolution; estuarine processes; and the names of specific river basin deltas. Review Results/Synthesis and Discussion. Deltas provide humans important resources and ecosystem services leading to their intensive development. The impacts of this development, together with sea-level rise, threatens the sustainability of many river deltas. Various management and governance measures are available to help sustain deltas. Controls on land use, improved farming and transport technology, wetland habitat protection, and improved governance are some that might help sustain the economic and ecological services provided by deltas. However, increased population growth and the impacts of climate change will put increased pressure on deltas and the benefits derived from them.

1. Introduction

Rivers and the water, sediments and other substances in them result from both natural and anthropologic processes that take place on their watersheds. The greater the flow velocity in rivers the greater will be the quantity of sediment and organic substances contained in them. When the river water reaches a lake or ocean or even just flat ground, its velocity, and thus carrying capacity, decreases. This causes a deposition of some of the sediment and other substances the water is carrying, often creating a delta shaped landscape. Deltas act as filters, sinks, and reactors for waterborne materials. They can become rich in land, water, and ecological resources. This review focuses on the sustainability of such river deltas that are developed and providing economic as well as ecosystem services to those living in the deltas and their surrounding regions.

Coastal river deltas form diverse habitats. They can be the source of sand and gravel needed for making concrete. Some contain substantial reserves of oil and gas. Deltas may provide a coastal defense buffer against storms. They can be a source of water for meeting domestic and industrial demands. They can provide recreation and tourism opportunities and be a source of plant-based medicines. Deltas can be attractive sites for agricultural and fish production. Many deltas have become major
food baskets for their regions. Deltas often become centers of industry and trade. This in turn typically leads to the development of major urban and transportation centers (Ericson et al. 2006, Bianchi and Allison 2009, Overeem and Syvitski 2009, Wang et al. 2011b, Campell 2012, Kuenzer and Renaud 2012, Anthony et al. 2014, Anthony et al. 2015, Pennington et al. 2016, Sebesvari et al. 2016, Briney 2019, Lauria et al. 2018).

Given all these attributes, it is not surprising that deltas have attracted socio-economic development involving agriculture, urbanization and industrialization. Today, coastal river deltas are among the Earth’s more densely populated areas (Syvitski et al. 2009, Fan et al. 2017, Tejedor et al. 2017, Angamuthu et al. 2018, Hagenlocher et al. 2018, Nicholls et al. 2018, Rahman et al. 2018).

Some studies estimate the annual value of ecosystem services derived from major deltas worldwide to be in the trillions of US dollars. The value derived from delta wetlands are largely due to their physical features and the biodiversity of their ecosystems. Figure 1 identifies deltas that are considered developed. Our literature search focused on the sustainability of deltas such as these (Giosan et al. 2014).

Major river deltas are spread out, mostly along the coasts, from the arctic to the tropics (see figure 1). China’s largest urban development networks occur on deltas and adjacent lowlands. The Mississippi Delta supports the largest fishery in the US and is the largest migratory bird flyway site in North America. The capital of Indonesia, Jakarta, was built on the Ciliwung delta. Agriculturally dominated deltas include the Ayeyarwady, Ganges–Brahmaputra–Meghna, and Mekong deltas. The agriculture, industry, service and tourism, sectors in the Nile delta are major contributors to Egypt’s economy. Agriculture activities remain a major part of the urbanizing California Bay-Delta. The Rufiji Delta contains the largest area of estuarine mangroves in East Africa. The wetlands of the Lena delta are the summer homes to extensive wildlife. The Okavango inland delta is the largest breeding site for birds and other wildlife in Southern Africa. The Danube delta remains one of the best preserved deltas in Europe. These are only few examples illustrating the importance of deltas. Many of the world’s deltas are facing sustainability issues, as will be discussed in the remainder of this review (Breber 1993,
Panin 1999, Ochieng 2015, Yang et al 2002, Doody and Hamerlynk 2003, Yaney-Aranicina and Day 2004, Burg 2007, Elsharkawy et al 2009, Overeem and Syvitski 2009, Van der Most et al 2009, Abd El-Kawy et al 2011, Kuenzer and Renaud 2012, Bucx et al 2014, Small et al 2018).

2. Sustainability

2.1. Definition
There are many definitions of ‘sustainability’ but all contain the notion of time and the maintenance if not improvement of the services or benefits derived from, in this case, developed river deltas. The physical, economic, ecologic, environmental, and social state of any river delta will surely change over time, whether due to changes in climate, in technology, or what humans do that impacts the state of their deltas. Given such changes, a measure of a delta’s sustainability is the extent that the benefits derived from the use and management of that delta can be maintained or increased over time.

The benefits derived from a river delta can be economic, environmental, ecologic, and social. To assess delta sustainability, it is helpful to focus on the changes in the state of each of these four types of benefits derived from a delta. The state of each of these components will no doubt vary over time. Hence it is often convenient to define sustainability in terms of the resilience and vulnerability of specific state indicator values.

Both resilience and vulnerability terms recognize that changes in benefits occur. Resilience relates to the notion of how quickly a decrease in benefits will recover to the level previously achieved. Vulnerability refers to the extent or duration of a decrease in benefits. Of course this can vary over time. There can be tradeoffs among measures of resilience and vulnerability associated with the state of any component of sustainability or among the economic, environmental or social components themselves. If the resilience of a state indicator is increasing over time, and its vulnerability is decreasing, the delta can be considered sustainable with respect to that indicator of sustainability (Sebesvari et al 2016).

2.2. The challenge
With much of their lands just above or below sea level, many developed river deltas along coasts are at risk due to land subsidence and flooding. The likelihood of land subsidence is often increased by human activity, such as upstream sediment trapping in reservoirs, sand mining, accelerated sediment compaction, and control of river channels. With rising sea levels, their vulnerability to flooding will likely increase both in terms of extent and duration. Meeting the growing needs for water supply and sanitation, maintaining ecosystem integrity and the quality of the air, land, and water environments in deltas given the demographic growth and economic activities taking place on them, is a continuing challenge. Failure to meet this challenge in any delta will reduce the benefits over time derived from that delta. It will not be considered sustainable (Syvitski 2008, Foufoula-Georgiou et al 2013).

2.3. Sustainability components

2.3.1. Physical
Deltas respond to environmental change by shrinking and expanding over time and space. Both the runoff and sediment load delivered to the delta and then to the sea are dominant factors affecting the evolution of a delta. The complex channel networks in a delta influence how water, sediment, and nutrients are spread over its land surface. These channel networks affect the evolution, functionality, and resilience of deltas. Numerous publications are available describing the geomorphic processes that create deltas, and the different types and sizes of deltas that can form over time.

In recent decades, almost all river deltas have been impacted by human activities, and by the increased frequency and severity of extreme runoff events. As a result, delta vulnerability is increasing. Examples include deltas of the Ebro River, Mekong River, Mississippi River, Nile river, Pearl River, Yangtze River, and Yellow River. Recent research suggests that 85% of the river deltas around the world have shrunk during the first decade of this century due to sediment capture in the upstream reaches of their river basins (Mikhailova 2003, Walling 2006, 2008, Le et al 2007, Snedden et al 2007, El Banna and Frihy 2009, Syvitski et al 2009, Wang et al 2010, Zhang et al 2010, Yu et al 2011, Gupta et al 2012, Abdarabo and Hassen 2015, Fan et al 2018).

The processes that create and maintain many deltas have been threatened by a variety of stressors. These include groundwater pumping leading to subsidence, sea-level rise leading to increased flooding and erosion, river diversions and upstream dam development leading to reduced sediment and altered river flow regimes, mining sediment from river channels also leading to reduced sediment transport and increased erosion, the logging of coastal forests leading to more erosion, the drainage of wetlands and local exploitation leading to land degradation, erosion, and salt water intrusion. Understanding these interactions is becoming increasingly important to assess threats to and opportunities for long-term sustainable development (Kuenzer et al 2014, 2014b, Twilley et al 2016, Basset et al 2019).

2.3.2. Economic
The land and water resources and ecosystem services provided by deltas can attract economic development. Developed deltas often contain extensive industrial and commercial areas as well as agricultural land, all
contributing to the economy of the region. In addition, some deltas are sources of sorted sand and gravel, and oil and gas. Finally, the coasts and rivers near deltas often provide opportunities for inexpensive transport of the agriculture and industrial goods produced on deltas (Xu 2003, 2005, Miao et al. 2010, Wang et al. 2012, Kong et al. 2015).

The rapid and continuous expansion of agriculture, industry and residential areas on deltas, their associated wetlands, lakes and river systems are altered, often in ways that increase risks of flooding and erosion and environmental quality degradation. This in turn can reduce the economic growth taking place on a delta. Mitigation of these risks usually means increased taxes, insurance and infrastructure costs (Youpeng et al. 2010).

These development problems facing deltas have been called a multi-trillion-dollar issue that can impact public safety, trade, and regional wealth. Engineering structures may be able to reduce some of the risks of economic decline but only with continued sediment supply and deposition. ‘An adequate and reliable supply of sediment is a core determinant of long-term delta sustainability’ (Foufoula-Georgiou et al. 2011, Tessler et al. 2015).

Floods in developed deltas can lead to substantial decreases in a country’s economy. Han Meyer and Renske Peters (2016) estimate that populations vulnerable to flooding by storm surges will multiply tenfold or more over the 21st century, impacting over 100 million people each year. Because of increasing flood risk and flood hazards, migration to deltas and coastal areas can quickly turn into the reverse. Floods in New Orleans (in 2005) and east Japan (in 2011) resulted in out-migration, many of whom never returned (Marchand et al. 2012).

Urbanizing deltas can not only be adversely impacted by increased flooding due in part to sea level rise but also can contribute to causes of climate-driven sea level rise by being centers of oil and gas production. The world’s largest centers of oil and gas processing are situated in deltas. In these deltas much of the economy is based on trans-shipping, storage, processing, financing, accountancy and insurance associated with the oil and gas industries. Transitions to more renewable energy sources could reduce the role of deltas as hubs of fossil fuel-based economies to become centers of clean energy-based economies (Meyer and Peters 2016).

2.3.3. Environmental
The impact of industrialization and agricultural activities, and their accompanying transportation networks and urbanization, typically bring with them the excessive discharge pollutants into the air, land and water. This is not unique to deltas. The discharge of pollutants into the environment, whether solid, gaseous, or liquid, degrades the quality of the environment, including their ecosystems, that otherwise make deltas attractive places to live and work. Pollutants can be both an aesthetic and public health issue as well as lead to increased costs of using the delta’s land and water resources (Syvitski et al. 2005, 2009, Syvitski 2008, Anthony et al. 2014, Wolters and Kuenzer 2015).

2.3.4. Social
Developed deltas are excellent examples for studying the actions we all take to shape our physical, economic and social environments. Developed deltas tend to be densely populated. In some of these deltas urban development has led to the merging of multiple population centers forming mega-cities. Conversely the populations of some deltas are not being attracted to city centers, but rather living along the banks of rivers and in villages or rural settlements. These differences in population pressures are due in part to climatic, economic, and environmental factors (Bucx et al. 2014, Szabo et al. 2016).

Social and biophysical processes operating in developed deltas can impact the long-term sustainability of not only the delta but of the surrounding region as well. We still have much to learn about how the effects of physical and environmental changes occurring on deltas impact demographic and social processes. In some deltas the increased vulnerability has resulted in increased rates of out-migration, Others are experiencing in-migration. Human in-migration to coastal and delta areas has often increased social inequality. This is especially evident for people settling in areas that were not previously urbanized and often having the highest risks of being flooded. Polluted air and water and inadequate infrastructure, including housing construction, only adds to the economic and social risk exposure of the relatively poor (Marchand et al. 2012, Szabo et al. 2015c, Renaud et al. 2016, Brondizio et al. 2016a, Lauria et al. 2018).

What makes the problem of the urban poor in delta areas more challenging to address is the lack of risk-awareness, or if inhabitants are aware of this risk, they do not have the ability to do anything about it. Poor communities tend to face many social challenges and hazards. This includes political and police corruption and crime. Increasing the socio-economic resilience and thus the sustainability of many urbanizing deltas often involves tradeoffs among a multitude of different risks. To insure sustainability, overall risk management has to lead to a higher quality of life and health for all social groups, including those who are disadvantaged and living in the slums (Meyer and Peters 2016).

2.3.5. Ecological
Human activities upstream of deltas, such as the construction and operation of dams, and the mining of sand and gravel from upstream river channels, can impact water and sediment flow regimes so as to degrade delta ecosystems. Dams can trap sediment, release hungry water that erodes downstream
channels, and alter the natural variation of flow regimes. Upstream sand mining can also reduce the supply of sediment reaching the delta. Both can result in a decrease in the extent of the downstream delta. The consumptive use of water upstream can increase salinity levels downstream as less fresh water flows reduce the resistance of salt water inflows from the coast. Both upstream and on-site construction, diversions for irrigation or domestic water supplies, and land alteration are also capable of impacting the extent and productivity of delta ecosystems.

Deltaic wetlands and coastal ecosystems are facing increased risks of flooding caused in part by sea level rise and subsidence. Floods modify landscapes and ecological systems and adversely impact the socio-economic activities that depend on delta resources. Added to ecological impacts are those due to urban and industrial development, and associated pollution; and the reduced infiltration capacity of, and increased runoff from, residential (especially urban) and industrial lands. Other causes of ecological change include the effects of erosion, deforestation and degradation of natural wetland areas; higher use of recreational or protected areas leading to increased noise and light pollution; increased agriculture activities leading to increased use of fertilizer, pesticides, antibiotics, and thus increased water pollution and a loss in biodiversity (such as a shift from natural protective mangroves, reed beds, shoreline forest into aquaculture areas); and changes in water flows and sediment dynamics (Li et al 2004, Kuenzer 2007, Saito et al 2007, Overeem and Svytis 2009, Svytis et al 2007, 2009, Leinenkugel et al 2011, Kuenzer et al 2011a, Kuenzer and Renaud 2012, Marchand et al 2012, Anthony et al 2015, Fan et al 2017, Xie et al 2017, Lam et al 2018).

2.4. Threats to delta sustainability: some examples
Many deltas, including the Ebro, Mississippi, Nile, and Yangtze river deltas suffer from a lack of sediment due to upstream dams. In Pakistan, one-fifth of the Indus delta plain has been eroded since the river was first dammed in 1932. In China, the northern shore of the Yellow River delta has retreated several hundred meters each year for the past several years. Even the dams in the Amazon River basin have and are resulting in adverse ecological and environmental impacts.

The Eastern Scheldt estuary experienced overall rise and subsidence. Floods modify landscapes and ecological systems and adversely impact the socio-economic activities that depend on delta resources. The conversion of wetlands to agricultural, residential and commercial areas is causing subsidence in the California Bay-Delta. Wind erosion along with

The entire Mississippi River Delta is subsiding largely due to canalization for enhanced flood control and navigation. This has reduced wetland water and sediment flow. Reduced sediment supply is the main cause of the subsidence taking place in portions of the Mekong and Nile deltas.

Because of river damming and river sand mining, the rate of land accretion in the Pearl River delta has declined to 40% of what it was over the previous 145 years in response to less fluvial input. By 2100, land losses from rising sea levels alone could reach 5% for higher deltas such as the Ganges–Brahmaputra or the Krishna–Godavari, 30% for the Mekong, Nile and Yellow, and more than 80% for the lower Danube delta. By mid-century, the Godavari, Mississippi, Orinoco (Venezuela) and Sao Francisco (Brazil) deltas could experience greater than 10% land loss from flooding. Increased flooding due to subsidence will impact close to half a million people in the Ganges–Brahmaputra, Mekong, Mississippi, Nile and Yangtze deltas (Glenn et al 1996, Frihy 2003, Vericat and Batalla 2006, Ericson et al 2006, Blum and Roberts 2009, Svytis et al 2009, Giosan et al 2014, Tessler et al 2015, Tang et al 2016, Latrubesse et al 2017, Xing et al 2017, Yang 2018).

Other major river deltas that are being impacted by local sea level rise include the Rio Grande (USA/Mexico), Magdalena (Colombia), Parana (Argentina), Niger (Nigeria), Mahanadi (India), Brahmani (India), Ganges–Brahmaputra (India/Bangladesh), Irrawaddy (Myanmar), Chao Phraya (Thailand), Pearl (China), and Yangtze (China). Similar impacts are occurring in numerous smaller deltas in North America, Europe and Asia. Even better-preserved deltas such as the Danube, the most extensive wetland in the European Union and a global biodiversity treasure, will lose its network of channels, lakes, Marshes and dunes that is the habitat for thousands of plant and animal species, some of which are threatened (Stanley 1996, Sanchez-Arcilla et al 1998, Stanley and Randazzo 2001, Thomas et al 2002, Morton et al 2005, Chu et al 2006, Ericson et al 2006, Woodroffe et al 2006, Svytis and Saito 2007, Wang et al 2007, Blum and Roberts 2009, Svytis et al 2009, Yang et al 2005, 2011, Maan et al 2018, Anthony et al 2015, Wang et al 2015, Higgins 2016, Liu et al 2018, Luan et al 2016, 2018).

The Chao Phraya delta in Thailand is sinking each year because of groundwater use. The Po delta in Italy has subsided by over several meters during the twentieth century, mainly as a result of methane extraction. Much of the Po delta is already below sea level and kept dry by artificial banks, levees and pumps. But as Marshes falter, vegetation dies and halts soil formation (Giosan et al 2014).

In the Ciliwung delta subsidence is threatening the north of Jakarta, is caused in part by groundwater extraction. The conversion of wetlands to agricultural, residential and commercial areas is causing subsidence in the California Bay-Delta. Wind erosion along with
ground water pumping has caused over 9 m of subsidence over the last 150 years of development. Levees protecting the Sacramento–San Joaquin delta are vulnerable to earthquakes. Local geologists estimate there is a 60% chance of an earthquake before 2032 that would cause multiple failures, and flood thousands of farms and homes in the Bay Area. The Ayeyarwady and Parana deltas are witnessing higher rates of subsidence than replenishment, and thus, together with sea-level rise, increasing risks of flooding (Buxx et al. 2014, Higgins 2016).

In many urbanizing deltas the combination of intense dredging, land subsidence and sea level rise has resulted in salinization and reduced freshwater supplies. This is especially applicable in deltas in arid regions, such as the Nile, Sacramento–San Joaquin, Tana, and Zambezi deltas. river Water use has increased considerably in these deltas, making sea-water intrusion and salinity of soils and groundwater more likely (M¨ulliman et al 1989, Yanez–Arancibia and Day 2004, Yang et al 2005, Ericson et al 2006, Syvitski and Saito 2007, Overeem and Syvitski 2009, Syvitski et al 2009, V¨or¨osmarty et al 2009, M¨ulliman and Farnsworth 2011, Dai et al 2014, Dai et al 2016, Meyer and Peters 2016, Wei et al 2017).

The Marsh and mangrove destruction in deltas located in the tropical-cyclone belt has reduced flood protection and damaged communities and economies. Examples include the Ganges–Brahmaputra in India and Bangladesh, and the Irrawaddy Delta of Myanmar (Giosan et al 2014, Szabo et al 2015b, Wu et al 2018).

Wetland conservation can be a shield against hurricane impacts where hurricanes occur, such as in the Mississippi River Delta. But development on the Mississippi Delta has reduced wetland areas. About one third of the delta is currently protected against inundation and part of this area is dry land. Some 4000 km$^2$ of coastal wetland that existed in the 1930s has become open water. This land loss has resulted in part from (a) flood control levees along the Mississippi river, (b) the reduced suspended sediment flowing into the delta from upstream sources (c) oil and gas extraction in the delta, (d) altered wetland hydrology due to canal infrastructure, (e) salinity intrusion, (f) shoreline wave erosion, (g) sea level rise, and (h) soil compaction in the delta (Buxx et al 2014).

In the Ayeyarwady and Ganges–Brahmaputra–Meghna deltas riverbank erosion is a serious problem. In the Tana and Zambezi deltas more extreme river flows caused by upstream dams causes local damage and even some loss of life for those living on the floodplains. Reduced natural flow and sediment regimes resulting from upstream dam operation tempts people to move closer to the fertile delta river banks. Yet when high precipitation events occur, these delta communities are caught by surprise by the erosion and river course changes that occur (Brown and Nicholls 2015).

Other deltas continually experiencing shoreline erosion include the Chao Phraya, Ebro, Huanghe, Mekong, Nile, Rhone, Song Hong, and Volga deltas. The Chao Phraya River flowing through Bangkok, Thailand, has experienced substantial delta loss. Parts have subsided to more than a meter below sea level (Day et al 1995, Stanley and Warne, 1998, Anthony and Blivi 1999, Saito et al 2007, Saito 2008).

In the Krishna delta widespread seawater intrusion is transforming the fresh groundwater to brackish/saline water. With more dams across the Krishna and the Godavari rivers under construction and/or being contemplated, together with increasing groundwater and hydrocarbon extraction within the delta region, the health of the ecosystem and the wellbeing of the millions of people inhabiting these deltas are at risk (Saxena et al 2004).

Similar delta conditions have imperiled thousands of flood victims in the Irrawaddy Delta of Myanmar and the Ganges–Brahmaputra Delta of India and Bangladesh. In the Incomati and Ganges–Brahmaputra–Meghna deltas floods are a constant threat. Almost half of the area of the Cilwuang Delta is below sea level rendering some 6 million inhabitants, especially in the northern part of Jakarta, vulnerable to flooding. Most of the California Bay-Delta is below or just above sea level and thus susceptible to wide spread flooding. Such an event would adversely impact the water supply system serving over 20 million people in southern California (Buxx et al 2014).

Besides subsidence and sea level rise, more severe floods, longer duration droughts and higher temperatures. The frequency, duration, and strength of cyclones causing floods seem to be increasing, especially in the Asian deltas (e.g. Ayeyarwady and Ganges–Brahmaputra–Meghna), and in the Mississippi River delta. Climate change seems to be causing higher peak flows and lower low flows in the Rhone–Meuse and Danube deltas. The extreme variability of the climate of the California Bay-Delta is already impacting its hydrology as is the increasing average and extreme temperatures experienced in the Yangtze delta.

Turner et al (2018) and Syvitski et al (2009) reported that the intensity of human interventions across the world’s developed deltas is now so high that the functioning and evolution of many deltas can no longer be considered natural, placing a number of deltas in greater danger of erosion and inundation. Of particular concern are the challenges associated with the sustainability of the mega-deltas. The world’s largest deltas are massive geomorphological features which merit attention through their sheer scale. For example, the Ganges–Brahmaputra–Meghna delta is home to more than 100 million people. Others are home to the largest cities in the world, such as Cairo, Dhaka, Kolkata, and Shanghai, Other deltas can be critically important for food production (e.g. the Mekong Delta) or for gas and oil (e.g. the Mississippi River and Yellow River deltas). With the environmental stresses
on deltas expected to increase, both as a result of ongoing climate change as well as increasing population, urbanization and socio-economic change, the human impacts on the world’s deltas are likely to increase through the twenty-first century. This raises the question of how humans may better manage delta landscapes and ecosystems in the future.

Delta urbanization brings with it pollution that can adversely impact regional ecosystems and public health. Urbanization of the Ciliwung floodplain has outpaced its ability to manage its solid waste. Disposal of solid wastes in drains has reduced their discharge capacity and caused flooding. Most fish consumed in Hong Kong are farmed fish and are highly susceptible to various chemicals discharged from industrial sites nearby. Emissions from coal-power plants in the Pearl River Delta are major sources of Hg in the air, water and soil. In addition, this delta has become the world’s main manufacturer for electrical/electric equipment, textiles, footwear, furniture, etc, emitting a wide range of toxic chemicals into the environment. Chemical food contaminants are currently one of the key global food safety concerns (Bucx et al 2014, Caniani et al 2016, Lu et al 2016, Wong 2017).

The Yangtze River delta region is currently facing the need to improve its air, water and land quality to address public health issues and to maintain its high level of social development and urbanization. Every year, over 40% of China’s total sewage and industrial wastewaters are discharged into the Yangtze River (Driel et al 2015, Zhang et al 2017).

Eutrophication of surface waters in the Mississippi and Zambezi River deltas is a major issue. Inadequately treated sewage and fertilizer and other nutrient runoff from agricultural and urban areas are the causes of eutrophication. One of the most publicized water quality problems in the world is the growing hypoxic zone in the Gulf of Mexico adjacent to the Mississippi delta.

The Pearl River Delta area is possibly the largest water pollution hot spot in East Asia. Air pollution emissions from intensive energy consumption has been a major issue in the Pearl River Delta region exceeding more than three times the limit set in the new National Ambient Air Quality Standards of China. If this level could be reduced below the World Health Organization guidelines, approximately 40,000 related premature deaths would be avoided in the region every year (Xie et al 2011, Jin et al 2016, Yang et al 2018, Hou et al 2019, Zhao et al 2019).

Another pollutant hotspot is the densely populated Niger River Delta. It has been heavily polluted by oil and hydrocarbons, stemming from petroleum operations since the late 1950s. Groundwaters and soils have been heavily polluted, which has destroyed many aquatic and agricultural communities. These spills have affected local population health in a number of ways. Lindén and Pilsson (2013) estimated that the widespread pollution could lead to a 60% increase in household food insecurity and a 24% increase in the prevalence of childhood malnutrition. This is in addition to the fact that the crude oil is likely hemotoxic and can cause infertility and cancer (Ana Sridhar and Bamgboye 2009, Howard and Olulu 2012).

These threats to the existing developed deltas can have regional, national, and international repercussions, including compromising existing trade networks, settlements, and ecosystems (Woodroffe et al 2006, Syvitski and Saito 2007, Nicholls et al 2008, Nicholls et al 2011, Seabold et al 2016).

3. Managing delta development

Given the threats developed deltas are experiencing, the question is can they be better managed so that their benefits to society can be sustained over time.

3.1 Land and water management options

Many of the delta threats involving sea level rise, sea water intrusion, the adverse impacts from urbanization and industrialization, including pollution, are interrelated. This calls for inclusive, integrated approaches towards delta development, management and governance.

Delta management faces an important challenge, as do we all wherever we are: accommodating more people and more demands for its resources and services over time. Upgrading infrastructure is one approach but it can lead to a further reduction of the natural carrying capacity of the delta. It is highly unlikely that increased development can be accommodated solely through more and bigger infrastructure. For example, the current plan for the restoration of the Mississippi delta calls for actions lasting for the next 50 years. If successful, it will just prevent future land loss, not recover the considerable amount of wetlands already gone (Bucx et al 2014, Chamberlain et al 2018).

Delta governance needs to be focused on land use planning and on the restoration and use of natural systems and processes. It needs to involve stakeholders who will be impacted. Sustainable solutions to delta problems can only be found when land use, infrastructure and the natural environment together with the desires of informed stakeholders are taken into account in an integrated manner (Marchand et al 2012).

An integrated land and water management approach is predicated on: (a) accepting that interactions between the environment (atmosphere, water, land, biota) and human activities (social, cultural, economic) are interdependent, (b) realizing that humans and climate-driven events are major driving forces behind most processes causing changes in deltas, (c) recognizing the importance of the quality of the environmental and its impact on human activities and
health, and (d) implementing a long-term perspective that is adaptive, anticipatory, preventative, and sustainable (Yanez-Arancibia and Day 2004).

At the coast, hard barriers such as levees, dikes and locks may be reasonable options to prevent erosion, flooding or sea water intrusion. But such projects are expensive. Where retreat is an option, reshaping the coast’s sandy beaches, barriers and mudflats may allow the overall delta landscape to adapt to higher sea levels. Urbanized deltas will create the most acute pressures for infrastructure solutions. But in cities such as Shanghai, Bangkok and Dhaka, infrastructure and buildings will have to adapt to recurrent floods and consider evacuation plans.

The feasible options available for protection will depend largely on the particular delta and the funding available. Decisions regarding which lands to preserve and which to abandon are unavoidable. For example, Pakistan cannot revive the Indus delta without jeopardizing its irrigation system, one of the largest in the world. For rivers such as the Danube, Indus, or Mekong that flow through multiple countries, negotiations on sediment rights, like those on water allocations, can be complex.

But given climate change and economic pressures, restoration schemes and accompanying data collection, modelling and real-time monitoring, need to be implemented sooner rather than later if sustainable development is to be cost-effectively achieved (Giosan et al 2014).

Technological alternatives available to delta land use managers include flow control structures such as dykes, dams, sluice gates, levees, canals, and other protective works, wastewater treatment facilities, water-saving technology, fresh water storage structures, desalinization plants, elevating settlements, implementing sustainable ‘green city’ options, and disaster preparedness measures including early warning systems and building evacuation shelters and designating evacuation routes and procedures.

In many deltas technological as well as institutional measures are being applied to land and water management. Water is being managed to increase rice production in the Mekong delta and to reduce land subsidence and subsequent flooding in the Ciliwung, Ganges–Brahmaputra–Meghna, and Mississippi river deltas. In the Ayeyawady delta large polders are protected by embankments, storage tanks and drainage canals to enable paddy cultivation and prevent salt water intrusion. People are being paid for implementing various environmental protection measures in the Yangtze delta. In the Incomati delta a strategy exists for developing a science and technology hub to reduce poverty. Research is aimed at stimulating innovative public-private partnerships in the Nile and Rhine-Meuse deltas. Low scale technological developments in villages of the Ayeyawady, Parana, Tana and Zambezi deltas have focused on roads, bridges, information and communication facilities around the irrigation infrastructure.

Drainage networks originally designed for irrigation and other agricultural purposes are increasingly being subjected to urban drainage as well. This poses new challenges to land and water managers (Bucx et al 2014).

River and sea transport has historically been a primary engine of the economic development of river deltas. The Mississippi, Rhine-Meuse, and Yangtze river deltas are among those having well-developed transport infrastructure that serves a major harbor and city. In the central US, the Mississippi River serves as a major shipping corridor, transporting goods, both upstream and downstream.

Ports and shipping channels have been a major feature serving the economic activities in many deltas. As economic activities in deltas increase, so do the needs of their transportation infrastructures. In the Yangtze Delta the expanding city of Shanghai constantly places a demand on its infrastructure capacity. The capacities of the roads and railways in the deltas of the Ciliwung and Ganges-Brahmaputra-Meghna deltas and to a lesser extent of the Mekong and Nile river deltas currently limit the rates of their economic development. The capacity of roads in Jakarta is insufficient to meet the growth of traffic, causing severe traffic delays. Where investments in highways have been made, such as in the Parana delta, they can lead to increased urban sprawl. In the Ayeyarwady delta the benefits that could be derived from steps taken to improve existing and develop new ports, are limited by the need to also improve the supporting transportation, communication, and energy infrastructure capacity (Bucx et al 2014).

In addition to transportation infrastructure, inadequate water supply and sanitation infrastructure can also be an issue, especially in developing country deltas. A lack of safe water supply and sanitation systems becomes a public health problem that can impact the benefits derived from the delta system. For example, inadequate piped water supply infrastructure in Jakarta is causing increased groundwater use for basic water needs. This in turn is leading to increased rates of land subsidence and risks of flooding.

The lack of adequate water supply and sanitation infrastructure in the Parana delta impacts over half of its population. The sewage system network serves only about 20% of its population. Those living outside the main villages in the Zambezi delta suffer from inadequate water supply and sanitation services. Similar conditions exist in the Ayeyarwady delta, along with arsenic contamination and salt water intrusion. Inadequate water supply and sanitation infrastructure is exposing those who must drink from the Tana River in the Tana River Delta to water-borne diseases. Inadequate infrastructure also prevents a large percentage of those living in the Zambezi delta access to safe drinking water.
Meeting and managing the demand for potable water is an increasing issue in many highly urbanized deltas. The conversion of forests to agriculture crop-land and urban developments in the Ciliwung delta has resulted in more severe water shortages during dry seasons. Fresh water supplies are also increasingly stressed in the Yangtze delta in part due to Shanghai’s increasing water demand. Increasing water demands and limited water supplies in the California Bay-Delta is increasing the risks of fresh water shortages and severe droughts. Low river flows in the Incomati, Ganges–Brahmaputra–Meghna and Mekong deltas makes them vulnerable to salinity intrusion. Water shortages during the occasional dry years in the Rhine-Meuse delta adversely affect agriculture, energy (cooling water) and shipping.

3.2. Working with nature—ecosystem approach
Within the delta, management strategies can take advantage of natural processes. Multiple channels can be dug to spread water and sediments across the delta plain and enhance Marshes or wetlands, fill storage ponds and extend delta lobes. Deliberately breaching levees during floods or redirecting a river to fill basins can enhance natural backwater effects and promote wetland formation.

In the Danube delta, dredging of new fishing channels off the main river has increased sediment deposition as well as fish populations., The control of river-sediment supply for rice agriculture on the Ebro delta has increased mud retention on the delta. In some places delta lands are rising faster now than the sea level rise and the rate of subsidence.

Ecological alternatives can include protection belts consisting of coastal forests (mangroves, melaleuca); creation and designation of nature areas and national parks, natural wetlands, planting of salt-tolerant/drought-resistant/deep-rooting species, avoidance of practices leading to land subsidence, and minimizing wind speed and evaporation (Pitt et al 2001).

3.3. Stakeholder involvement
Involvement of stakeholders and citizens helps generate societal support for management or policy decisions. Obtaining public and political support for any proposed action or project is a precondition for successful and sustainable delta management. For example, a bottom-up approach to decision making in California involves workshops and public meetings and consensus building before infrastructural investments are made. Increasing interaction between engineers and citizens in the Mississippi River delta citizens has occurred since the 2005 hurricanes. Environmental NGOs in the Danube Delta Biosphere Reserve area are facilitating communication between the public, the stakeholders, and the agencies managing or impacting the delta’s development. Civic groups along with research institutions are promoting environmental protection in the Parana Delta (Bucx et al 2014).

Public education is a major component of successful stakeholder involvement, and no less so in delta management. Educational topics can include climate change related subjects comprising geography, ecology, and basic natural sciences, interactions of population and environment, strengthening awareness for the value of delta ecosystems, fostering information sharing, and low-energy/low-carbon resource use. The exchange of information among multiple urbanizing deltas can contribute to discussions of best practices regarding design, land and water use planning and management, engineering and governance.

Managers of deltas attempting to deal with floods, repair damaged or degraded ecosystems and control use of land and water will need the continued participation of informed local stakeholders and citizens, well-trained professionals and academics in the science disciplines, planning, design and in engineering. Scientific knowledge of a delta’s physical, biotic and abiotic processes, as well as its societal, demographic and economic activities, is critical to effective delta management. Knowledge and use of advanced information technologies like Geographic Information Systems (GIS) and Remote Sensing can also help in understanding the processes taking place in particular deltas. Seijger et al (2016) outline an approach for involving stakeholders in strategic delta planning including water management, agriculture and urban development, and environmental protection of delta planning along with a research agenda designed to encourage the use of this participatory approach.

Many non-governmental organizations are focused on facilitating public participation processes, including those pertaining to delta development and management. In The Netherlands NGOs are actively influencing policy and implementing delta development and environmental protection plans, not only in Europe but also in many developing regions worldwide. The World Wide Fund for Nature is assisting China in restoring water supply systems, conserving wetlands, promoting biodiversity, and enhancing natural ecosystems in the Yangtze Estuary (Bucx et al 2014, CGIAR Research Program on Water, Land and Ecosystems (WLE) 2018).

3.4. Legal and governance measures
In The Netherlands and Vietnam, laws require public participation in regional land and water use planning, as they do in other countries. The 2007 ‘Ordinance of Grass Root Democracy’ specifies that all community development and environmental protection policies and projects in Vietnam, including those involving the mitigation of adverse climate change impacts, must be discussed and agreed to by representatives of the affected communities. In Bangladesh development policy and guidelines require public inputs before
becoming operational. In Mozambique regular committee meetings and public hearings occur where stakeholders can express their views, offer suggestions, and ask clarifying questions concerning development decisions. In Argentina the Free Access to Public Environmental Information Act provides public access to government information at national, provincial or local levels. The Tana Delta Land Use Plan provides for the involvement of all stakeholders in the decisions that are to be implemented (Kuenzer and Renaud 2012, Vermaat and Eleveld 2013, Meyer and Peters 2016).

Delta governance is a critical factor in achieving sustainable delta development. Governance measures such as advisory panels, decrees, rules, laws, and regulations can facilitate, and support the integrated management of deltas and the effective use of delta resources. Governance failure risks are high in Africa and in some northern deltas. The least at-risk deltas are in Europe and North America. However, deltas at the end of international rivers such as the Colorado Delta and Danube Delta present governance challenges because of their transboundary aspects (Ma and Tao 2010, Driel et al 2015, Gerlak 2015, Schröder and Waibel 2015, Rhode 2017).

Public organizations involved in the governance of some developed deltas may be able to create a reinsurance market that could promptly mitigate losses due to failures in delta management, especially in extreme hydrologic events.

3.5. Public-private partnerships
There are numerous ways to facilitate cooperation between the private and public sectors. In Bangladesh there are increasing public-private partnerships in infrastructure development, especially related to transportation, irrigation and power. In Vietnam the government and the private sector cooperate in addressing environmental and climate change issues. In the Danube Delta public-private initiatives exist in the tourism (including agri-tourism), fishing, and small business sectors. Public-private partnerships in the financial sector are becoming increasingly common in the Nile Delta. In Mozambique the water sector is becoming less centralized, more involved in the private sector and increasingly recognizing the economic value of water. The government is transferring more of its administrative oversight of some water resources infrastructures to the private firms.

Finding the right balance between government and private sector interests can be a challenge. Even defining what is ‘right’ may depend on the perspectives of who are asked. In the Mississippi River delta, the lobbying power of the shipping and petroleum industries has given them ways to do what they want to do without governmental interference in the delta even if environmentally destructive (Buox et al 2014).

4. Research needs
River deltas are complex systems of interrelated ecologic, social, and economic components. Their vulnerability is a function of not only the processes occurring within the delta, but also by external processes originating from the ocean, upstream areas, the subterranean, as well as from overall climate. The physical and biological changes that deltas experience over time, whether natural or human-induced, are not fully understood or predictable and hence challenge those attempting to manage them. For example, agriculture, industrial and urban developments in deltas consists of interdependent components and processes that bind multiple cities, economic activities, socio-political organizations, water supply and transportation infrastructure and environmental factors together into one big complex, and often poorly understood, system. Quantification and modeling of cause and effect relationships among components that simultaneously sustain deltaic wetlands as well as urban ecosystems coupled with the uncertainty and subjectivity of human behavior is a challenge. This motivates continued research to better understand the impacts of alternative management plans and policies on the sustainability of developed deltas (Loehle 2004, Wolters and Kuenzer 2015, Brondizio et al 2016b, Khan and Valeo 2017, Li et al 2017, Sun et al 2018).

Developing realistic and effective delta restoration strategies requires an understanding of the natural deltaic processes that govern land growth over time. Knowledge of rates of land growth are needed to evaluate whether it is possible to significantly offset the high rates of present-day land loss and if so, how best to do it. Knowledge gaps could be reduced by real-time monitoring of water and sediment redistribution, subsidence or ecosystem dynamics in particular deltas. For most deltas, knowledge of existing sediment budgets and ratios of mud, sand and organic soils in the upper few meters of a delta plain—crucial for preventing drowning—as well as what they should be for the delta to be sustainable, are still uncertain (Chamberlain et al 2018).

4.1. Dealing with uncertainties
Many processes that govern or impact the development and functioning of river deltas are not well understood. This explains the growing interest in dealing with this ignorance in a systematic way in hopes of increasing delta resiliency (speed of recovery) and reducing delta vulnerability (extent of damage) given any major destructive event. For example, the University of California is addressing the risks of floods, earthquakes and climate change, all of which threaten the California Bay-Delta. Several studies addressing flood vulnerability and climate change impacts in the Mekong delta in Vietnam are helping local people deal with these risks. The management
plans of the Danube Delta Biosphere Reserve Authority are reviewed and modified every few years as appropriate given the changing risks. The government of Mozambique disseminates updated flood risk information prior to each flooding season along with advice on how to reduce the risks of being flooded. Cyclonic storm surge warnings alert people living in the delta and coastal areas of Myanmar. Engineering firms and government agencies in The Netherlands are continually developing flood risk management strategies that include early warning and recovery. Their adaptive delta management plans are built based on scenarios that extend up to 100 years in the future and account for their uncertainties (Bucx et al 2014).

5. Conclusions: are deltas sustainable?

Deltas worldwide have been subject to rapid development and tend to be among the most densely populated regions in their respective countries. Deltas and their estuaries provide important services that support economic activities and societies. In recent years, intensive development activities, including land reclamation for urban or industrial use, sand extraction, and dam construction; together with sea-level rise, and groundwater abstractions among other activities have seriously threatened the sustainability of many deltas and their estuaries.

The reasons for this differ, depending on the particular delta. The Ciliwung, Ganges Brahmaputra Meghna and Nile deltas are among the deltas whose land and water demands are stressed to meet the needs of increasing populations. These demands together with inadequate infrastructure can lead to delta degradation. This is evident in the rapid declining ecosystem services in the California Bay-Delta and Mississippi River Delta due to loss of wetlands. A similar situation exists in the Ayeyarwady delta that is vulnerable to severe hydrologic events such as cyclones, storm surges and extreme rainfall. Insufficient infrastructure also contributes to the degradation of the Incomati and the Tana deltas (Werner and Simmons 2009, Sun et al 2012, Chuai et al 2014, Hussain et al 2014, Meyers et al 2014, Anthony et al 2015, Cui et al 2015, Paiva et al 2016, Xu et al 2016, Andrews et al 2017).

But the current assessment of delta health worldwide is not all negative. Examples include the Danube, Mekong, Rhine-Meuse, Parana, Yangtze and Zambezi deltas. The state of the Rhine-Meuse delta and its infrastructure can be considered sustainable, mainly because of the relatively moderate demands for its land and water and its relatively effective governance. The Danube delta appears sustainable mainly because of the very low population density. The Yangtze and Mekong deltas have high land and water demands that are currently being met by existing infrastructure, but these demands are increasing. Demands for land and water use in the Zambezi delta has been relatively low compared to the resources available. However, changing flow regimes and ecosystem habitats resulting from the operation of upstream dams may put additional stresses on the natural resources of these deltas. Land and water use in the Parana delta is considered sustainable but the growth of the Buenos Aires Metropolitan Area in the lower delta will increase the demand for its natural resources.

Looking into the future one must hope that we will have the knowledge, the technology, the economic resources and political will to successfully manage the development of our river deltas, and thus continue to benefit from the services they provide. Surely increased population pressures associated with industrialization and urbanization and climate change...
(including greater extents and durations of extreme hydrologic events) will put increased demands on delta land and water management in ways that may not be sustainable over time.

For example, in the Ayeyarwady Delta, California Bay-Delta, Ganges Brahmaputra Meghna Delta, Mekong Delta, and the Mississippi River Delta there exist opportunities to improve infrastructure in ways that could reduce the adverse effects of climate change. However, given more extreme population and climate scenarios, the sustainability of many of the remaining deltas of the world will likely diminish (Bux et al. 2014).

While many deltas suffer from similar problems, the solutions most appropriate for each delta are specific and unique. There is no single best practice on how to sustain the benefits derived from a river delta. Every delta has its own biophysical aspects; dominating economic activities; population densities; culture and social life; land use patterns; agriculture, environmental, industrial and urban forms and networks and issues; governance structures; and financial means. The resilience of a delta population largely depends on socio-economic and political circumstances as much as geographical ones (Kuenzer and Renaud 2012, Vermaat and Eleveld 2013, Szabo et al 2015a, Meyer and Peters 2016).

6. Data availability statement

Data sharing is not applicable to this article as no new data were created or analysed in this review.

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