**RESEARCH ARTICLE**

**Evolving deltas: Coevolution with engineered interventions**

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Deltaic environments are often densely populated with high socio-economic values, and thus are hotspots of climatic, environmental and anthropogenic change. Large scale engineered structures, such as dike systems, have played an important role in shaping both environmental and socio-economic conditions in deltas, with such interventions more likely where there is a high population and a wealthy economy. Engineered interventions interact with the morphological evolution of the delta, reducing or removing sedimentation and accelerating subsidence, increasing the consequences of flooding and necessitating further adaptation. They also encourage further development, reinforcing this feedback. Thus, in these cases, the deltaic landscape and associated livelihoods can be considered to be the result of a coevolution process between natural delta processes and human engineered interventions. This paper explores this hypothesis. It analyses the history of large scale engineering interventions and their implications in five representative, large, populated deltas across the globe (Ganges-Brahmaputra-Meghna, Yangtze, Rhine-Meuse-Scheldt, Mekong and Nile). The results demonstrate coevolution has occurred and indicate that the response type and the management approach of these engineered structures have significant implications for future delta development. To understand and manage unintended consequences and the development of lock-in trajectories in deltas, a systematic understanding of delta development, including these coevolution processes is essential.

**Keywords:** Engineered adaptations; deltas; hazards; response; drivers; impacts; management; coevolution

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1. Introduction

Deltas are located where a river has deposited a large amount of sediment over time in a standing body of water, such as the sea, a large lake or a reservoir (Schmidt, 2011, Woodroffe, 2010). Mid to low latitude deltas are often favourable locations for human habitation due to their flat land, fertile soils (Svistvik, 2008) and rich supply of freshwater (Pont et al., 2002), in contrast to high latitude deltas, such as the Lena, Siberia, which are essentially uninhabited. These characteristics make mid and low latitude deltas some of the most populated regions in the world, containing one in fourteen of the global population (Day et al., 2016). This in turn has meant that the land cover of many deltas has been significantly altered to primary agricultural uses and dense rural settlement: more recently major cities and megacities have developed on or adjacent to many deltas (Li et al., 2011, Comoretto et al., 2007, Comtois and Dong, 2007, Woodroffe et al., 2006, Saito, 2001).

Humans have exploited deltas for their services over long periods, particularly for agricultural uses (Atahan et al., 2008). Deltas may be prosperous in terms of their outputs and services; however, they are also susceptible to many hazards due to their location and low-lying nature. Hazards include storm surges, fluvial flooding and erosion of both coastal and riverine areas, as well as subsidence, relative sea-level rise and pollution. This can have severe impacts on the delta, its population and its services. For a recent example, Hurricane Katrina hit the Mississippi delta coast including the city of New Orleans in August 2005, bringing severe winds, surges, waves and record rainfall. This led to the deaths of 1570 people and $40–50 billion in monetary losses, through the destruction of infrastructure and disruption to trade, etc. (Kates et al., 2006). Hazards can also provide benefits, for example floods bring nutrient rich water and sediment which can benefit future crops (World Bank, 1989). This was particularly clear in the annual Nile flood, prior to the implementation of the Aswan dam, which brought nutrient rich water to the delta, allowing for successful agriculture and aquaculture (Nixon, 2003).

The dynamic nature of life in a delta, as well as the exposure to hazards, have led to a long history of adaptation, from the scale of the household, up to large collective flood defence systems. Adaptation is defined as a process, action or outcome in a system (household, community, group sector, region or country) in order to better cope with (manage or adjust to) some changing condition, stress, hazard, risk or opportunity (Smit and Wandel, 2006).
This paper considers engineered adaptations that protect and enhance a delta against a variety of hazards. This can take place at different scales; here we focus on engineering systems rather than individual engineering components, for example polders and city defences. Humans have engineered adaptation strategies to reduce the impacts of the large variety of hazards in deltas (Renaud et al., 2013). Table 1 gives examples of both infrastructural and non-infrastructural adaptations that can be found within deltas.

Coevolution is a long established concept within biological and evolutionary science (Porter, 2006). It is defined as the reciprocal evolutionary change between interacting species, driven by natural selection (Thompson, 2005). The term coevolution has been used to describe the relationships between butterflies and food plants (Ehrlich and Raven, 1964), predator and prey (West et al., 1991) and parasites and their hosts (Legendre et al., 2002), as well as many other examples. Coevolution is becoming more frequently used as a concept within non-biological disciplines to define systems that are not independent from one another. Within deltas, the ongoing interaction of natural processes and human interventions might therefore be described as a coevolutionary process. Coevolution in deltas would reflect the feedback loop or interaction between natural processes and human actions: each has an effect on the other and hence an inter-dependent interaction initiates and continues. Deltas are dynamic systems and engineered adaptations have played a key role in their development, in some cases over centuries. In this paper, we analyse the role of coevolution in populated deltas, discussing how the natural processes of the delta have interacted with engineered interventions and vice versa.

Previous research discussed the role that engineered adaptations have on delta evolution, considering the development of individual deltas over time. It is noteworthy that the concept of coevolution is not explicitly considered within these examples, but is implied. For example, van Staveren and van Tatenhove (2016) discuss the interplay between nature and engineering technology in the Dutch delta system. Van Koningsveld et al. (2008) also describes how the Rhine-Meuse-Scheldt delta has developed over many centuries due to technological developments of the engineered interventions implemented to tackle a variety of hazards, such as flooding. A key example of this is the ongoing subsidence (and loss of sedimentation) which has increased the risk of flooding and so managers have responded by building (or increasing the height of) dykes (Van Koningsveld et al., 2008). Similarly, Grossi and Muir-Wood (2006) analyse changing flood risk within New Orleans (Mississippi delta), again focussing on the impacts of engineered adaptations. They demonstrate how the growing flood losses in New Orleans was a consequence of the anthropogenic alterations of the natural landscape. As the city and port area expanded, low lying swampland was reclaimed and developed to produce a subsiding city below sea level, dependent on dikes and pumped drainage. Coevolution is implied within all of these examples, highlighting the interplay between the natural delta processes and hazards and how these have been governed and shaped by the addition of engineered interventions, over time.

The aim of this paper is to analyse to what extent the coevolution process is apparent within populated deltas. This will be achieved by addressing the following four research questions:

- How have deltaic communities responded to the hazards they are exposed to in terms of implementing engineered adaptations?
- Does the type of engineered adaptation used vary with the hazard type, economic development and/or the land use of the delta area?
- What are the implications of these interventions for the coevolution of deltas?
- What recommendations or insights could be made for future delta planning and management based on these findings?

This study reviews and analyses published and grey literature in order to understand the specific deltaic characteristics and assess drivers, responses and impacts that such adaptations have had, using five representative delta case studies across the world. The analysis is organised into appropriate sections in order to answer the above research objectives across the five deltas. The paper is structured as follows: Section 2 discusses the case studies assessed in this study; Section 3 looks at the type and frequency of engineered adaptations; Section 4 identifies the drivers of engineered adaptations; Section 5 assesses the management approach to implementing engineered adaptations within deltas and Section 6 considers the impact that engineered adaptations have on the delta. A discussion of the findings of this study is located in Section 7, finishing with a conclusion in Section 8.

### Table 1: Examples of Infrastructural and Non-infrastructural adaptations within deltas. DOI: https://doi.org/10.1525/elementa.128.t1

| Infrastructural adaptations | Non-infrastructural adaptations |
|-----------------------------|---------------------------------|
| Dikes                       | Floating rice                   |
| Seawalls                    | Crop insurance                  |
| Cyclone shelter             | Afforestation                   |
| Floating houses             | Beach nourishment               |
| Pumping stations            | Early warning systems           |
| Sluice gates                |                                 |
| Storm surge barrier         |                                 |

### 2. Case study selection

A preliminary literature review of thirteen populated deltas across the world identified a number of key attributes which might influence the coevolution process. These were as follows: economic status; types of hazards and impacts; population density and large scale engineered approaches.

Based upon this initial study, five representative mid to low latitude deltas were selected to further investigate: (1) Ganges-Brahmaputra-Meghna (Bangladesh), (2) Yangtze
(China), (3) Rhine-Meuse-Schelt (Netherlands), (4) Mekong (Vietnam) and (5) Nile (Egypt). These deltas are exposed to numerous hazards and managers have used engineered adaptations as the main strategy of hazard management, with some more advanced than others. For example, the Mekong and the Ganges-Brahmaputra-Meghna deltas use simpler engineered adaptations (e.g. earthen dikes) in contrast to the Yangtze and the Rhine-Meuse-Scheldt (e.g. floodgates and storm surge barrier). These deltas have been well studied, providing the necessary data for this investigation. Also, they each contain a densely populated city within the delta, allowing a comparison between urban and rural areas. These contrasting settings found within the five case studies were believed to be able to provide a good overview and understanding of populated deltas across the world. A short overview of the selected deltas is given below.

The Rhine-Meuse-Scheldt was chosen as it is the most technologically advanced delta in the world, with interventions such as storm surge barriers being used for over half a century. A large proportion of global delta managers, who experience similar hazards to the Rhine-Meuse-Scheldt, seek advice from Dutch delta managers on managing their problems. Hence, further analysis of this delta is useful to understand the adaptation pathway the Rhine-Meuse-Scheldt has taken and make more informed recommendations to other deltas.

The Nile was selected as it is a good example of where upstream engineering, such as damming, has eliminated some hazards but exacerbated others. In the Nile’s case, the Aswan dam stopped river flooding but significantly increased the rate of coastal erosion. Dams are being built across numerous rivers around the world, and so the Nile case study is representative to many other deltas.

The Yangtze is a site of rapid urban expansion and land reclamation particularly within the coastal area. There is still, however, a distinct urban and rural contrast within the delta, similar to that of the Mekong. Both of these areas have huge investments within the coastal zone and can be used as case studies for deltas which are also in the development stage, converting agricultural land to dense urban settlements.

The Ganges-Brahmaputra-Meghna is one of the poorest, most hazard prone deltas in the world and uses less advanced methods of engineered interventions. The impacts of hazards within this delta have been huge and in some cases catastrophic, with large loss of life. The Ganges-Brahmaputra-Meghna can therefore be used as a case study for developing, hazardous deltas.

The delta boundary within this study follows the 5 m contour line from SRTM datasets. This is the location where the key coastal processes occur and the area that is most affected by hazards linked to sea level rise (Lazar et al., 2015). The delta boundaries are delineated with the ArcMap GIS software. Figure 1 shows the location and delta boundary of each of the studied deltas and Table 2 summarises the key characteristics of the five study sites.

Figure 1: Location and delta boundary of the five studied deltas. The location and delta boundary of each of the studied deltas. Map A shows the global context, B shows the location of the Ganges-Brahmaputra-Meghna (Bangladesh), C the location of the Rhine-Meuse-Scheldt (Netherlands), D the location of the Nile (Egypt), E the location of the Yangtze (China), F the location of the Mekong (Vietnam). DOI: https://doi.org/10.1525/elementa.128.f1
3. Types and frequency of engineered adaptations

Within the five studied deltas, the frequency of engineered interventions varied. Table 3 summarises the frequency of occurrence of common engineered adaptations found within the five deltas based on an assessment of the literature. Each engineered intervention was ranked between 0–3 depending upon the frequency of use. For example, beach nourishment is a common practice in the Rhine-Meuse-Scheldt and is not observed in the Ganges-Brahmaputra-Meghna, and so was ranked 3 and 0, respectively. The ranking criteria was as follows:

0- Not found within the delta (minimum score)
1- Found very rarely throughout the delta
2- Used within some regions of the delta
3- Found very frequently within the delta (maximum score)

Table 3 shows that dikes, sluice gates and pumping stations are the most common engineered interventions, highlighting that water management and flood control is a key issue within all of the deltas. It also demonstrates that engineered adaptation is widespread in all deltas and various approaches are used together in engineered systems.

The Rhine-Meuse-Scheldt delta scored the highest with 9 types of engineered adaptation being used, while the Ganges-Brahmaputra-Meghna delta scored the lowest, with 6 types of engineered adaptations. The Rhine-Meuse-Scheldt is wealthier than the Ganges-Brahmaputra-Meghna delta, so it can afford a greater diversity of engineered adaptations. The longer history of heavy engineered adaptation in the Rhine-Meuse-Scheldt delta may also be an important consideration.

4. Drivers of engineered adaptations

A driver of engineered adaptation is a factor that promotes the implementation of an engineered intervention within the delta in order to minimise risks and/or maximise land use potential. The driver may act alone or in combination with other drivers.

Six key drivers have been identified during the literature review, and are generally present within all of the deltas studied, but with varying levels of influence and are shown within Figure 2. The most important will be further discussed within this section.

4.1 Hazards

Environmental hazards in this study are defined using the definition from Smith (2009). ‘They are limited to events originating in, and transmitted through, the natural and built environments that lead to human deaths, economic damage and other losses above certain predefined thresholds of loss’. Hazards can be categorised into two types: slow onset and rapid onset, depending upon its timescale. For example, a slow onset hazard in deltas is subsidence which accumulates over lengthy periods of years to centuries, so the impact is not observed immediately. In contrast, rapid onset hazards occur over a much shorter time frame: e.g. storm surges. Table 4 summarises the slow and rapid onset hazards relevant to the five study areas. The table was populated using information obtained from the studied literature.

The deltas considered in this study are particularly vulnerable to a variety of rapid onset hazards due to their location and low elevation of the land. These hazards have in most cases, caused detrimental, long lasting damage to the deltas, which has led to both long and short term disruption to the delta system. This investigation showed...
Table 3: Frequency of use of engineered adaptations within the five deltas. DOI: https://doi.org/10.1525/elementa.128.t3

| Rhine-Meuse-Scheldt | Nile | Ganges-Brahmaputra-Meghna | Yangtze | Mekong | TOTAL SCORE | References |
|---------------------|------|---------------------------|---------|--------|-------------|------------|
| Beach nourishment   | 3    | 2                         | 0       | 0      | 0           |            |
| Seawall             | 2    | 3                         | 1       | 2      | 0           |            |
| Storm surge barrier/floodgate | 3 | 0                        | 0       | 1      | 0           |            |
| Coastal/river groyne | 3 | 2                         | 0       | 1      | 2           |            |
| Dike/levee/embankment | 3 | 1                         | 3       | 3      | 3           |            |
| Breakwater          | 3    | 3                         | 0       | 1      | 1           |            |
| Sluice gates        | 3    | 1                         | 3       | 3      | 3           |            |
| Pumping station     | 3    | 3                         | 2       | 3      | 2           |            |
| Cyclone shelter     | 0    | 0                         | 3       | 2      | 1           |            |
| Afforestation       | 1    | 1                         | 2       | 1      | 2           |            |

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Figure 2: The main drivers of engineered adaptation in deltas. The six main drivers of engineered adaptation within the five study deltas. DOI: https://doi.org/10.1525/elementa.128.f2
Table 4: Slow and rapid onset hazards within deltas. DOI: https://doi.org/10.1525/elementa.128.t4

| Slow onset hazards | Rapid onset hazards |
|--------------------|---------------------|
| Coastal erosion    | X                   |
| River erosion      | X                   |
| Saline intrusion   | X                   |
| Climate variability (unpredictable monsoon, drought etc.) | X |
| Sea level rise     | X                   |
| Subsidence         | X                   |
| Cyclone            |                     |
| Coastal flooding/Storm surge | X |
| River flooding     | X                   |
| Earthquakes        | X                   |

that extreme events were a significant driver in the implementation of engineered adaptations, particularly in the case of the Rhine-Meuse-Scheldt, Yangtze, Mekong and Ganges-Brahmaputra-Meghna, all of which are vulnerable to either cyclones or large storm surges.

For example, the Ganges-Brahmaputra-Meghna, is vulnerable to frequent and powerful cyclones, which form over the Bay of Bengal (Ali, 1999). Bangladesh is low lying, densely populated and has a high percentage of its population in poverty, all of which have led to an increased vulnerability to the effects of cyclones (Paul and Routray, 2011). The cyclone in 1991 killed 138,000 people (Bern et al., 1993) in addition to damaging water supplies, causing loss of earnings and infrastructural damage, as well as many other long and short term impacts (Paul and Routray, 2011). In order to help protect the vulnerable population that are exposed to cyclones, the government and non-governmental organisations (NGO’s) have implemented a cyclone warning system and cyclone shelters within villages that are most at risk. These are solid elevated constructions, which can accommodate between 700 and 2000 people, depending upon their size. The cyclone shelters are multi-functional, serving as schools and offices when they are not being used in emergencies (Ministry of Environment and Forests, 2009). Continuous investments from various organisations has resulted in the establishment of 2130 cyclone shelters since 1960 which have hugely reduce deaths during cyclones (World Bank, 2012). 3,406 people lost their lives in the 2007 cyclone, with cyclone shelters playing a key role in reducing the number of deaths compared to 1991 (Paul, 2009). Many more cyclone shelters are planned in vulnerable areas of the Ganges-Brahmaputra-Meghna (Rahman and Islam, 2015).

Other rapid onset hazards that have occurred within the studied deltas are the 1953 storm surge which impacted the Rhine-Meuse-Scheldt and killed 1835 people (Gerritsen, 2005) and the floods of 1998 in the Yangtze which caused mass disruption to the agricultural land use and thus severe economic damage (Zong and Chen, 2000). Typhoon Linda caused significant damage to the Mekong delta in 1997, leading to the destruction of 300,000 houses as well as other losses (Nguyen, 2007). Due to the small elevation of tidal surges and the absence of river floods since the construction of the Aswan High Dam, the Nile does not seem to experience significant rapid onset hazards at present.

Deltas are also exposed to slow onset hazards such as subsidence, caused by natural compaction of sediment and groundwater extraction/drainage of organic soils, and erosion because of their riverine and coastal location. Subsidence can lead to an increased frequency of flooding, as well as saline intrusion within the affected area. Many hazards have been observed in deltas for long time periods, for example coastal and river erosion and seasonal changes in river flow and sediment discharge. These hazards have often been exacerbated by human influence. All of the deltas in this study are exposed to these trends, some more so than others. For example, the Nile has severe rates of coastal erosion, particularly at Rosetta and Damietta (White and El Asmar, 1999). This is primarily due to upstream damming reducing the amount of sediment that is transported downstream (Abd-El Monsef et al., 2015). The dam was initially built in order to control the annual floods of the Nile, provide water for irrigation and capture hydropower. As a consequence of the dam, sediment was trapped upstream, preventing the accretion of the delta, making coastal erosion more significant as sediment is not being replenished (Broadus et al., 1986). River erosion and flooding in the Nile delta has however been significantly reduced due to this upstream damming (Ericson et al., 2006). The other deltas in this investigation are expected to show similar trends in the future, with more upstream engineering being planned; such as damming and urbanisation, which will have a significant negative effect on the delta due to the reduction in sediment supply and water flow.

A slow onset hazard present within the Yangtze is water pollution. Water pollution and the associated adaptation has been researched in Lake Taihu, which is in the Yangtze delta. Land use change e.g. more extensive and intensive agriculture, and huge populations i.e. more waste and water waste, have led to the water becoming polluted. This water is used for irrigation as well as a source of drinking water. In order to reduce this, pumping stations have been built to add water from the less polluted Yangtze River as well as from floodwaters, utilising the excess water that may have previously led to disruption within the delta. This has seen positive effects on the lake’s waters such as a reduction in the nitrogen concentration and an increase in the dissolved oxygen concentration (Yang and Liu, 2010). Pumping stations are also present within the other studied deltas, with the main purpose of irrigation for agriculture, keeping low land dry and controlling water levels of lakes and rivers, for example. They are important for reducing water levels on the land following a larger flood event and to reduce water logging, particularly in the Yangtze and the Ganges-Brahmaputra-Meghna, where increased investment in pumping stations has been observed.

The approaches to engineering differ with economic status. For example, the Yangtze uses concrete breakwaters
in order to reduce the rate of coastal erosion (Yan and Feng, 2011). Coastal erosion is also a problem within the Mekong, which is less developed. However stakeholders tackle this issue by using bamboo as the primary material for the construction of breakwaters (Albers and Schmitt, 2015). Utilising the resources that are abundant within the delta, provides a cheap, sustainable and effective adaptation strategy, particularly within developing countries. This could be encouraged in other deltas, where

In order to establish the relative importance of different hazards within the deltas, the main hazards were ranked depending upon the frequency, impact of the hazard, as well as how long the delta is affected by the hazard. All of the data was collected from published literature, including news articles and reports, which detail the extent of hazards within each of the deltas. The duration included both, how long the delta was exposed to the hazard and the recovery time, post-event. This was determined by the extent of damage the hazard caused, the GDP of the delta, the amount of aid received, as well as in some cases, explicit data for recovery time. Each of the categories were scored as defined in Table 5. These metrics provide a clear distinction and comparison between hazards and deltas. The final score of each hazard was calculated as the sum of the individual scores (Table S1, Supplementary document) and is represented graphically in Figure 3.

Table 5: Evaluation criteria and assigned scores during the delta hazard analyses. DOI: https://doi.org/10.1525/elementa.128.t5

| Frequency of hazard         | Score |
|----------------------------|-------|
| More than once a year/ongoing | 100   |
| Every 1–10 years            | 10    |
| Greater than 10 years       | 1     |

| Spatial extent of hazard    | Score |
|----------------------------|-------|
| Directly/indirectly affected over five regions of delta area and affects other countries | 100   |
| Directly/indirectly affected between two and five regions of the delta area | 10    |
| Directly/indirectly affect one region of delta area | 1     |

| Severity extent of hazard   | Score |
|-----------------------------|-------|
| Major e.g. hundreds of people severely impacted- deaths, loss of land, unrecoverable economic loss, long recovery time | 100   |
| Moderate- few hundred people impacted-transport links destroyed etc. | 10    |
| Minor- very few people affected, minor disruption to everyday life | 1     |

| Recovery time of delta after the event | Score |
|----------------------------------------|-------|
| Over a year                            | 100   |
| Months                                 | 10    |
| Days                                   | 1     |

The results show that saline intrusion and subsidence ranked highly in all deltas. This is due to the fact that saline intrusion can cause long term impacts to the delta, particularly in terms of the soil quality, water quality and agricultural production. Saline intrusion is exacerbated by coastal hazards such as cyclones and storm surges, as well as other hazards such as subsidence. River flooding and river erosion is also widespread, but is less of an issue where the catchment is highly managed, as exemplified by the Nile.

The scores given for each of the variables were then averaged in order to give an indication of which hazards are significant in an ‘average delta’. It is clear from Figure 3 that subsidence, saline intrusion and coastal flooding are the three most prominent hazards within these deltas, with coastal flooding scoring lower due to its low score in the Nile delta.

Extreme events and their implications on other drivers, such as land use, have a large influence on whether engineered adaptations are used within an area. In order to reduce the impacts of these extreme events, engineered adaptations have been used to protect the delta population and its associated services. Populated deltas therefore rely heavily on engineering in order to protect the delta system from rapid onset hazards.

Most hazards within deltas are naturally occurring. However, anthropogenic influence has made the effects of these hazards more prominent. Humans have engineered deltas in order to try and reduce the impacts of these, which has generally had a positive impact on the delta system, for example increased GDP or food security. Human influence can however have negative effects on the natural evolution of the delta system. For example, upstream damming in the catchment has restricted the amount of freshwater and sediment reaching the coast, meaning that deltas are now at a greater risk to subsidence and erosion, due to the fact that they can no longer accrete and maintain their land elevation (Syvitski et al., 2009). This has encouraged further engineered interventions within the delta itself. This is a clear example of upstream interventions triggering further engineered interventions within the delta, although this is a one-way relationship from the catchment to the delta.

4.2 Land use
All of the deltas in this investigation were first settled by humans in order to exploit them for their agricultural services, several millennia ago. Agriculture took place very close to the banks of the rivers in the deltas due to the supply of freshwater and nutrient rich sediment, which was a favourable environment for growing crops. However, in all of the deltas, frequent river flooding led to crops being destroyed and a reduction in harvest. This led to engineered adaptations being installed hundreds of years ago along the banks of rivers with the purpose of preventing the river water from entering the land. These were built and managed by the local communities by increasing the height of naturally occurring river levees (Van Koningveld et al., 2008, Wohl, 2011, Liu et al., 2015, Nghia et al., 1994, El-Nahry and Doluschitz, 2010). Earthen
river embankments were built along the rivers in order to control their flow and prevent the agricultural areas from being frequently flooded (Frihy, 2003).

The Mekong and Ganges-Brahmaputra-Meghna rely on less technologically advanced methods of engineering such as earthen embankments for agriculture, as this is still the dominant land use. Controlled flooding is a technique that is becoming increasingly popular within delta management and is particularly evident in the Mekong (August dikes) and more recently Ganges-Brahmaputra-Meghna (Tidal Flood Management) (Khadim et al. 2013; Marchand 2014). This method allows embankments to be overtopped or breached in order to allow high nutrient, sediment rich river water to flood the land, and fertilise it, as well as increasing the elevation of the land. In the Ganges-Brahmaputra-Meghna, Tidal Flood Management is used in areas where mitigation is desperately needed, following issues created by polderisation, such as subsidence and poor agricultural output. These areas include Khulna in western Bangladesh, where a structural solution to solve

Figure 3: The importance of hazards within each of deltas and in 'an average' delta. (Brackets show the scores given to each variable (order from left to right: frequency, spatial extent, severity extent, time). DOI: https://doi.org/10.1525/elementa.128.f3
issues was not supported by the local population, and so this technique was used as an alternative. Tidal Flood Management is seen as an environmentally friendly and cost effective solution, which has been proven to make land suitable again for agriculture (Islam 2006; Khadim et al. 2013).

The integration of sluice gates into the embankments became a common addition within all of the deltas, as it allows for easy management of the river water for controlled flooding. They also allowed excess water to be drained from the land, back to the river. Due to the developments of the engineered adaptations, a sense of security was created, as the population believed that they could control the river and its flow.

The Yangtze, Rhine-Meuse-Scheldt and parts of the Nile have further developed from agricultural land use to industrial due to economic growth and investment generated from the previous agricultural land use. This growth saw the urbanisation of parts of the delta, which led to a large population influx into these areas. The value of the land increased, but the areas are still susceptible to the hazards described above. This saw a change in the type of engineered adaptation used in these locations, with hard defences such as concrete seawalls and storm surge barriers being built. Such structures tend to be found in the most valuable areas of deltas such as major cities or ports. Those areas that are less economically developed such as rural agricultural areas, are less able to fund such interventions. The level of the economy can therefore be seen to influence adaptation. This is particularly the case for the Ganges-Brahmaputra-Meghna (Nicholls et al., 2016). There is a clear interaction between land use and economic interest of the managers, with the land uses that have a higher economic value, having more money spent on engineered interventions.

The location of deltas makes them ideal areas for trade and export, which has thus led to an industrial land use, particularly within the Yangtze, Rhine-Meuse-Scheldt and some areas of the Nile (Chen and Zong, 1999, Van Koningsveld et al., 2008, Redeker and Kantoush, 2014). Large ships are used for trade, and this requires deep river and coastal channels in order for the ships to enter the ports. This has seen the implementation of large scale engineered adaptations, for example in the Yangtze, breakwaters have been built across the river mouth (Yafeng et al., 2000). This prevents the river from silting up and minimises future dredging costs for navigation.

Recreational uses of land within the delta also drives the type of engineered adaptations. This is particularly the case in the Nile and to a lesser extent in the Rhine-Meuse-Scheldt, where tourists and locals use the beach for recreation and holidays, so they are maintained through beach nourishment programmes and groynes (Colijn and Binnendijk, 1998, Frihy, 1996, Roeland and Piet, 1995).

It is clear that land use change and intensification is a key driver in the use of engineered adaptations within all five of the deltas studied. The more sophisticated and costly the engineered implementation, the greater the likelihood that the land use behind it has a high economic output e.g. cities, as land use tends to drive the type of adaptation used. A change in land use leads to developments within the delta as a system, such as increased population or development of infrastructure, influencing the engineering approach and further adding to the coevolution of the delta.

4.3 Other key drivers
Many other drivers lead to the implementation of engineered adaptation within a delta area, including technological developments such as improving pumps and forecasting of events, while foreign aid to improve adaptation infrastructure is important in developing countries. Each delta in this investigation is exposed to the six identified drivers at different scales, and these change over time as the delta becomes more developed, thus changing the delta system and its engineered adaptation needs.

The advance in technology has driven developments in large scale engineered adaptations implemented within deltas. This has been more frequently observed within the Yangtze and the Rhine-Meuse-Scheldt, but has also taken place within the Nile, Mekong and in the Ganges-Brahmaputra-Meghna, at a much lower scale. The use of storm surge barriers or floodgates in the Rhine-Meuse-Scheldt and the Yangtze are evidence of how both hazard forecasting as well as engineering has developed (Bijker, 2002, Seavitt, 2013).

Upstream catchment engineering such as dam building (Abd-El Monsef et al., 2015), urbanisation and channel realignment has led to the need to implement engineered structures within the delta area, due to their associated problems. In the case of the Nile, the impacts of closing the Aswan Dam have been extensively studied. Such impacts include complete elimination of the sediment travelling to the Nile delta, which has in turn led to increased rates of erosion of the coastline (Frihy and Lawrence, 2004). This is also predicted to be the case for the Yangtze delta due to the Three Gorges Dam (Yang et al., 2006).

5. Management approach and its implication upon the sustainability of engineered adaptations
Delta management is essential for the protection of the land and population, and thus its emerging form is important in shaping the coevolution of deltas. The management approach involves analysing who is responsible for implementing the engineered adaptation, as well as focussing on who is responsible for its maintenance throughout its life. This has varied over time and between the deltas that were studied within this investigation, amongst other factors. The management approach has a considerable impact on the design and reliability of the engineered adaptation.

Management approaches can be categorised into top down or bottom up (Kwadijk et al., 2010). Top down management is when decisions and actions
are implemented by large, authoritative groups, e.g. government. In contrast, bottom up management is generally an individual/local scale initiative and occurs at a more local level. Generally, top down management involves the systematic implementation of engineered approaches to a large area, based on expert knowledge. Bottom up management involves smaller-scale engineering approaches which tend to consider the needs of individuals and local communities, for example allowing the continuation of agriculture. This management approach also implements a greater number of non-engineered approaches, such as crop diversification.

All of the deltas considered here historically followed a bottom up approach with farmers managing the river at a local level by building dikes. Within the Ganges-Brahmaputra-Meghna and rural areas of the Mekong and Yangtze, maintenance of these structures is still bottom up (Nicholls and Goodbred, 2004, Le et al., 2007). However, over time, and especially the last 50 years, authority of the land passed to water boards and more authoritative bodies, which thus changed the management approach of the other deltas to a more top down approach, with the government responsible for building and, in some deltas, maintaining the engineered intervention (Van Koningsveld et al., 2008, El-Raey, 1997).

Intensification of land use and growing populations contribute to driving a change in the management approach taken to reduce the risk of destruction of expensive development and dense populations. The top down management approach is particularly evident in the city of Shanghai, within the Yangtze delta, where huge developments and urbanisation of land has led to the implementation of sophisticated, technologically advanced engineered systems (Chen and Zong, 1999). In contrast, the rural areas of the delta initially followed a bottom up management approach to managing hazards, this involved local people building and maintaining interventions. This has subsequently changed to a more top down approach (Gu et al., 2011). This is also similar in the Mekong and the Ganges-Brahmaputra-Meghna deltas. One of the key problems within these deltas is a lack of effort to maintain these structures. Locals are expected to look after and repair the structures, but this does not always occur for a range of reasons such as land use conflicts and low capacity, leading to increased risk of failure.

In the Ganges-Brahmaputra-Meghna, there is a large reliance on external organisations to help fund and design the structures, due to limited community based knowledge and funding (Asian Development Bank, 2002). The government have implemented action plans over the years which has led to some positive responses. However, it is very common for local people to interfere and modify the structures to satisfy their local needs, e.g. requiring irrigation water for agriculture or cutting the dykes to allow saltwater aquaculture. This highlights the importance of a participatory approach with the local people to understand their needs and requirements, which should be integrated within the top down strategies and designs.

Top down approaches, for example in the Rhine-Meuse-Scheldt, ensures regular inspection and maintenance of structural works, reducing their likelihood of failure (Van Koningsveld et al., 2008). This protects the vulnerable delta and its population from the issues described above and ensures the day to day functioning of the delta. Inspection is much more thorough, although more infrequent in the top down strategies compared to that within bottom up management, due to the large spatial area of the interventions. Given that the land in the Rhine-Meuse-Scheldt is mainly below high tide levels, and often substantially lower, the consequences of a defence failure are more serious than in the other deltas. This top down technique requires a large economic investment funding the necessary governance institutions and the works they carry out. However, without this, the risk of failure would rise and become unacceptable.

One possible solution to this infrequent monitoring, is recruiting and educating the local population as to how to inspect and maintain the infrastructure. It is in the local's interest to maintain these structures to a high standard as they protect their land and property from the hazards. This will therefore increase the frequency and the thoroughness of the inspection, and thus ensure the quality of the engineered infrastructure is maintained, as well as potentially reduce the costs of top-down inspection.

It is therefore essential to consider who is responsible for implementing and maintaining engineered adaptations within the deltas, in terms of playing a role in the sustainable development of the delta. A top down approach can seem to be the most effective in some cases. However, these initiatives are generally costly and have widely failed to consider the views at a community-based level. This can, in turn, lead to conflict and deliberate damage to the engineering structures, degrading their function and increasing the risk of failure. In terms of maintenance, education of the local population is key as this can significantly reduce the probability of failure of the defence and the associated consequences.

6. Impacts of the engineered adaptation on the delta

The implementation of engineered adaptations has a significant effect on the evolution of the delta system, both positive and negative. Without the system of engineered adaptations, the deltas would not be able to be able to support the large populations and their economies in the way they do today. Impacts can be categorised into primary and secondary, whereby secondary impacts are a result of primary impacts.

Engineered adaptations have led to an increase in agricultural development within all of the deltas, due to the stability provided. This meant that agriculture became increasingly beneficial to the delta communities, providing food security and the opportunity to export excess produce and earn an income from the land. This led to increases in population and hence a greater demand for space for both agriculture and settlement, which often led
to reclamation of land that was not previously habitable (Pittock and Xu, 2011, Ward et al., 2009).

In some areas of the deltas, the success of agricultural development has been followed by industrialisation and then the development of a service economy. The associated increase in income and investment, has seen the land use change from agricultural to urban, with major cities or even megacities now being located within or close to the studied deltas such as Alexandria in the Nile, Shanghai in the Yangtze, Rotterdam in the Rhine-Meuse-Scheldt, Can Tho in the Mekong and Kolkata and Dhaka in the Ganges-Brahmaputra-Meghna. This has led to substantial development and investment in these areas and greatly raised land values (Wu, 2003). Consequently, an upgrade in engineered adaptations has been observed within these areas, including larger, more sophisticated engineered structures. For example, part of Dhaka is now protected by a concrete floodwall, having previously been protected by earthen embankments (Asian Development Bank, 2002). This then leads to further development and investment to the area, raising potential flood losses, which can then drive demand for more adaptation.

Engineered adaptations have many impacts on the delta system. These impacts can feed back into the drivers of engineered adaptation identified above and exacerbate the vulnerability of an area. This creates a feedback loop which implies that further or upgraded engineered adaptation will be required to manage the growing risks. For example, if subsidence continues, sediment is excluded, and sea-level rise also intensifies, the delta will lose elevation and be ever-reliant on engineered adaptations (e.g. dykes) once they have been initiated (van Staveren and van Tatenhove, 2016). This encourages continued upgrade of the engineering systems. Defences also lead to the creation of a sense of security by the delta population as widely observed in flood plain observations (White, 1945). This has in turn led to growing developments, migration of people and investment in the land that was previously identified as vulnerable to one or more hazard. There is a danger that the engineered adaptation could therefore create a false sense of security. If the engineered adaptation was to somehow fail or an event of a greater scale than the design return period occurred, the population and the infrastructure etc. behind the structure will be significantly impacted e.g. Hallegatte et al. (2013).

There are multiple pathways that a delta can follow in terms of the implementation of engineered adaptation; however, some have reached a stage of ‘lock-in’. This occurs when stakeholders have a reduced number of choices, compared to what may have been available to them in the past. Initially, delta managers may have been able to choose from many adaptation strategies, including both engineered and non-engineered options. However, due to the decisions made, the number of options available may significantly decrease, which leads to stakeholders having limited options, or possibly just one. An example of lock-in is when stakeholders have no other option but to continuously heighten, strengthen, or expand existing structures (Wesselink et al., 2015). All of the deltas considered here are locked-in (e.g. Rhine-Meuse-Scheldt) or are in danger of being locked-in (e.g. Mekong).

One of the key reasons why lock-in occurs is that it is typically the cheaper and politically acceptable option for the manager to pursue. Technological advances are expensive to implement and it is economically more efficient to continue along the line of the existing pathway (e.g. heightening or reinforcing current structures) as opposed to introducing a completely new strategy, which may also be faced with opposition from communities, for example (van Staveren and van Tatenhove, 2016).

Based on the five deltas considered in this study, a qualitative timeline of the typical steps of coevolution between the human system and the delta system of the studied deltas was produced (Figure 4). Note that the Nile

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**Figure 4:** Schematic timeline of the coevolution between the delta and human system. A schematic timeline showing the interaction between the delta and the human system, the present day state of the studied deltas is identified with arrows. DOI: https://doi.org/10.1525/elementa.128.f4
fits the timeline least well due to its exposure to different hazards and thus different management approach (hence the dashed line). The schematic timeline highlights the feedback between the human and delta system, which governs the coevolution of the delta. The five deltas are marked on the timeline to indicate their present stage of development. The major constraint of development of the human system is the ability to invest in engineered adaptations and research; therefore the deltas that were located in the Lower Middle Income bracket are at an earlier stage of development than those in the Higher Income bracket. This schematic timeline can inform delta planners, particularly in the less developed deltas, to anticipate problems that may be experienced if they continue pursuing the same development trajectory as the more developed deltas. Avoiding lock-in to a specific adaptation is of particular benefit, as it will provide the stakeholder with more decisions. The Rhine-Meuse-Scheldt delta is the most advanced and has been investing in methods of improving the sustainability of the delta system through ideas such as ‘Building with Nature’ (Kabat et al., 2009). Hence, innovation in engineering adaptation in deltas continues and this is expected to influence the future coevolution of deltas.

7. Discussion

Coevolution occurs due to the interaction between natural processes and human interventions within deltas, and is observed within the five deltas considered in this study. Human interventions, in all of the deltas, have led to unforeseen problems, such as environmental degradation, and fewer but larger consequence floods, which has in turn led to further engineered interventions being used in order to attempt to reduce the associated impacts. The deltas in this investigation are at varying stages of coevolution, reflecting the economic state of the country, technological developments and land use, with those deltas with a poorer economy e.g. the Ganges-Brahmaputra-Meghna being at an earlier stage of coevolution compared to wealthier deltas such as the Rhine-Meuse-Scheldt. This investigation also identified that upstream damming was a possible trigger for enhanced engineered adaptations within the delta. However, this is not coevolution as the effect is one-way, from the catchment to the delta. Coevolution occurs within the deltas between the slow evolution of the delta (loss of relative elevation), human development and rising land values and demand for safety from the delta residents. In this way, originally natural deltas can evolve into large valuable areas below normal tidal elevation that are dependent on flood defences and pumped drainage.

The deltas in this investigation were selected due to the variety of hazards that they are exposed to, as well as the different engineered approaches used. It is clear that those deltas which have a smaller economy, such as the Ganges-Brahmaputra-Meghna, have the least and most simple adaptations and are therefore at a greater risk to hazards. However, it is also clear that engineered adaptations play a key role in the development of deltas, as change in land use, increase in population and increased development have all been observed as a consequence.

Responses to hazards can either take a precautionary or responsive approach. The former is when experts forecast hazards and then structures are designed and built in order to protect the area before they occur. A responsive approach is when engineered adaptations are built following the experience of a hazard such as erosion or flooding. Historically, the deltas studied took a responsive approach to building engineered adaptations. This was generally driven by river floods, which occurred within the riparian zone, leading to damage of agricultural land. River floods caused economic losses and a reduction in food security within all of the deltas. As a response to this, the locals built river embankments to control the floodwater and these have been progressively upgraded since. For example in the Mekong delta, water control was seen as a central aspect to the development of agriculture requiring the implementation of engineering structures to control floods and salinity intrusion, which had previously affected the land (Käkönen, 2008).

Most adaptations remain reactive, as the uncertainty associated with a precautionary response type prevents stakeholders from investing in such developments. The Dutch Delta Programme is, however, a key example of a precautionary response strategy. It was established in 2008 as a response to Hurricane Katrina, which caused extensive damage and disruption within the Mississippi Delta (Kates et al., 2006), and reminded the Dutch of their high vulnerability to large coastal storms and related hazards. The goal of the Programme was to protect the Dutch delta both now and in the future, with a changing climate, as well as guaranteeing fresh water during dry periods (Van Alphen, 2015). Other deltas are adopting a similar delta plan approach, including the Mekong and the Ganges-Brahmaputra-Meghna, with the creation of the Bangladesh Delta Plan 2100 (Schiermeier, 2014, Nicholls et al., 2016).

This study shows the importance of stakeholder engagement within future delta policy and management. Ensuring needs are met, and education of the purpose and maintenance of these structures is provided, will ensure the longevity of effective engineered interventions and positively enhance the delta. Predictive modelling is a technique which can be used to analyse the impact of interventions, prior to their implementation. It is important to acknowledge the implications of engineered interventions on social, economic and environmental aspects of the delta system. This has been achieved by Chen et al. (2012), who categorised factors of flood dynamics in the Yellow River, into positive feedback loops, which led to the flooding of the basin in the seventeenth century. Methods such as this, will ensure the concept of coevolution is understood by delta managers, as well as being able to investigate future scenarios which may occur. Using this type of methodology may be able to ensure lock-in is avoided and more sustainable options of delta management are investigated.
8. Conclusion
This paper explores the concept of coevolution between humans and natural processes within deltas. Natural processes have shaped the deltas, making them attractive areas to live, but also producing hazards. Four research questions were identified and explored throughout this paper. The key findings will be discussed below.

Humans have used engineered adaptations over long time periods (centuries) in order to enhance their lives and development of the delta. Within the five deltas considered here, engineered adaptations are the primary solution to protecting the delta and its population from the multiple hazards that occur. When these adaptations have failed, the response has been to upgrade and enhance them, rather than investigating alternative approaches. In this way, ad hoc interventions have evolved into more complex engineered defence systems. More recently, delta managers have begun to explore alternatives to large scale engineered adaptations, in order to ensure the sustainability of the delta. Such methods include the ‘Room for the River’ project in the Netherlands, and afforestation of mangroves in coastal Bangladesh. However, these approaches do not replace existing defences and are better considered as new enhancements to the defence system.

The type of engineered adaptation used varies with hazard type, economic development and land use. Areas which have experienced severe hazards, such as cyclones and flooding, causing huge damages, including loss of life and economic disruption have developed complex engineered defence systems to reduce their impact in the future. Slow onset hazards, such as subsidence and erosion, are much harder to engineer against, and engineered interventions to counter the rapid onset hazards enhance these slow onset hazards, especially subsidence and loss of relative elevation. Those deltas which fell into the lower economic bracket (particularly the Mekong and the Ganges-Brahmaputra-Meghna) tend to have less engineered adaptation systems compared to those in the higher income bracket (Yangtze and Rhine-Meuse-Scheldt), but there is a trend of enhancement in all deltas. The type of engineered adaptation used also varies with land use. Urban areas (e.g. Alexandria, Nile) tend to have more costly, hard engineered structures to protect the high value land and assets. In contrast, agricultural areas tend to have simpler, lower cost engineered interventions, such as earthen embankments.

There is a clear feedback loop between natural delta processes and human engineered interventions, which has led to the coevolution of the deltas. Four out of five deltas considered in this study showed a similar trajectory of adaptation, reflecting that they are exposed to similar hazards and similar management approaches. The deltas are at different stages of the trajectory due to varying economic development. The Nile fits least well to this timeline, due to its micro-tidal environment, exposing the delta to different hazards.

Being able to understand these coevolutionary processes allows for more informed future management of deltas. Recognising that engineered adaptations may have some negative effects on deltas is important. However, the main solution to dealing with these negative impacts is to implement further, more sophisticated engineered solutions, rather than abandoning engineered approaches. These, ideally, should be consistent with the natural processes of the delta (i.e. ‘Building with Nature’) to avoid (or at least minimise) long term and costly lock-in situations.

Further investigation into non-intrusive solutions for hazard protection is important to ensure the sustainable coevolution of deltas in the future. Current research into the future management of deltas focusses on the maintenance of the delta’s relative elevation, which should be encouraged as it would assist with reducing the impacts of sea-level rise, subsidence and erosion (Syvitski et al., 2009). In addition, education of local and national delta stakeholders is also vital so they understand the dynamic system on which they depend. Key issues are good governance and funding of the maintenance of the engineered systems on which these populated deltas depend. Lock-in situations are of particular interest in terms of recognising them, and trying to minimise or avoid them in the future.

Data Accessibility Statement
All of the data used within this article can be found within the text and in the Supplemental File.

Supplemental File
The supplemental file for this article can be found as follows:

- Table S1. Frequency, impact and temporal implications of main hazards within the case study deltas DOI: https://doi.org/10.1525/elementa.128.s1

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The authors have no competing interests to declare.

Author contributions
- Contributed to conception and design: ACW, RJN, AL
- Contributed to acquisition of data: ACW
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