Managing for Resilience in Coastal Deltas

Implications of Competing Ecological and Engineering Paradigms

Master Thesis (30 EC)

Kyle Noboru Wada (6370276)
k.n.wada@students.uu.nl
Supervised by Dr. Murray Scown
Second reader Dr. Stefan Dekker
7 August 2020

Universiteit Utrecht

Abstract

Coastal deltas are one of the most important landforms both for human settlement and general ecosystem health, which are existentially threatened by onset global change (i.e. Climate change). Therefore, careful consideration in sustainable environmental management strategies must be taken to safeguard them. This report attempted to address a potential bias when utilizing a key term when discussing and crafting these management strategies: “Resilience”. This bias has the potential to undermine the overarching goals of sustainable environmental management within deltas and even within other biophysical systems. Utilizing a systematized literature review found that there is a clear theoretical dichotomy, in management goals and application, between the two prominent paradigms, which are understood as “Ecological” and “Engineering” resilience. 5 performance indicators were then presented for each resilience paradigm as a framework for understanding the level of resilience of 15 coastal deltas for either paradigm. Data for these indicators was then collected from a variety of sources ranging from international organizations (i.e. United Nations) and published papers. The hypothesis of the thesis report inferred a significant negative correlation between the two rankings, which would suggest that the level of resilience in a delta within one paradigm would negatively influence the other. Final results displayed no significant relationship between the two paradigms and thus a statistical conclusion could not be made. Nonetheless, these findings are still useful on a case-by-case basis to understand by which dimensions each delta is lacking within each resilience paradigm. Recommendations were presented to address how to help develop future research into the topic.

Table of Contents

1. Introduction

1.1 Physical Processes of Deltas

Coastal river deltas are major landforms which are created by the deposition of sediment from river flow and are predominantly influenced by the ability of sediment from upstream to be transferred along the coast and surrounding catchment areas. The building and shaping of the delta landscape can be controlled by both natural processes and human engineering. In the context of natural processes, the balance between the role of tide level, wave strength, and river discharge (Nienhuis et al., 2019), slope/gradient of the catchment area, extent of the network of distributaries (streams that branch off and flow away from a main river channel), and sediment type in the alluvium (loose soil that has been eroded), form the natural physical structure/shape and extent of coastal deltas. Human influence within deltas affect the efficiency of these natural processes in the form of damming of the main rivers, levee construction, dredging, groundwater extraction, and general land use for agriculture and industry (Nicholls et al, 2020). These processes also affect and are affected by ecological components and interactions within the delta.

1.2 Ecology of Delta Systems

Deltas are ecologically important both as habitats and energy sources for many terrestrial and aquatic species as well as plant biomass. These ecological components, in turn, provide the delta with benefits such as sediment trapping through vegetation, protection from waves in the form of mangroves and coral reef beds, animal landscape influencers such as from bivalves, and water filtration/ flood protection from wetlands. Dynamic interactions between each of these components within the delta are difficult to understand and currently understudied within the environmental academic community (Volke et al., 2015). Improper management due to this uncertainty can potentially erode the efficiency of these components in the long run. This has implications to human societies that inhabit these deltas as they also benefit from its essential ecological services such as coastal flooding defense, drinking water, fertile agricultural areas, and vast economic opportunities.

1.3 Socioeconomics of Delta Communities

As of 2019, over 500 million people reside in and around delta systems or 7-10% of the human population in an area comprising 1% of the Earth’s total land mass (Nicholls, 2020). There is incredible variability in these delta societies in terms of their development. Some examples of this variability range from the Rhine delta (the Netherlands) which is a highly engineered landscape where the population enjoys a high quality of life, to the Lena (Russia) and Amazon (Brazil) deltas where the natural landscape is largely unexploited by humans. Nonetheless, compared to other landscapes, deltas often have better agricultural soils, industrial opportunities, access to the oceans for trade, and marine food sources, all of which attract migration and settlement (Nicholls et al., 2020). Key development trends within the literature across deltas also indicate further increases of population, intensification of land use, and scaling of industrial capacity through this century (Nicholls et al., 2020). Considerations on the potential risks of this development must be taken into account as even small changes in the hydrological, physical, and geochemical parameters can cause profound effects on ecosystem health and human livelihoods.

1.4 Risks to Delta Systems

With incredibly high population/economic densities residing in primarily low-lying elevations and with dynamic physical and ecological processes, delta systems are of prime and immediate focus areas for the risks. This can be attributed to slow onset processes from local to global scales such as climate change induced sea level rise and disaster events including drought and catastrophic flooding (Hill et al., 2020). Additionally, deltas and their component parts are under constant human-driven pressures from economic development. An example of these; the Mekong delta is currently facing a myriad of environmental issues including water scarcity, relative sea level rise (RSL), and extreme subsidence (Minderhoud et al., 2019). This will increase in the near future by the increase in hydroelectric activities upstream, agriculture and aquaculture, and groundwater extraction in the delta itself. This is not an exclusive situation of the Mekong as every coastal delta will have increases in certain external and internal risks. A proper framing of environmental management of these risks are thus needed in delta societies to prepare for and mitigate these risks, maintain key ecosystem functions, and increase the livelihoods and security of the people that inhabit them.

1.5 Managing Risk Through Resilience

The long-term sustainability of socio-ecological systems, such as deltas, requires thoughtful management of scarce resources and functionality through identifying, assessing, and controlling the internal and external threats to the system. Current management strategies revolve around the concept of the “resilience” of these systems and theories of how to enhance it for maximum effect. Resilience is the degree an ecological system can absorb disturbances without changing the system structure and process that control its behavior (Holling,1973). Within the scope of delta systems this concept is incredibly important due to both the potential near-to-medium-term, high-impact transformations which will occur due to climate change and human development. Understanding resilience and implementing management strategies based on it would, in theory, maintain important biophysical processes and to sustain human reliance on them. Unfortunately, there is little consensus regarding an appropriate way to define or measure resilience.

1.6 Knowledge Gap

Currently, within the scope of environmental management, there is a tendency to understand resilience within the scope of one of two prominent paradigms: “Ecological resilience” and “Engineering Resilience”. The literature behind this implies a direct dichotomy between the two, where the goals of one can possibly infringe on the other. On the surface, there is an implication that ecological resilience favors a near complete evacuation of human influence from natural systems whereas engineering resilience leads to a path of lock-ins and complete, unjustifiable reliance on artificial infrastructure. From the perspective of this research, many NGOs, and some international sub-organizations (e.g. the UNSDGs and FAO) utilize ecological resilience thinking within the literature. Reciprocally, the majority of international and national organizations and institutions prioritize engineering resilience thinking when using the word “resilience”. This limited theoretical consensus on resilience means any management theory based upon the theory of resilience may also have a confused foundation. Therefore, when debating policy issues within the scope of environmental policy design, there is a risk of “resilience” becoming a “buzzword” with little credibility. Serious implications thus arise, which could affect future environmental management policy. Should the policy makers adopt an ecological resilience mindset through preserving natural spaces in spite of fast industrial growth or an engineering resilience mindset by building more dykes and levees which could have the potential of failure due to the increasing stresses of sea level rise? Furthermore, are policy makers even aware of the fundamentally different assumptions of a particular resilience mindset upon which they base their decisions? Future policy decisions to address cases like these will have to have a base consensus understanding of resilience and the different paradigms that shape and polarize it. However, such consensus is obviously currently lacking, and the consequences of managing a particular resilience mindset in deltas is unknown as there is a scramble to understand sustainability in these systems. This thesis aims to address these knowledge gaps in managing for resilience in deltas.

2. Thesis Design

2.1 Research Aim

The overall aim of this thesis is to understand the distinction between two prominent and contrasting resilience paradigms —ecological and engineering resilience — as a way to inform future environmental policy goals in coastal deltas. This aim is accomplished by first focusing on identifying the key theoretical differences between ecological and engineering resilience paradigms as a whole. After this, the factors that influence delta system processes are identified, then conceptually linked with ecological and engineering resilience paradigms. This involves constructing a list of indicators that characterize the resilience of each of those factors from the perspectives of the two differing paradigms. A comparative assessment between the two paradigms is conducted using data on the identified indicators in 15 delta systems. Finally, an index and ranking system on the deltas is constructed to understand the distinction between the paradigms and the consequences for basing management decisions upon one or the other resilience paradigm.

This thesis does not make a definitive assessment on the level of resilience of deltas themselves, rather it is an analysis of how resilience can be assessed differently from the two perspectives and the consequences of this for managing for resilience in deltas. The connection and distinction between competing resilience paradigms is still yet to be studied fully and will be important to initiate ongoing research into the field and, hopefully leading to a consensus view on the topic.

2.2 Research Questions/Hypothesis

To accomplish the research aim, the following research questions will be answered:

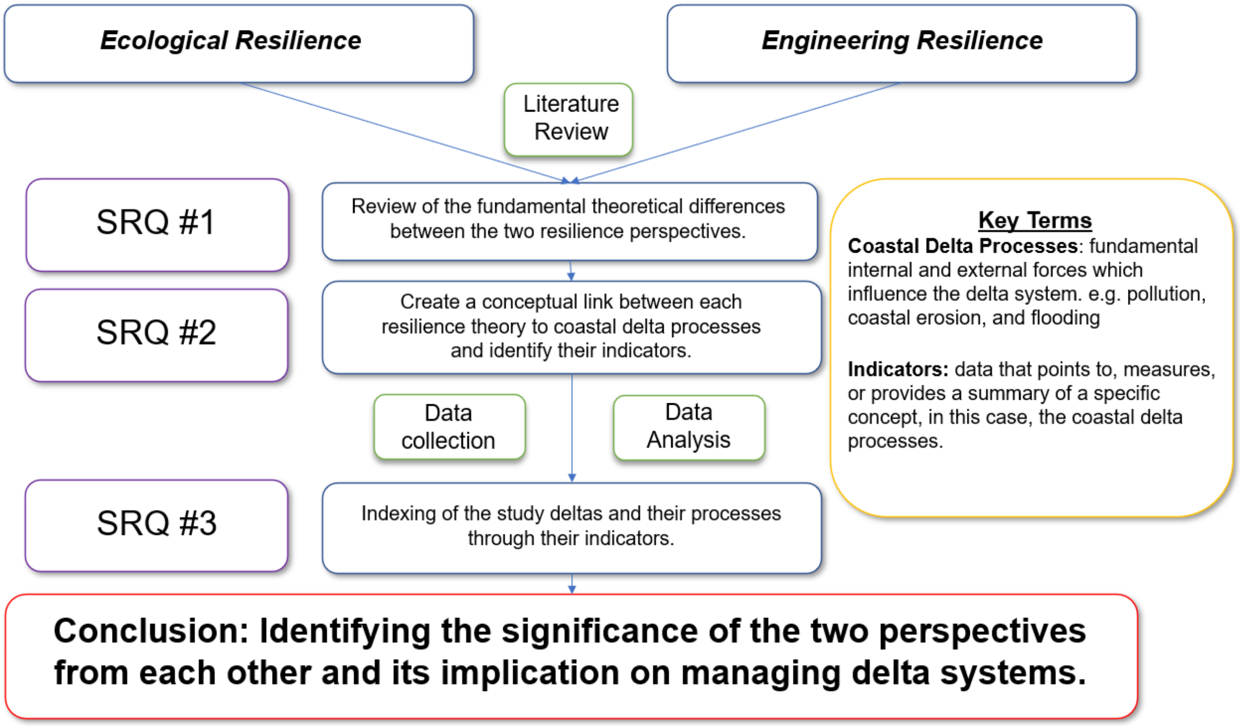
Main: What are the differences between ecological and engineering paradigms within the context of coastal delta systems?

1) What are the fundamental similarities and differences in the definitions of ecological and engineering resilience?
2) What processes are important to the fundamental structure of coastal deltas in terms of ecological and engineering resilience and how can these be measured using indicators?
3) How are specific deltas comparable when analyzed through each resilience lens?

Null hypothesis: There is no significant correlation between how deltas are assessed under the two resilience paradigms.

2.3 Structure of the Thesis

The structure of this thesis is shown in figure 1 to help understand the format of the research and its progression.



Coastal Delta Processes: fundamental internal and external forces which influence the delta system. e.g. pollution, coastal erosion, and flooding

Indicators: data that points to, measures, or provides a summary of a specific concept, in this case, the coastal delta processes.

Conclusion: Identifying the significance of the two perspectives from each other and its implication on managing delta systems.

figure 1: Conceptual framework underpinning this thesis. A literature review is used to understand the distinction between the two perspectives of resilience: ecological and engineering resilience. Next, these two resilience paradigms are conceptually linked to key delta processes. Finally, deltas are evaluated through each resilience perspective using suites of indicators developed throughout the thesis. Each step is also indicative of the research process that was undertaken and how they are linked to the research questions (Sub-Research Questions SRQ).

2.4 Methodology

In order to answer SRQ1, a systematized literature review was conducted to establish the fundamental theoretical differences of the two resilience perspectives generally. This systematized literature review also used backward and forward citation tracking to understand the academic history of the concept. This method was utilized to first understand and archive the broad concept of “resilience” and how it has evolved and disseminated into different academic paradigms and eventually into the two specifically regarding environmental management. This exploration in distinguishing these paradigms answered sub-research question 1 which is to define the theoretical differences between the two main resilience-based environmental paradigms.

To answer SRQ 2, a conceptual framework was constructed linking key adverse coastal delta processes and how they are managed with the two resilience paradigms. Indicators to evaluate delta resilience are selected based on this conceptual framework. The adverse coastal delta processes, more specifically, will be the natural and anthropogenic risks that deltas are prone to be affected by. The relationship between these processes and the management responses based on the two paradigms of resilience was a sample of performance indicators that will demonstrate the level of resilience response to those processes. This identification and data collection of performance indicators will determine whether the society that inhabits the delta concentrates their resources and attention on either one of the paradigms' approach to environmental management or the other. Proxy indicators were used in instances of difficulty in accessing data. The justifications of these indicators were supported by another systematized literature review. From here, a sub-methodology will be made in order to answer SRQ 3, in which a methodological model is built upon this link.

For SRQ 3, indicator data was collected and indexed for 15 delta coastal. The 15 coastal deltas studied are distributed around the globe and span different levels of development, hydrological and biophysical conditions, and size/scale. The list of coastal deltas are as follows: Rhine, Mississippi, Yangtze, Yellow, Po, Nile, Amazon, Mekong, Lena, Danube, Ganges, Indus, Krishna, Orinoco, Volta. The variability among study deltas is important to help illustrate the situation of different coastal deltas globally. In order to compare the two paradigms, indexes were constructed for each of the indicators. Data from each set indicators was transcribed in excel and also included important peripheral data (year of data extracted, region type, sources, etc.), which is displayed in the appendix tables. Each delta in each of the indicators was given a range standardized value from 0 to 1 in comparison to the lowest and highest resilience valued delta, respectively. Each of these indexes acts as an equal weight "indicator score" which will be aggregated in a final separate index which aggregated all of the delta indicator scores and was used to give the delta an overall "resilience score". Each delta has a resilience score, one for each resilience perspective and was given a ranking of 1-15 (1 being least resilient and 15 being most resilient). A Spearman rank-order correlation test will be conducted in the program, R, to understand the level of statistical relationship between the two paradigms which will answer the main research question of identifying the level of dichotomy between ecological and engineering resilience based management. Correlation of the two resilience indices across the 15 deltas would indicate that there is little relative difference in assessing delta resilience using the two different paradigms and their associated indicators developed here. However, if the indices are not well correlated, there may be serious consequences for basing management for resilience upon one or the other paradigms.

2.5 Overview of Deltas

Figure 2 displays the geographical locations of the 15 deltas. Short background descriptions of the 15 deltas are also given to give context to their unique settings.

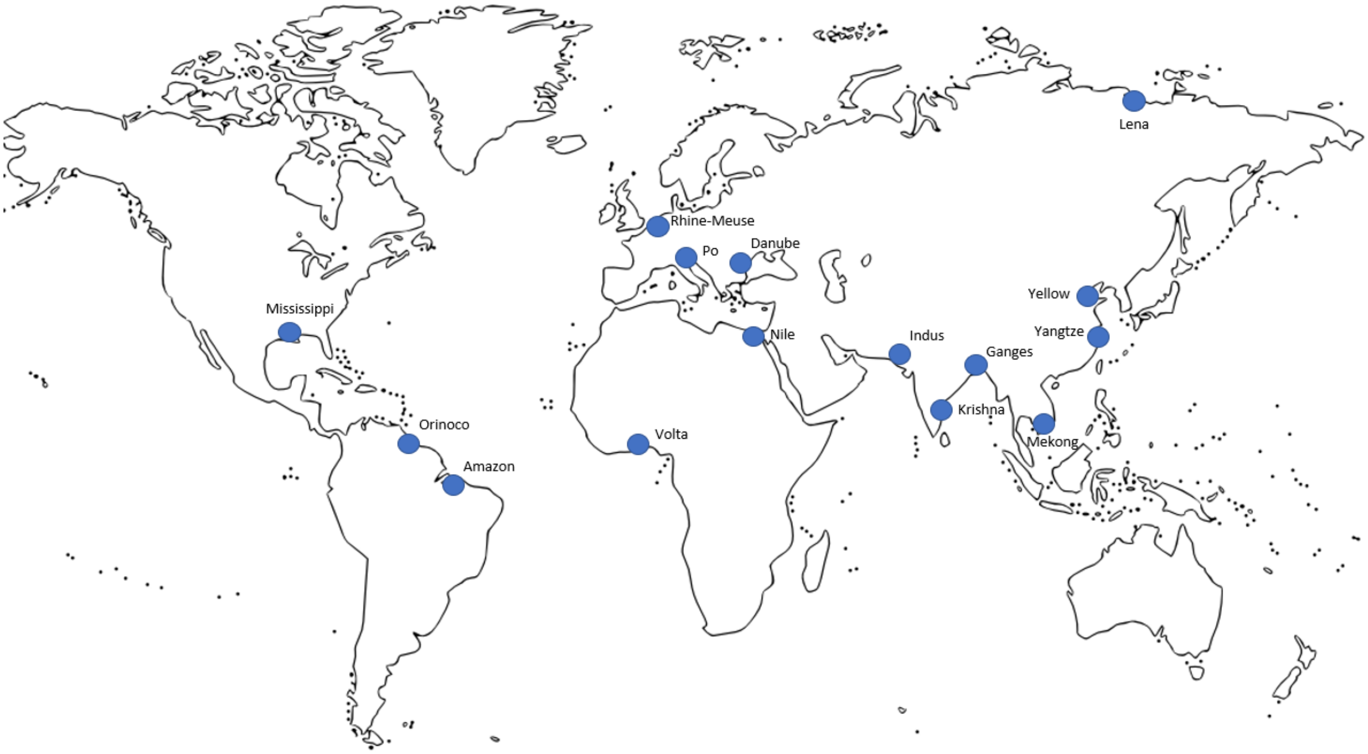


Figure 2: World map with geographical dot points of the 15 study deltas. Map png was adapted from a public-domain image from: https://www.wpclipart.com/geography/world_maps/world_maps_2/world_map_outlines.png.html

Rhine-Meuse, The Netherlands:

The Rhine delta, or the Rhine-Meuse, was created where the Rhine river brings water/sediments from the southeastern Swiss alps through the French-German border, then through the German Rhineland and splits throughout the Netherlands, finally discharging into the North Sea. Covering around 25,347 km2 and exclusively the whole of the Netherlands, is the largest in Europe (Tockner et al., 2009). Human manipulation of the Rhine started approximately from the 13th century, which translated into the construction of dams, groynes, canals and straightening the river bends to prevent the river channels from splitting which made transportation throughout the river more accessible (Stouthamer & Berendsen, 2001). Today this trend continues as the delta is home to the port of Rotterdam, which is protected by a series of large public flood protection projects collectively known as “delta works”.

Mississippi, Louisiana, United States of America:

The Mississippi river delta lies in the southeastern part of the state of Louisiana and protrudes out into the Gulf of Mexico. It is formed from the discharge and deposition from the Mississippi river and its catchment area, which goes through most of the mid-western states of the US. The delta covers around 28,800 km2 (Ericson et al., 2006) and is home to a major city, New Orleans. Due to the frequency of hurricanes, the delta gets continually inundated with flooding with one of the worst happening in 2005. Hurricane Katrina caused $125 billion and over 1,200 deaths and became especially worse due to a levee failure and neglect of flood-control measures (Sills et al., 2008).

Yangtze, China (PRC):

The Yangtze delta consists of a large and varied catchment area with many tributaries, lakes, ,wetlands and drains out into the East China sea. It is primarily formed from the main river, the Yangtze, which can trace its source to the Tibetan Plateau, around 6,300 km away. The delta covers around 34,100 km2 (Ericson et al., 2006) with Shanghai being the biggest metro area situated at the mouth of the delta. Upstream of the main river, the world's largest hydroelectric dam was constructed in 2006 to both provide massive amounts of electricity and control downstream floods, which has historically caused many casualties and infrastructure damage. This dam has also been controversial as it has caused massive ecological change and has displaced around 1.3 million people (Stone, 2011).

Yellow, China (PRC)

The Yellow delta is influenced by the Huang He (Yellow river) which, as with the Yangtze river, originates from the Tibetan Plateau. The delta itself is 5,710 km2 (Ericson et al., 2006) with the largest city, Dongying, having a population around 2 million people. The river is also the most sediment laden in the world and its basin is responsible as the "birthplace of the original ancient Chinese civilization" due to its historically fertile soils (Elvin & Cuirong, 1998). It is also known for its frequent devastating floods with one of the worst floods causing the deaths of over 2 million people in 1931.

Po, Italy

The Po river is the longest river in Italy (652 km) which is sourced from the Cottian Alps. The delta itself is 729 km2 (Ericson et al., 2006) and drains into the Adriatic Sea. In terms of the socio-economic characteristics, the delta has a thriving tourism industry mainly deriving from the cultural and natural heritage sites that inhabit it. The wider basin or "Po Valley", has a population of 15 million people, which is approximately a third of the total population of Italy and one of the most important industrial/agricultural areas in Europe.

Nile, Egypt

The Nile river is the longest river in the world with two major sources being located at Lake Victoria (in Tanzania, Uganda, Kenya) and lake Tana (Ethiopia) which eventually drains out into the Mediterranean Sea (Smith et al., 2019). The total delta area covers around 24,900 km2 and the shoreline stretches approximately 240km from Abu Quir to Port Said (Frihy, 2003). Although the delta makes up only around 2% of Egypt's total land area, it is home to approximately 41% of the population (Gebremichael et al., 2018). This fact, more or less, has been true since the first Nile civilizations going back millennia. Currently the largest hydroelectric dam in Africa is under construction called the "Grand Ethiopian Renaissance Dam" which, controversially, may have the potential to drastically restrict river flow to both Sudan and Egypt (Wheeler et al., 2016).

Amazon, Brazil

The Amazon river is the second longest river in the world with the source being the Mantaro River in Peru. However, the drainage basin is considered to be the largest in the world in terms of water discharge and an area of 7,050,000 km2. The banks of the main river system and floodplain exhibit very little human influence and manipulation unlike many other large delta systems (Fricke et al., 2019). The area of the delta itself consists of 106,000 km2 also making it the largest delta in the world (Ericson et al., 2006).

Mekong, Vietnam

The Mekong Delta is located at the southeast tip of the Indochina peninsula and is in Vietnam. The delta plain is the third largest in the world with an area of 49,100 km2 (Ericson et al., 2006) with a catchment area of approximately 795.000 km^2. The catchment area of the Mekong river is in five different countries: China, Myanmar, Laos, Thailand, and Cambodia. The region is primarily known for its rice production and massively contributes to Vietnam’s position as the world’s second top exporter of rice after Thailand (Smith, 2013).

Lena, Russia

The Lena Delta is located in the northern region of the Far Eastern Federal District of the Russian Federation. The main river (which the delta is named after) is sourced in the Baikal mountains and is 4,294 km long, making it the 11th longest in the world. The delta itself is 21,000km2 (Ericson et al., 2006) and is frozen throughout most of the year.

Danube, Romania

The Danube Delta is located on the eastern coast of Romania and drains into the Black Sea. The main river, which is what the delta is named after, is sourced in Germany and flows through 7 EU countries (Germany, Austria, Slovakia, Hungary, Croatia, Bulgaria, and Romania) and 3 non-EU countries (Serbia, Moldova, and Ukraine), making the second longest river in Europe. The delta itself is 4,000 km2 and is one of Europe’s least populated regions (Ericson et al., 2006). Additionally, this ecosystem is an important habitat for many migrating birds, fish, and plant species.

Ganges, Bangladesh

The Ganges Delta (also known as the Sundarbans Delta and Bengal Delta) is the world's largest delta and encompasses the country of Bangladesh and a part of the Indian state of West Bengal. The main rivers, the Brahmaputra and Ganges, are sourced in Tibet and India respectively and contribute to the region having one of the most fertile agricultural soils in the world. The delta itself is 87,300 km2 (Ericson et al., 2006) and is frequently flooded from heavy upstream snow melt and tropical cyclones from the North Indian Ocean.

Indus, Pakistan

The Indus Delta is located in the southern region of Pakistan and flows into the Arabian Sea. The river, which is where the delta gets its name, is sourced in Tibet, and flows through the length of the country. The delta itself is 6,780 km2 (Ericson et al., 2006) and has the largest mangrove forests in the world and is an important habitat for many marine and bird species (Hogarth, 2007).

Krishna, India

The Krishna Delta is located in the Southern region of India and flows into the Bay of Bengal. The Krishna River is one of the major sources of irrigation for many provinces within South India and the subsequent extraction has historically exceeded its minimum environmental flows (Keller et al., 1998). The delta itself is 2,000 km2 (Ericson et al., 2006).

Orinoco, Venezuela

The Orinoco Delta is located in the North Eastern region of Venezuela and flows into the Atlantic Ocean. The Orinoco River has two sources in Venezuela and Colombia and is the fourth largest river in terms of water volume discharge. The delta itself is 25,600 km2 (Ericson et al., 2006) and has a diverse variety of flora and fauna.

Volta, Ghana

Situated on the Gulf of Guinea and within the Republic of Ghana, the Volta delta shares its name with Lake Volta which was formed from the result of the Akosombo dam. Within the banks of the river and along the banks, there is a robust sand-mining operation which has reduced sedimentation rates in the delta. The delta itself is 2,430km2 (Ericson et al., 2006).

3. The Distinction Between Ecological and Engineering Resilience Paradigms (SRQ #1)

3.1 What is resilience and how do we define it?

From the historical expansions of the original idea of resilience, a universal and current definition can be understood as the capacity of a system to absorb disturbance and reorganize while simultaneously undergoing change and performing the same fundamental functions. (Walker et al., 2004). Simple examples of systems can be found, for example, in ecology with animal populations where disturbances occur within the system periodically and oftentimes without warning. Disturbances or "perturbations" can be understood in this example as sudden shifts in ecological organization which result in die-offs or population booms. 'Resilience' of these systems comes through the sustaining aspects of each system's "resilience capacities" to maintain these functions and adapt while simultaneously undergoing change from perturbations (Holling, 1973).

This ability to cope or system resilience capacities is the culmination of the factors in a system state that can bolster its preparedness against possible future external or internal stresses or "perturbations" (Smit & Wandell, 2006) These 'system resilience capacities' can be broadly broken down into three basic dimensions: 1) absorptive coping capacity or persistence, 2) adaptive capacity or incremental adjustment, and 3) transformative capacity or transformational response (Tanner et al., 2017). Examples of absorptive capacities/persistence infers the stability of a system at a given time; for instance, the population size of a species that can resist perturbations. Adaptive capacities are the inherent traits that systems possess that respond to stresses such as biological fitness in animal populations. Transformative capacities are the mechanisms that systems utilize once conditions change due to disturbances or in anticipation of change; for example, animal populations migrating due to either being forced out or embodied instinct.

After a transformation into an alternate stable state, or "regime shift" (due to a large enough perturbation) these systems exhibit new state equilibriums (Folke et al., 2004). Equilibriums, in this context, are stable conditions of the system that allow certain functions to exist excluding disturbances. Again, using the example above, this would imply that after population collapses, a new set of system dynamics arise from the previous pre-disrupted state, i.e. from animal population stability to exponential increase or perpetual population/decline. Once the system is a new regime, it also implies that there is a new set of capacity attributes that surround the system equilibria that are distinct from that of the previous state (Folke et al., 2004). If the system, which once exhibited flexibility of these capacities in regime shifts, dynamically transitions into a fatally fixed state, this is what is known as a "critical transition" or "tipping point" (Scheffer et al., 2009). In animal populations, an example of this situation would be the functional extinction of the population. This is where a population has declined to a point of either genetic or reproductive impotence, thus the system has fundamentally changed to near permanence. Going back from this system state to its original state would be very difficult if not impossible due to the high resilience displayed by the new critical state (Scheffer et al., 2009). It is also important to realize in these distinctions that 'resilience' itself does not always necessarily imply desirability nor is it suitable for life; as an undesirable state can exhibit high resilience (Walker, 2020). Take for example a polluted aquifer, in which the state becomes highly resistant to change back to an undisturbed state yet is not favorable.

Figure 3 displays these elements through a cross sectional view of a system's resilience. Highlighting the "snapshot sampling" of the figure shows this process of crossing a threshold in a "cup and ball" model where the ball is the system state. The arrows exhibit these perturbations or stressor(s) which push the system towards the threshold or cup edge and into another "cup" or regime. The depth of the "cup" is the stability of the regime or state itself and its ability to cope against further perturbations. When the cup becomes too deep for any other perturbations to transition back to another stable state this would imply a critical transition. These elements make up the basic structure of resilience and which are unanimously recognized by academic research groups (Quinlan et al., 2016). Despite this, there is wide variation on how "resilience" is interpreted by the wide range of academic disciplines.

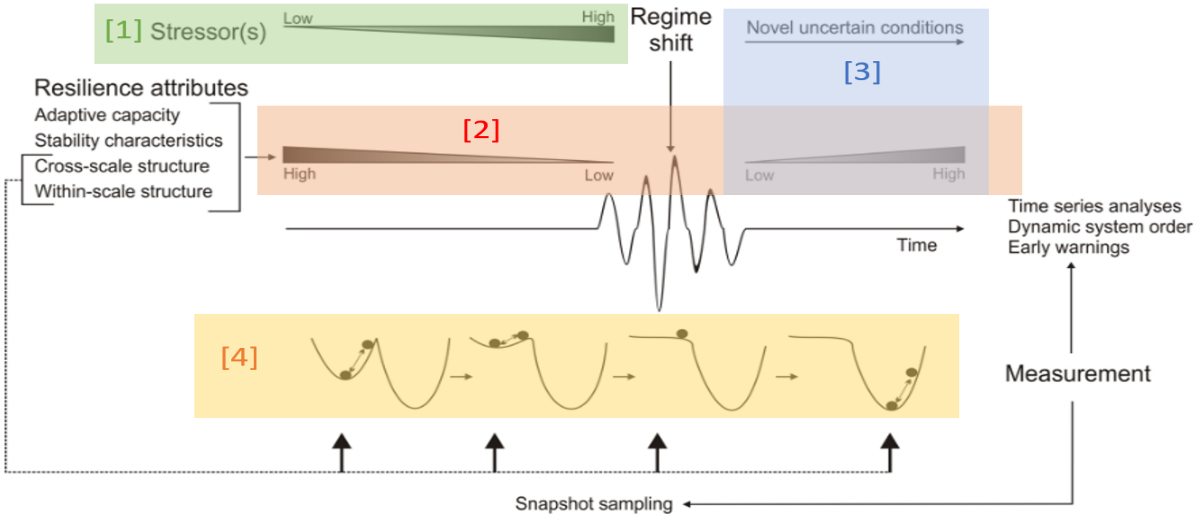


Figure 3: Conceptual model of a transition in a resilience-based system. [1;green] Increasing pressure from stressors which can include both internal and external. [2;red] Degree of resilience attributes which summates adaptive capacity and level of stability. [3;blue] "Novel uncertain conditions" illustrates the inability to measure the level of stress, stability, and resilience attributes of a new regime pre-transition. [4;orange] "Snapshot sampling" shows the cross-sectional view of the "cup-and-ball" illustration which shows the system's (ball) response to stress (arrow) within regimes (cup). (Adapted from Baho et al., 2017)

Many academic disciplines have come up with their own interpretation of the definition of resilience in systems, which include social, social-ecological, developmental, social-economic, community, psychological, engineering, and ecological resilience (Quinlan et al., 2016). Between the majority of these, there is much overlap, albeit with different focuses and strategies. For instance, social and developmental resilience both deal with the organization of communities but have two vastly different emphases in which to contextualize them. Social resilience can be described as the, "ability of groups or communities to cope with external stresses and disturbances as a result of social , political and environmental change" (Quinlan et al., 2016, p.678). Meanwhile, developmental resilience is the "capacity of a person, household or aggregate unit to avoid poverty in the face of various stressors and in the wake of myriad shocks over time" (Quinlan et al., 2016, p.678). Both of these paradigms address these underlying issues of community development and resilience, yet social resilience addresses the social dimensions of a community while developmental resilience tries to understand the economic vulnerability of impoverished groups.

The subtle divergences in the focus and measurement methodologies of each resilience paradigms are important to understand the emphasis of how to define resilience in the first place (Tanner et al., 2017). As each paradigm might develop two contrasting conclusions on resilience to the same system, this implies that management and policy strategies, utilizing either focus exclusively, will also deviate from each other in terms of intent. This also implies that resilience is becoming more of a “buzzword” and is applied beyond its original scope, which has the potential to dilute its meaning as described in the paragraph previous (Tanner et al., 2017). Despite this, all of these types of resilience are valid within their scopes, as they all still do have well-founded theoretical basis (Tanner et al., 2017).

Within the context of management for coastal deltas, ecological and engineering resilience are the most relevant as they encompass environmental and anthropomorphic systems. So, for the purpose of this thesis, this paper will focus exclusively on ecological and engineering resilience due to their often fundamental opposition to each other in terms of goal outlook, ideas of measurement, and dominance in political and managerial ideology in terms of environmental systems management. The next section will highlight these concepts through featuring the fundamental differences within the ecological community and its most prominent definitions of resilience.

3.2 The Current Debate: Engineering vs Ecological Resilience-Based Management

The following section describes the many dimensions of two prevailing and popular resilience paradigms: the ecological ethos and the engineering ethos. At their root, there is a basic understanding that there is a distinct dichotomy between them which are known as “dynamic” and “functional” resilience (Holling, 1996; Tanner et al., 2017).

Ecological Resilience

Ecological resilience, as defined by the founding theorist of this idea, C.S. Holling, can be defined through a more biophysical and geographical scope where maintaining the existence of function within a system is crucial (Holling,1996). This can be understood as the “dynamic” form of resilience, where there are inherent aspects of non-linearity, adaptation, transformation, evolution, and system complexity within the paradigm (Pimm et al.,2019; Tanner et al., 2017; Quinlan et al., 2015). This interpretation parallels the overarching resilience definition as described in the previous section in which resilience is considered as, in part, a process of transformations and adaptations between system states.

A “complex system”, such as a coastal delta has many components and interactions that all contribute to what the system inherently is and continues to be; from the role of fluvial dynamics to the existence of sediment disrupting bivalves (e.g., mussels) and the feedbacks involved between them. Each of these components and interactions can be considered one or few of the “resilience capacities” (absorptive, adaptive, transformative) which have functions to play within the complex dynamics of the system as a whole and its resilience. Complex systems analysis takes a comprehensive understanding of how every mechanism interacts with one another which can oftentimes be either prohibitively difficult to understand or subject to unproductive uncertainty. From the ecological resilience perspective, therefore, there is also an assumption that the paradigm’s management style revolves around avoiding unintended consequences stemming from this uncertainty.

If one were to take the ecological resilience paradigm in its fundamental form, ecological resilience-based management policies on complex systems should be more of a “guiding” instead of a “steering” management style where the system’s resilience capacities should not be directly manipulated (Walker et al., 2020). This “guiding” management style attempts to limit human influence from the system as to prevent or limit non-endemic disturbances on resilience capacities rather than overtly manipulating these capacities to withstand disturbances. This also allows for the occurrence of naturally derived disturbances and transitions into alternate states, albeit. Additionally, there is the ultimate goal of completely avoiding the critical transition at which point there is no going back to alternate regimes. In other words, this view assumes that humans do not have the capacity to understand complex ecological systems and, therefore, management policies should reflect a “hands-off” approach. For example, placing a cap on the amount of nitrogen inputs into the system to prevent eutrophication or banning wetland dredging to avoid catastrophic flooding. These policies would help transfer the resilience process from human manipulation to naturally derived processes in order to preserve transitions into alternative regimes. However, this allowance for alternate regimes (with an exception of critical transitions) can present a potential challenge to ecological management.

The ecological perspective takes a fundamental stance of the ecological system and its existence over periods that extend past human time scales (Holling, 1996) which can imply certain challenges to crafting environmental policy to address present issues. The most prominent dispute is whether a certain “stable and/or desirable state(s)” be preferred over a “bad or undesirable state(s)” and who, politically and ideologically, has the authority to make decisions on this basis (Tanner et al., 2017). For example, a freshwater lake can exhibit states that are in a range between clear and turbid. These characteristics imply different functionality, processes and feedback within the same system; for example in terms of solar penetration, the clear lake would exhibit higher underwater vegetation growth or be able to support aquatic life compared to the turbid lake, which would not have that functionality. Each of these states or “regimes” can exist within the same physical system yet exhibit traits exclusively from each other. This poses a challenge to balancing the needs for both ecological health and human settlement as there is little consensus that transitions between these states is desirable for certain policy goals (i.e. keeping the lake clear for aquatic life or to allow for more economic usage in the lake which might mean allowing some turbidity). Additionally, if one were to take this paradigm fundamentally, there should not be the consideration of “good” states or “bad” states but rather, an allowance for natural transitions between states without any artificial manipulation of resilience capacities.

Unfortunately for this sentiment, most complex biological systems and their capacities are already either directly or indirectly influenced by humans intentionally or not. If human influence and disturbance is unavoidable in a system, this has unavoidable effects on these system capacities. In turn, an ecological resilience-based management system might assume a decrease in economic utilization of these systems, which can hinder progress in underdeveloped nations. This has given rise to another form of resilience in the environmental management community: the engineering resilience perspective, which promotes a singular regime continuity through the direct manipulation of the system capacities.

Engineering Resilience

The other form of resilience assessed here, “engineering resilience” involves a more artificial and built environment centric scope where human engagement is the main driver. The inception of this paradigm first emerged as a critique by Holling to illustrate the tendency of the engineering and physical science community to utilize the word “resilience” as a way to advocate for a more anthropomorphic management of ecosystems (Holling, 1996). This perspective draws from the idea in environmental economics, in which ‘human capital’ can substitute ‘natural capital’ to enhance ecosystem services (Solow, 1993). Through this lens, “functional resilience” management takes shape where maintaining *efficiency* of the system is the crucial component of this perspective whereas maintaining the actual *existence* of ecological functions is the ecological perspective (Holling, 1996). This perspective emphasizes the stability of a system near one equilibrium state where, quantitatively, efficiency is determined by measuring the return time of recovery (Holling, 1996). In other words, if taking the example of the “ball and cup” of figure 3, this would imply that the goal of environmental policy within this paradigm will attempt to keep the system within a single desirable state or “cup” through managing or manipulating the resilience capacities in an attempt to resist transitions.

In the engineering resilience paradigm, these resilience capacities (absorptive, adaptive, transformative) of complex systems diverge from ecologically based resilience capacities in that this perspective is *dependent* upon human management and in service of human needs and development. In this case, engineering resilience capacities are the systems’ abilities to resist perturbations (Holling, 1996) through the robustness, mitigation, and preparedness of the society that inhabits the system. Additionally, these management practices are not exclusive to artificial infrastructural projects (dams, levees, floodwalls) as they can include seemingly “natural” infrastructure projects such as planting mangrove forests for flood protection or introducing a historically endemic species back into a habitat. These practices assume that there can be control of the system capacities to respond to potential threats.

Here lies the fundamental difference and point of controversy between the two paradigms: ecological resilience management attempts to avoid critical transitions with the fundamental allowance of alternate multiple regimes through preserving natural transitions whereas engineering resilience management attempts to prioritize a single “desirable” state by avoiding transitions at all. An illustration of this can be found in figure 4. With this comes the assumption of imposing order on a complex system that exhibits perturbations randomly and with increasing frequency, which can oftentimes be problematic.

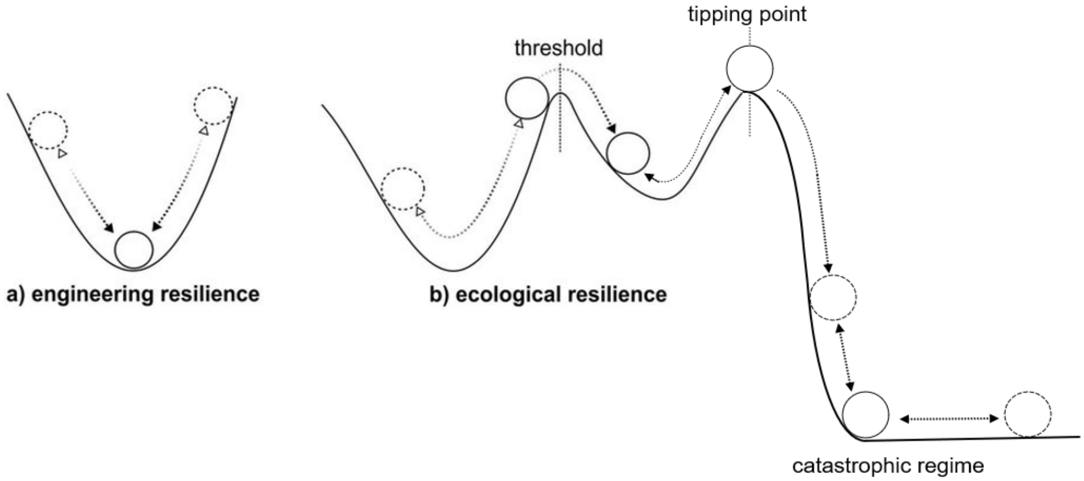
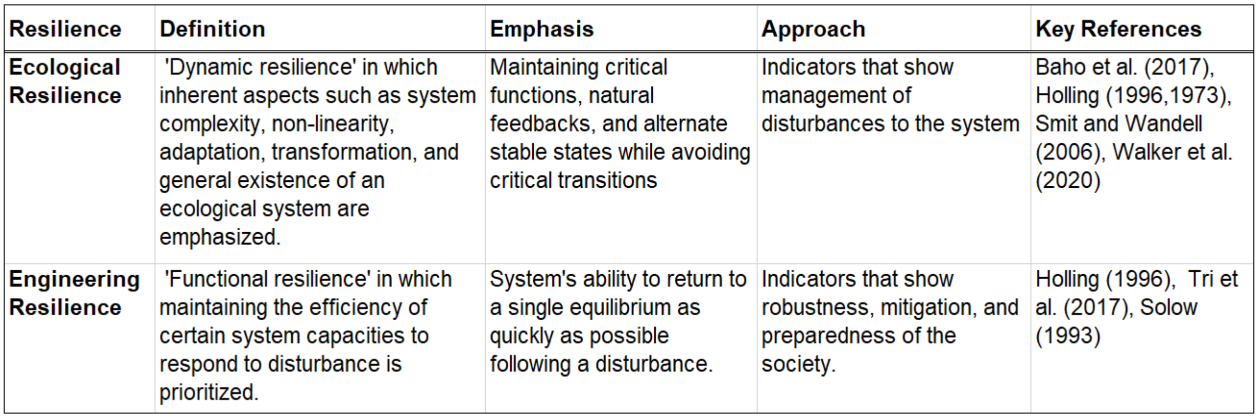


Figure 4: Comparison of the two emphases between engineering and ecological resilience. a) Engineering resilience focuses on a single, stable equilibrium (represented by the vertex of the parabola). b) Ecological resilience allows for the existence of multiple equilibria while acknowledging tipping points and the subsequent catastrophic regime. The system (represented on both by the circle) can pass a threshold and move into a new equilibrium. On the far right displays a critical system state or "catastrophic regime" in which further transition is unlikely (adapted from Tri et al., 2017).

The limitation from the engineering perspective has roots from the idea of "weak sustainability" where 'human capital' is oftentimes not sufficient enough to handle medium-to-long-term exponential change in an ecosystem such as when dealing with climate change (Noel and O'Connor, 1998). Through the constant need for maintenance and improvements on these engineering resilience capacities, it will therefore likely lead to a 'lock-in effect' (Holling, 1996) where these engineering options will be the exclusive option for coastal communities hereafter. Additionally, an engineering resilience based management system that exhibits high resilience presently is not necessarily sustainable if global onset changes are taken into account. A case example of this is the failure of the levees and floodwalls during hurricane Katrina in the New Orleans metro area. Due to poor construction methods and inadequate maintenance of the flood barriers and levees, many lives and homes were lost from the floods accompanying the hurricane (Sills et al., 2008). A now infamous district (lower ninth ward) in New Orleans became a basin where most of the floodwaters were concentrated and resulted in the most damage. Historical construction and settlement of this community had an implication of proper 'engineering resilience' towards flooding in its design (Rogers et al., 2015). This example highlights the many vulnerabilities and potential false sense of security for communities in these deltas as these extreme weather events become increasingly more frequent. The irony of the engineering resilience based management paradigm is that certain aspects of the system's resilience capacities may increase in the short-to-medium term, but the likelihood of critical transitions may increase in the longer term (Allen et al., 2019). This comes from the incredible difficulty to effectively manage and/or even completely understand a complex system, such as a delta, due to the lack of precise knowledge of the many interactions between components and processes within. In simpler terms, it is unknowable to accurately predict the amount of unintended consequences that affect the resilience process of stable states when human influence is included.

3.3 Summary of Ecological vs. Engineering Resilience-Based Management

From this review of both of the resilience paradigms' management theories, it is now clear the parameters that each works within. To summarize the goals of each management paradigm, the ecological perspective advocates more of a guiding style in crafting ecological management policy towards maintaining the existence of multiple sets of natural resilience capacities to avoid critical transitions by directly limiting human-derived disturbances to the system. Conversely, engineering resilience relies upon a management style which aims to boost its resilience capacities against disturbances through active measures such as infrastructural development to avoid any transitions to alternate states (Walker, 2020). Although there is definitely an explicit importance of natural ecological drivers of delta systems in resilience-based management, there will always be an external economic and developmental incentive to counteract or economically re-evaluate these processes. This presents a glaring problem as neither paradigm can yield to the other. A simple real-world example of this would be choosing whether to preserve natural landscapes or construct a dam for the goal of water availability and flood protection. Preserving natural habitats has the immediate benefit of many ecosystem services such as permeable surfaces, biodiversity preservation, water filtration and recreation. Although this may sound uncompromisingly positive, this does not take into account the immediate needs of human development such as flood control, economic development, and the predictability of stable state regimes. In other words, the frequency and variability of perturbations and their ability of shifting to alternative regimes are higher in more natural systems which is not ideal for human settlement. On the other side, choosing the dam will result in immediate positive stability benefits to the stakeholders in the short term (more freshwater, controllable river flow, electricity generation). Unfortunately, this does not take into account an uncertain future in the changes in hydrology from climate change. This can include the increase in the frequency of droughts and floods which will eventually make the initial justification of the dam obsolete. Moreover, this state scenario where the dam exists could possibly lead to a critical transition faster. Utilizing "resilience" in either context to argue for ecological management practices could have radically different conclusions in the future. These ideas are illustrated in table 1. where definitions, emphasis on goals, managerial approaches and the key references of each resilience paradigm are laid out. The main takeaway from the literature should be the assumption that ecological and engineering resilience are inherently diametrically opposed to each other in nearly all aspects. The next section of the report will explore this through linking the risks to coastal deltas and each paradigms' resilience indicators that indicate the resilience capacity of these systems. Through this exploration, the report will set up the focus of data collection in currently studied delta communities.



Resilience	Definition	Emphasis	Approach	Key References
Ecological Resilience	'Dynamic resilience' in which inherent aspects such as system complexity, non-linearity, adaptation, transformation, and general existence of an ecological system are emphasized.	Maintaining critical functions, natural feedbacks, and alternate stable states while avoiding critical transitions	Indicators that show management of disturbances to the system	Baho et al. (2017), Holling (1996,1973), Smit and Wandell (2006), Walker et al. (2020)
Engineering Resilience	'Functional resilience' in which maintaining the efficiency of certain system capacities to respond to disturbance is prioritized.	System's ability to return to a single equilibrium as quickly as possible following a disturbance.	Indicators that show robustness, mitigation, and preparedness of the society.	Holling (1996), Tri et al. (2017), Solow (1993)

Table 1: Resilience definitions within the different broad scopes and relevant references.

4. Delta Resilience and Their Indicators (SRQ #2)

The following section establishes the links between fundamental conceptions of ecological and engineering resilience and the functions and processes of coastal delta systems. This will involve identifying the indicators that imply particular levels of resilience through each paradigm. Indicators are required to assess whether ecological and engineering perspectives give different assessments of delta resilience, and thus have different implications for managing for delta resilience. In this section, an identification of potential useful indicators for each resilience paradigm and conceptually linking them to key delta processes using the theory of resilience, as presented in chapter 3, was constructed. Through this examination, it will help build on the methodological model for SRQ 3 in which an overall index will be made through the data collection from these indicators.

4.1 What is being measured

When trying to link the two paradigms of resilience to the ecological integrity of complex systems such as coastal deltas, there needs to first be an understanding of what the fundamental goals are in this context. Quantitatively, resilience (in both paradigms) can broadly be reduced to how much disturbance that can be taken in by a system before the system's structure is fundamentally changed over long-time scales (Holling,1973). As it is near impossible to comprehensively understand or have a consensus on the dynamics between the intricate processes, components and feedbacks of coastal deltas, this report will not attempt to measure the ability of each deltas' resilience in terms of the quantitative measurement of single resilience capacities (in either resilience management paradigm) and their relations to transitions into alternative regimes. Reciprocally, however, predicting and estimating the thresholds of transitions (and tipping points) can help abstractly understand resilience. (Pimm et al., 2019).

One theory to potentially predict system transitions and theoretically understand resilience through its entire process comes in the form of measuring "recovery times" or the amount of time it takes to get back to an equilibrium from a perturbation or "shock". When witnessing that the recovery times become increasingly longer as more perturbations occur, this is what is known as "critical-slowing down" which can indicate the system nearing a threshold. (Scheffer et al., 2009). Unfortunately, this is still highly speculative and could potentially be misused as a predictive modelling tool if the observation clearly shows nearing a threshold which by that point could be an unstoppable positive feedback into passing the threshold. Thus comes the paradox of utilizing this management tool of quantitatively measuring resilience through the potential for transitions of specific components of a complex system. It can only be done when studying historical data, which by that point could render the information ineffective as a predictive modelling tool for ecological management (Pimm et al., 2019). The system will exhibit different capacities and could already be in the process of undesirable positive feedback loop(s) (Scheffer et al., 2009). Also, there is no guarantee that any particular transition will not result in a critical transition where there is little chance of going back to a previous stability state.

Resilience of complex system organizations such as with coastal deltas, resilience should be understood and practiced qualitatively as a descriptor, a measure, and a tool (Allen et al., 2019). In other words, the need to analyze "complex systems" qualitatively is due to the fact that they are composed of many interactions between many functions and processes within a group which, as a whole, can exhibit functions that can be unique. This research will utilize “resilience indicators” to help determine if a delta is exhibiting high resilience (utilizing the two theories) within a sample of dimensions.

These resilience indicators will avoid measuring the efficacy of specific inclusive resilience capacities of coastal deltas that could insufficiently infer causal effects such as the “number of upstream dams and levees and their capacities to resist flooding”. In other words, there is too much uncertainty to what extent the strength of a certain capacity will increase or decrease flooding (or other risks). Nor will there be an attempt to utilize time series analyses to understand the potential of these system states to transition. The use of these single capacity indicators also has the possibility of having direct reciprocal effects on the other paradigm. For example, the measurement of “the number of dams and levees upstream” could imply positive engineering resilience capacities, but at the implied detriment of the goals of ecological resilience management. This creates an undesirable amount of ambiguity and does not address the complications of contextualizing system complexity. Therefore, the resilience indicators in this report are either the ultimate outcome of these systems’ resilience or factors that influence the efficiency of the whole or multiple system resilience capacities and the interactions between them. Studying each resilience paradigms qualitatively through these peripheral indicators is more effective in describing the current status of a specific delta system’s resilience capabilities.

This research will attempt to take an adequate sampling of these “peripheral resilience indicators” from each resilience paradigm’s management strategy. First this requires clear guidelines on the qualifications and restrictions of each indicator within their respective paradigms according to the literature review conducted in chapter 3. This is to both help justify the indicators within the paradigms and verify that there will be little overlap between them. As mentioned previously, due to the fact that there is little consensus to quantitatively measure resilience in complex systems, this justification is necessary to back up the approach of this report. Through this, a clear distinction can be made between the indicators that will set up chapter 5, in which an indexing of the 15 study deltas will be made. A statistical conclusion can then be made on the correlation between the indicators. This should conclude if there is a dichotomy in management style which will answer the overarching research question. Before going into these guidelines, risks (adverse coastal delta processes) will be identified to help understand the forces which have the potential to fundamentally shift the functionality of the deltas’ states and processes. These risks can be understood as potential catastrophic states in which each resilience paradigms’ management styles are attempting to ultimately avoid.

4.2 Risks to Coastal Delta systems

Subsidence - This is the sinking of land surfaces caused by the gradual loss of groundwater and fossil fuel/mining extractions. Runaway subsidence can cause major damage to infrastructure, buildings, and agriculture. There currently is not a viable solution to reverse subsidence but ceasing underground extraction projects is the only alternative solution to stop continual reduction in surface elevation. Proven examples include the city of Tokyo which banned groundwater/natural gas extraction in the early 1960’s and has shown a complete halt in cumulative subsidence in 1975 (Erkens, 2014).

Water Pollution and Eutrophication - Deltas are extremely susceptible to runoff pollution from human settlement, industry, and agriculture. These pollutants can range from petroleum, mining effluent, pesticides, sewage, and nitrogen/phosphorus enrichment which can induce toxic abiotic environments including eutrophication. Eutrophication is the state where a body of water becomes enriched with excess nutrients. This can lead to algae blooms and “die-offs” which subsequently leads to a state of aquatic hypoxia where dissolved oxygen lowers past a critical threshold to support marine life. (Langdon et al, 2016)

Catastrophic Flooding - Flooding is a common natural process in coastal delta systems caused by tidal forces, increased precipitation, and abnormal upstream events. Effects from this process are typically mitigated by natural unrestricted watershed access (i.e. “room for the river” initiatives and low human development) and permeable surfaces. Human development in deltas and the increase of impermeable surfaces exacerbates the catastrophic flooding risks to its settlements and ecosystem health. (Konrad, 2003) Frequent flooding caused by sea level rise can also exacerbate salinization which has implications on agricultural productivity and groundwater.

Drought - Drought is also a common process in coastal delta systems where there is significant human development and settlement. A combination of low precipitation, inadequate surface water management, and unmitigated groundwater extraction can have devastating effects on the landscape of deltas. These include lower water quality, reduction in animal populations, desertification, and wetland area reduction (Gustafson et al., 2014).

Land degradation - Land degradation is defined by the United Nations Convention to Combat Desertification (UNCCD) as, “the reduction or loss of the biological or economic productivity and complexity of rain fed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from a combination of pressures, including land use and management practices” (UNCCD, 1994; pp.4). This also takes into account external drivers, a variety of processes that exacerbate degradation, natural properties of land, regional socio/cultural/ecological services, and human necessities (UNCCD, 1994).

Loss of Biodiversity - Biodiversity is an important fundamental aspect of ecosystem function that is also both directly and indirectly involved with functions such as biomass productivity, soil formation/protection, freshwater resources preservation, nutrient recycling, and climate stability (Hooper et al., 2005). The definition of biodiversity usually refers to the amount of variety in populations and the gene pools of plant, animal, and microorganism species in an ecosystem. Human development and the subsequent direct loss of biodiversity can adversely affect both the geography and ecosystem functions such as in coastal deltas (Hooper et. al, 2005).

Salinization - Salinization is the process of which soil becomes saline when in contact with salt/brackish water. This can come in the form of natural drivers such as tidal inundation and from anthropogenic sources such as excess groundwater extraction and irrigation (Rahman et al, 2019). In either case, this has direct implications for both agricultural productivity and freshwater security. This process can also be considered a potential critical transition especially for aquifers and soils (Benton et al, 2017).

4.3 Guidelines on the Indicators

This section will outline the objectives of the indicators of the two resilience-based management paradigms. These will act as the “goalposts” for the justifications of the indicators that will be outlined in the section following.

To start with, the objective of the ecological resilience management paradigm is to avoid the tipping point into one of the multiple catastrophic regimes (as outlined in the section previous) meanwhile allowing for transitions into alternate stable states (Holling,1996). Therefore, these indicators will not show empirical evidence for manipulation of the resilience capacities themselves, but they will analyze the ability of each delta’s ecological management strategies’ abilities to manage external disturbances mainly from human development to infer the effectiveness of the system’s resilience capacities. However, many of the major deltas that will be indexed are currently affected by human development. Thus, there is a baseline assumption that the relative present conditions of every delta are the result of negative human influence. All of these indicators will assume the efficiency of ecological resilience management in deltas through the system components’ abilities to maintain the critical functions of the system through ease of natural transitions into alternative states and ultimately avoiding the critical transition. Therefore, the types of indicators will need to reflect ecological resilience by means of either specific efforts to curb direct effects of human development through policy or the measurable intensity of human development that act as pressures on the systems’ resilience capacities.

In contrast, the objective of the engineering paradigm within the scope of environmental management is to maintain efficiencies within the scope of certain infrastructural and technical aspects within the society inhabiting the delta. To use the “cup and ball” metaphor (figure 3), this involves the system to stay within a single state regime’s equilibrium. This infers that the management priority of those within this paradigm surrounds system stability through bolstering the desirable set of system capacities artificially. In the context of coastal deltas, this infers attempting to measure the level of intervention, both in investment and maintenance, taken by the delta societies to service and sustain human needs. For the purposes of this report, to emphasize, there will not be specific indicators on specific system components such as the prevalence of dams or levees as mentioned before. This is also due to the variability in design, efficiencies, and effectiveness of the infrastructure between each country and the endemic characteristics of each delta. Additionally, each delta societies’ specific goals are not universal in part due to the fact that the resilience capacities of each system are different. In other words, the infrastructure of each country is unique and would be impractical to compare between each other. These engineering indicators will infer each delta communities’ socio-economic capacity to both influence and maintain artificially managed resilience capacities. This flexibility allows for a more general indication of engineering resilience that shows the societies’ ability to meet the needs of the population within.

4.4 List of the Indicators

The following section identifies the indicators that will help diagnose ecological and engineering resilience of coastal deltas and the current state/trends that describe their success towards their ultimate goals. Descriptions and justifications will be provided for each indicator in terms of how they conceptually link to each resilience paradigm. Data will be collected in delta region specific datasets, where available, but will draw back on national or subnational datasets if the former is unavailable. It is recognized that the selected indicators do not equally affect or determine an individual delta's "resilience". However, it still cannot be determined to what objective degree they can be compared to each other due to the unavailability of research and difficulty of identifying the links between the components of complex systems like coastal deltas. Because of this limitation and the scope of this research, each indicator will be weighted equally to each other in terms of their significance towards their resilience definitions. In other words, the indicators will not be scaled differently between each other when indexed.

Ecological Indicators:

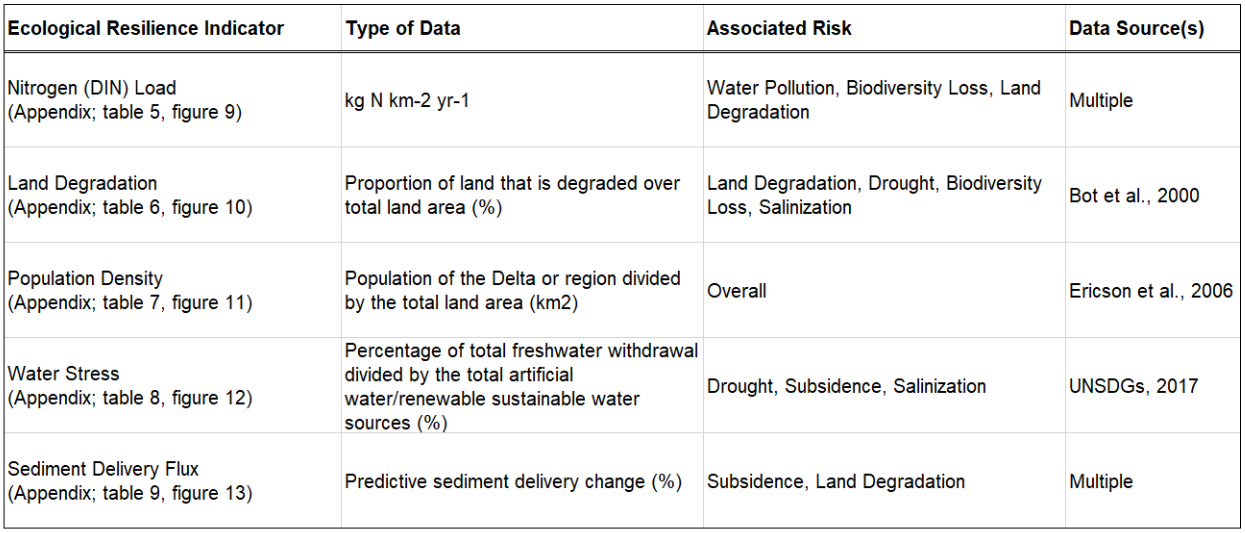
1)Nitrogen (DIN) Load - Nitrogen cycling and retention is essential for plant, animal, overall ecosystem health and continuity (Vitousek et al., 2002). Nitrogen in terrestrial ecosystems is naturally cycled through the air (nitrogen oxide), soil and water (ammonia, nitrates, nitrites) by the processes of ammonification, nitrification, and denitrification. Before the 20th century and the discovery of an artificial process of nitrogen fixation and fertilizers (known as the Haber-Bosch process), nitrogen was the limiting factor in many ecosystems (Appl, 1982). Currently many terrestrial ecosystems exhibit an excess of nitrates through these agricultural inputs and through other human-based sources such as treated wastewater and septic tanks. This excess of nitrogen in delta ecosystems can cause cascading effects (mainly eutrophication) as it moves downstream and into lakes, estuaries, and intertidal zones (Langdon et al., 2016). This indicator will specifically index deltas in terms of concentration (kg N km-2 yr-1) of dissolved inorganic nitrogen (DIN) within the basin area. Higher relative nitrogen present would indicate a higher likelihood of catastrophic eutrophication and thus a higher risk to the delta. DIN will be utilized as it assumes direct implication of human-added nitrogen sourced directly and indirectly from agriculture and municipal sewage runoff. This also has both high implications for marine biodiversity loss and to some extent, land degradation.

2)*Proportion of land that is degraded over total land area* - The data was collected and derived from an FAO published study which adapted the data from the GLASOD survey data from the ISRIC/UNEP. The GLASOD data utilized national experts to determine the types of degradation (water erosion, wind erosion, chemical deterioration, physical deterioration) estimate degrees of degradation (light, moderate, strong, extreme), the spatial extent of these degrees as a national percentage, and the human causative factors of degradation (deforestation, overgrazing, agricultural activities, overexploitation of natural resources, and industrial activities) (Bot et al., 2000). The specific dataset source's method consisted of aggregating the "severe" and "very severe" land area over the total national land area (and then multiplied by 100), which resulted in the "% if total area degraded" (Bot et al., 2000). For its purposes as an ecological indicator, a higher percentage would indicate a lower capacity for terrestrial ecological resilience. It would also indirectly impact drought through desertification, salinization through saline buildup, and biodiversity loss through habitat devitalization.

3)*Population Density* - The population density of a delta would be considered as an indirect indicator for the level of development and pressure on natural ecosystems. This index does not fully capture the context behind the numbers but what it does indicate is the vulnerability of the population at stake in the delta and the potential level of overall stressors on the system state. For this purpose and as an ecosystem resilience indicator, this indicator will be treated as both a vulnerability and a risk with higher population density inferring lower resilience. Land area that the population is compared against is the delta area according to the methodology of Ericson et al. (2005).

4)*Water Stress Index (%)* - The level of water stress nationally is derived from a calculation using three variables in the metadata from UN/FAO (2017). 1)Total freshwater withdrawal (TWW) is measured by freshwater withdrawal (through aquifers, rivers, and lakes) as a proportion of available freshwater resources to be used for irrigation, public, and industrial use. This does not take into account treated water from sources, or 2) total renewable freshwater resources (TRWR), that include desalinated water and sewage treatment facilities. Additionally, there is consideration for the baseline quantity of water to sustain terrestrial water ecosystems or 3) “Environmental water requirements” (ENV). These three sub-indicators are computed as the TWW divided by the difference between TRWR and ENV, multiplied by 100 and expressed in km3/year (UN/FAO, Metadata for indicator 6.4.2). A higher percentage in this metric indicates an increased vulnerability of both drought and subsidence through the pressure on groundwater resources.

5)Sediment delivery Flux (% change) - The physical landscape of coastal deltas are strongly influenced by wave, tidal and river forcing (Nienhuis et al., 2020). Additionally, delta landscapes are becoming increasingly vulnerable to declining sediment supply due to a variety of reasons including damming of rivers and upstream land use change (Nienhuis et al., 2020). All of these factors have implications for the rate of erosion along the coasts of deltas and terrestrial subsidence. Implications include increased risks from catastrophic flooding to sea level rise and infrastructure damage. A decrease in sediment delivery will indicate the basin societies’ level of artificial restriction of sedimentation through dams and levees. The data projects fluxes in sediment delivery from the periods of 1990-2019 and 2070-2099 and takes into account the effects from anthropogenic (damming) and global onset change (climate change scenarios) in its analysis (Dunn et al., 2020).



Ecological Resilience Indicator	Type of Data	Associated Risk	Data Source(s)
Nitrogen (DIN) Load (Appendix; table 5, figure 9)	kg N km-2 yr-1	Water Pollution, Biodiversity Loss, Land Degradation	Multiple
Land Degradation (Appendix; table 6, figure 10)	Proportion of land that is degraded over total land area (%)	Land Degradation, Drought, Biodiversity Loss, Salinization	Bot et al., 2000
Population Density (Appendix; table 7, figure 11)	Population of the Delta or region divided by the total land area (km2)	Overall	Ericson et al., 2006
Water Stress (Appendix; table 8, figure 12)	Percentage of total freshwater withdrawal divided by the total artificial water/renewable sustainable water sources (%)	Drought, Subsidence, Salinization	UNSDGs, 2017
Sediment Delivery Flux (Appendix; table 9, figure 13)	Predictive sediment delivery change (%)	Subsidence, Land Degradation	Multiple

Table 2: List of the ecological resilience indicators used for the index. Description of data used, associated risks, and data sources are also included.

Engineering Indicators:

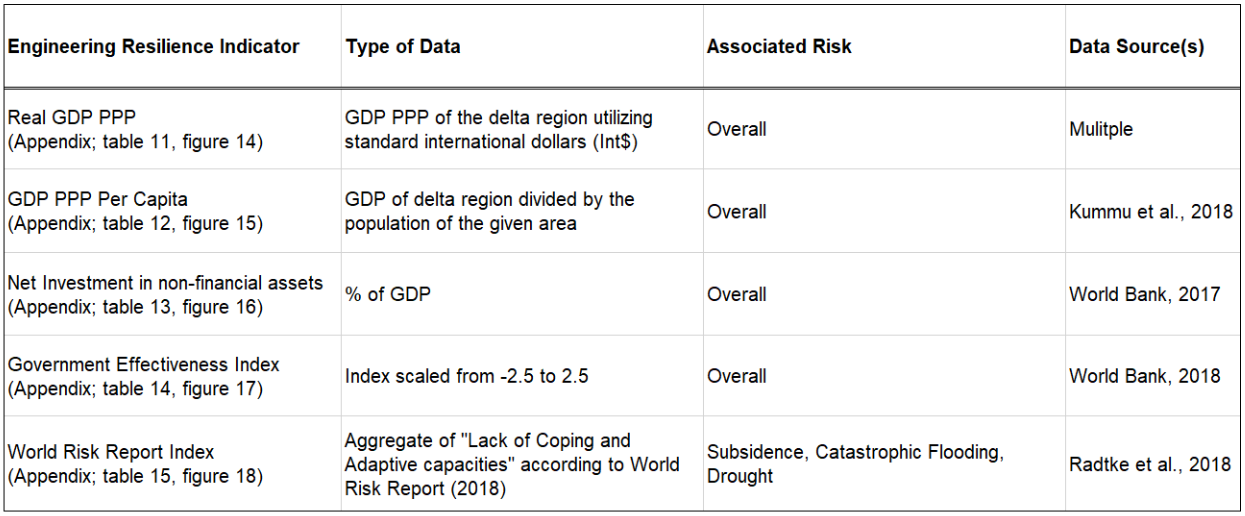
1)Real GDP aggregate PPP of the delta area (Regional or National) - Gross Domestic Product (GDP) is the aggregate total of the goods and services provided within the territory. Utilizing “real GDP” instead of “nominal GDP” figures takes into account inflation rate has on the actual value of GDP. Purchasing price parity (PPP) takes into account the standard of living and actual in-country value of the standard international dollar (Int$). This indicator will infer the concentration of assets that are worth safeguarding (Tessler et al. 2015). Additionally, high aggregate GDP for the nation or state within a nation suggests strong structural economic power and adequate engineered infrastructure to handle disaster events such as flood barriers and pumping stations. Sources on GDP figures range from international organizations (e.g. World Bank, IMF), national databases, and primary sources.

2)GDP per capita PPP (Regional) - Per-capita GDP is the GDP of the area divided by the population of the given area. Higher GDP per capita indicates more robust homes and better community infrastructure which reduces vulnerability (Tessler et al., 2019). The significance of this indicator differs from the real GDP figures as the latter focuses on regional or national financial preparedness through larger engineering goals (i.e. dams, floodwalls, levees), whereas this indicator focuses on local community responses to perturbations. The data is extracted from a global gridded dataset which extrapolated subnational GDP per capita figures based on administrative boundaries (Kummu et al., 2018).

3)Net investment in nonfinancial assets (% of GDP) - Net investments in national governments which do not include financial assets. This includes, “fixed assets, inventories, valuables, and non-produced assets” (World Bank, “Metadata for Net investment in nonfinancial assets”). Although this can assume a broad range which might fall outside of the scope of engineering resilience based ecological management, it can indicate the amount of significance a country places on public investment in infrastructure that bolsters resilience capacities within a single system state. Data is sourced from the World Bank database.

4)Government Effectiveness - An index created by the World Bank that measures metrics such as the quality of public services and civil service, rate of policy formulation and implementation, and the level of credibility of governments (Guisan, 2009). This index implies, broadly, the ability of the national government to allocate resources and construct short-to-long term plans to tackle issues. The World bank data is scaled from -2.5 to 2.5 where the minimum connotes negative effectiveness, the maximum connotes perfect effectiveness, and null being average.

5)Scores of Lack of Coping/Adaptive Characteristics (World Risk Report 2018) - The World Risk Report was published in 2018 by the Institute for International Law of Peace and Armed Conflict (IFHV) at Ruhr University and the Bündnis Entwicklung Hilft organization (Alliance Development Helps). This report includes a country specific index of a sampling of the countries’ engineering resilience capacities to prepare and mitigate against disaster scenarios (perturbations) (Radtke et al, 2018). Specifically the organization measured “coping capacities” (persistence capacities) which includes governmental disaster preparedness strategies, level of medical services and insurance coverage, and “adaptation capacities” which includes education of the population, a gender equality index, environmental status, and level of investment in public services (Radtke et al, 2018). In this case, the “lack of coping capacities” and “lack of adaptation capacities” indexes within the World Risk Report were aggregated to understand how a well-cited international organization understands the engineering resilience capabilities of nations. The exclusion of “transformative capacities” also indicates an implicit engineering resilience focus of the organization. Additionally, indexes like these directly influence both international and domestic policies and help shape future development towards bolstering engineering resilience capacities.



Engineering Resilience Indicator	**Type of Data**	**Associated Risk**	**Data Source(s)**
Real GDP PPP (Appendix; table 11, figure 14)	GDP PPP of the delta region utilizing standard international dollars (Int$)	Overall	Mulitple
GDP PPP Per Capita (Appendix; table 12, figure 15)	GDP of delta region divided by the population of the given area	Overall	Kummu et al., 2018
Net Investment in non-financial assets (Appendix; table 13, figure 16)	% of GDP	Overall	World Bank, 2017
Government Effectiveness Index (Appendix; table 14, figure 17)	Index scaled from -2.5 to 2.5	Overall	World Bank, 2018
World Risk Report Index (Appendix; table 15, figure 18)	Aggregate of "Lack of Coping and Adaptive capacities" according to World Risk Report (2018)	Subsidence, Catastrophic Flooding, Drought	Radtke et al., 2018

Table 3: List of the engineering resilience indicators used for the index. Description of data used, associated risks, and data sources are also included.

5. Result: Indexing Global Delta Systems (SRQ #3)

The resilience equal weighted stack charts (figures 5 & 6) and the overall resilience index (table 4) are presented below. Additionally, a comparison plot chart (figure 7) is presented to illustrate the difference in paradigm ranking for each delta. Deltas with higher overall resilience scores represented higher alignment to the objectives set by the resilience paradigms' management as presented in chapters 3 & 4. Tables for each resilience indicator datasets within the equal weighted stack charts are located in the Appendix (pp. 43-53). Furthermore, some of the key findings were also observed.

Overall, the ecological resilience scores ranged from 2.179 - 4.757 (table 4). The top 3 resilience scores from most to least resilient were as follows: Volta (4.757), Orinoco (4.605), and Lena (4.506). The bottom 3 ecological resilience scores were: Rhine (2.770), Yangtze (2.574), and Nile (2.179). Conversely, the engineering resilience score ranged from 0.495 - 3.583. The top 3 resilience scores from most to least resilient were as follows: Rhine (3.583), Mississippi (2.974), Yangtze (2.679). The bottom 3 engineering resilience scores were Ganges (0.877), Indus (0.651), and Orinoco (0.495). The engineering resilience index also displayed higher variation and lower average compared to the ecological resilience index (table 4).

Due to the equal weight and range standardization imposed onto the indicators, single indicators can greatly skew the overall score stack given to the deltas. For example, within the ecological resilience index the Rhine is given a score of 0 for the DIN index meanwhile its other indicator scores were high or average. Conversely, within the engineering resilience index, the Volta had relatively low scores for most of the indicators but exhibited a high score for 'Net Investment' which lifted its comparative ranking.

No Correlation – A Spearman correlation coefficient (rho) of -0.161 was observed between the ecological and engineering resilience rankings (figure 8). A p-value of 0.5667 was obtained which infers an acceptance of the null hypothesis put forth in the research design: There is no statistically significant difference between how deltas are assessed under the two resilience paradigms when utilizing correlation. In other words, overall, the level of resilience within one paradigm does not affect the resilience of the level of resilience in the other. However, when looking at individual deltas in the comparison chart (figure 7), some key points can be inferred.

The Rhine and Yangtze exhibited very high engineering resilience and very low ecological resilience, which would indicate a very industrial and urbanized delta society yet with some lacking ecological resilience capacities. The Orinoco and Amazon exhibited very high ecological resilience and very low engineering resilience, which would be indicative of a more intact ecosystem, yet underdeveloped. A few deltas exhibited high relative resilience for each paradigm such as the Mississippi, Yellow and Lena. This would indicate that these deltas are sustainably managed and balanced within each resilience paradigm. The Nile, Krishna Ganges, and Indus exhibited low resilience in each paradigm. This could indicate that there tipping points are more likely to occur and that the society living in that delta is lacking preparedness.

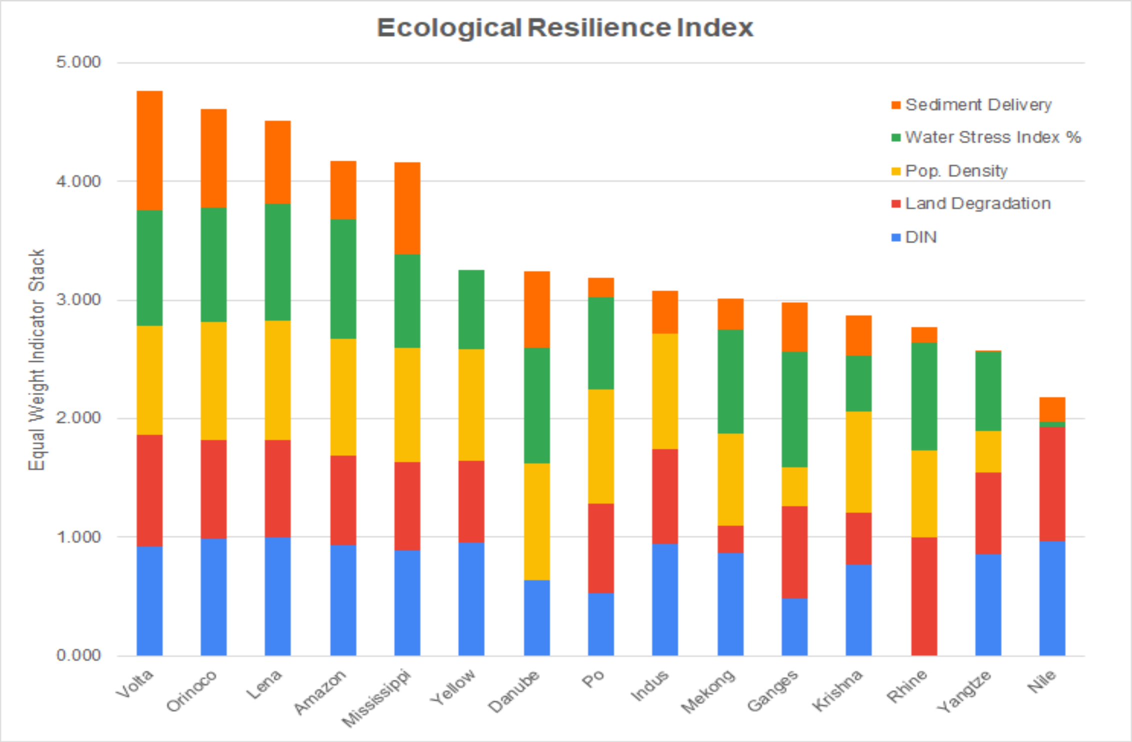


Figure 5: Ecological resilience Index for the 15 deltas in this study. This index is constructed from the aggregation of equal weighted scores of 5 indicators, ranging from national to regional data (footnotes are available in the appendix).

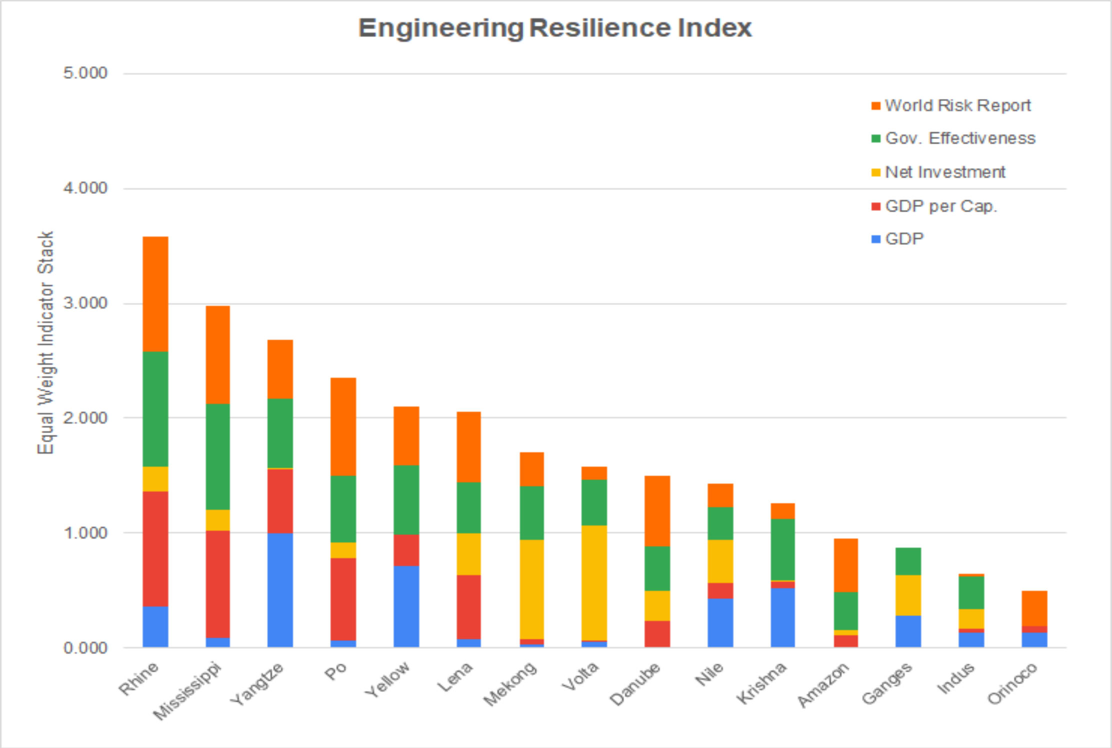


Figure 6: Engineering resilience Index for the 15 deltas in this study. This index is constructed from the aggregation of equal weighted scores of 5 indicators, ranging from national to regional data (footnotes are available in the appendix).

Delta	Country	Ecological Resilience Score	Engineering Resilience Score	Ecological Rank	Engineering Rank
1)Rhine	Netherlands	2.770	3.583	3	15
2)Mississippi	U.S.A	4.160	2.974	11	14
3)Yangtze	China	2.574	2.679	2	13
4)Yellow	China	3.247	2.102	10	11
5)Po	Italy	3.181	2.352	8	12
6)Nile	Egypt	2.179	1.436	1	6
7)Amazon	Amazon	4.174	0.955	12	4
8)Mekong	Vietnam	3.011	1.698	6	9
9)Lena	Russia	4.506	2.053	13	10
10)Danube	Romania	3.241	1.503	9	7
11)Ganges	Bangladesh	2.976	0.877	5	3
12)Indus	Pakistan	3.080	0.651	7	2
13)Krishna	India	2.869	1.260	4	5
14) Orinoco	Venezuela	4.605	0.495	14	1
15)Volta	Ghana	4.757	1.578	15	8
	Average	3.422	1.746		
	Stdv	0.778	0.853		
	CV	22.721	48.825		

Table 4: Final cumulative results of each paradigms' resilience scores for each delta. The deltas are ranked accordingly from 1-15 (1 being least resilient and 15 being most resilient). Averages, standard deviations, and coefficients of variation (CV) are also given for each resilience score.

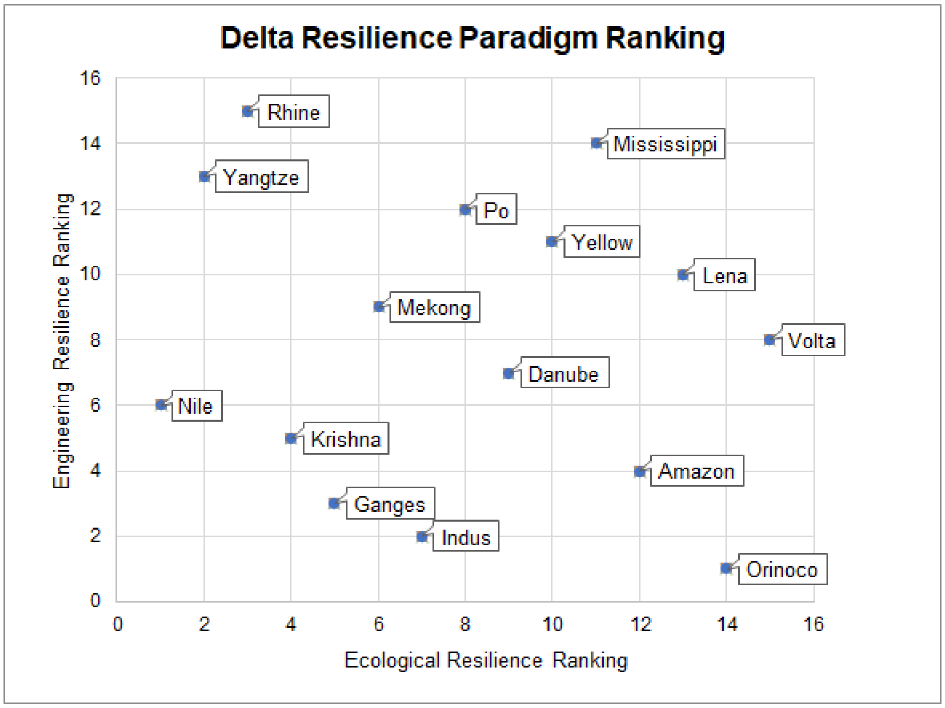
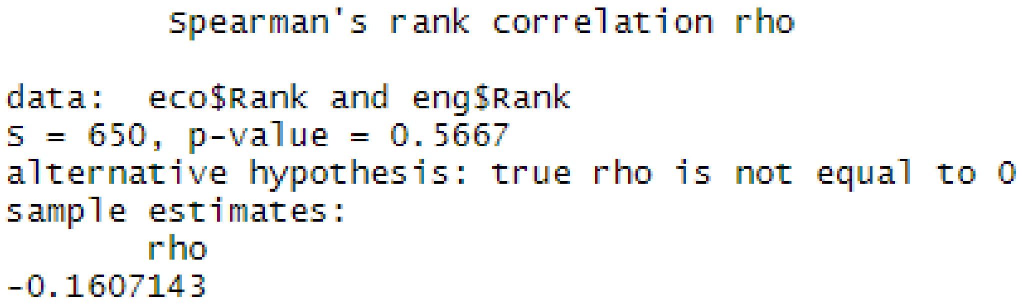


Figure 7: Resilience ranking comparison chart of the effectiveness rankings of the 15 coastal deltas according to their two resilience management styles. Deltas are ranked accordingly from 1-15 (1 being least resilient and 15 being most resilient).



```
          Spearman's rank correlation rho

data:  eco$Rank and eng$Rank
S = 650, p-value = 0.5667
alternative hypothesis: true rho is not equal to 0
sample estimates:
       rho 
-0.1607143 
```

Figure 8: Spearman’s rank correlation test in R. A p-value of 0.5667 was observed which is higher than 0.05 and thus not statistically significant. The correlation coefficient of -0.1607 (rho) was also observed which signifies a low negative correlation.

6. Discussion

6.1 Interpretation of the Results

The results from this research indicate low negative correlation and subsequently no statistical significance between the resilience scores of each delta. The null hypothesis is then accepted and, in other words, the level of resilience within one paradigm does not affect the resilience of the level of resilience in the other. This would imply that this delta resilience analysis should be done on a case-by-case basis, and that the argument supporting the idea of a pure dichotomy can be mistaken, given these results. Certain deltas within the indexes did exhibit large spread between resilience paradigm rankings such as the Rhine, Yangtze, Amazon, and Orinoco. However, some of the other deltas, such as the Krishna, Ganges, Yellow, Mississippi exhibit close to a positive correlation between the two paradigms. In terms of management, it would be helpful to utilize these results as a potential tool to understand which dimension of resilience is lacking rather than seeking a correlation. However, these mixed and inconclusive results may also be due to the overarching complexity and uncertainty of contextualizing complex systems and resilience-based management, which are at the root of the limitations of these results and of the methodology of the research overall.

6.2 Limitations of the Research

Due to the level of abstraction surrounding the concept of resilience and the difficulty/uncertainty of analyzing complex systems on any level, there are limitations in conducting research in this way. There still is also little consensus on the correct way to understand how to measure resilience itself in complex systems. This creates more flexibility on the design of this research, however, unfortunately, can also imply inadequate credible theoretical backing. Gathering statistical conclusions to answer qualitative research questions can also be subject to dispute. This could potentially also stem from the sample of indicators utilized to understand them.

The use of multiple sources within the same dataset can be problematic as displayed in each of the indicator tables in the appendix. This is due to the variability in methods used which can greatly skew the data. Unfortunately, this limitation was due to the unavailability of specific delta data within any single sources. Additionally, some of the methods used within certain indicators (especially with the UNSDG indicator data) could be problematic as the data is often self-reported by the country itself. Depending on the reliability of the specific country, the data could be embellished or altered in order to rank favorably in comparison to other countries. The use of non-regional data in some datasets were also problematic in terms of scalability especially for larger countries such as India, China, Russia, Brazil, and the U.S.A. Unfortunately, due to the inability of comprehensively interpreting coastal delta systems by their component parts (this is again due to the complexity of these systems), this was the most reasonable path of understanding resilience of these systems. Within the indexing itself, this unavailability of data limited the method that this research utilized.

In conjunction with the fact that the variability of methods within single indicators can skew the overall result, the indexing methods of range-standardization and equal weight stacking also can cause a skewing within the delta ranking. Within indicators that have outliers, such as the

Rhine in the DIN load index (figure 9), range-standardization would give the delta a zero score, meanwhile every other delta is given a relatively high score. When aggregating with indexes such as these, the overall scores would give results that would indicate that each individual indicator index is given an outsized importance. Alternative indicators were introduced to balance these outliers but were unfortunately rejected because of the limited availability of data in the datasets. These unavoidable conditions pose many limitations to this research overall, however, also presents many opportunities for future development into the topic.

6.3 Going Forward

As noted previously, the main aim of this report was not to make a definite and comprehensive quantitative conclusion on the resilience of coastal deltas. Rather, the goal of this research was to reveal the potentially problematic dichotomy in thinking of resilience-based ecosystem management and its role in coastal delta societies. Although there was not a statistically significant relationship to support this, the inconclusive results presented in this research can, in fact, open up research opportunities going forward.

The limitations of this research, mainly dealing with complex systems thinking, should be addressed with further research and with a transdisciplinary approach. Moreover, there should be honest discussion within the scientific and political communities to come to a consensus on the management of coastal deltas. Therefore, an increase in transdisciplinary research into deltas should be considered to completely understand the many components and interactions that influence deltas both biophysically and socio-economically that can be applied across all deltas. As mentioned multiple times in this report, it is incredibly difficult to both understand and apply management to complex systems but can be done through dialogue and consensus. This further exploration would also help develop more indicators to help diagnose the level of resilience in deltas for indexing. Adding more indicators with complete datasets and also broadening the number of deltas studied would mitigate the extreme weighted scoring values given to each delta. These measures could possibly give radically alternative results compared to the results presented in this research which may support the original hypothesis. Nonetheless, within the literature and theory, it still indicates a significant dichotomy between the paradigms. An alternative form of resilience could be developed further to address the fundamentalism presented by both paradigms.

As it stands, resilience in ecological management can be viewed as a coin with two sides: engineering and ecological. Utilizing “resilience” in either context to argue for ecological management practices could have radically different conclusions in the future. A perspective to circumvent this limitation is to take a ‘strong sustainability’ approach where human capital and natural capital are intertwined and the impact on one will inevitably affect the other (Noel and O’Connor, 1998). A new form of resilience thinking, known as socio-ecological resilience, started to develop at the turn of the 21st century which utilizes adaptive management as its core tenet (Folke et al., 2016). For this paradigm to be effective, though, constant monitoring and update of information of certain system components is required (Gunderson 2000). Additionally, consensus from the delta society, especially in democratic societies, is needed as there is an inherent allowance of multiple, sometimes undesirable system states (Chaffin & Scown, 2018). The potential importance of this perspective comes from the increasingly deep uncertainty in global changes such as in the effects of climate change pushing systems towards critical transitions, whilst still allowing for human communities to thrive.

7. Conclusion

Resilience theory and its relevance in current environmental management such as within coastal deltas is a relatively recent concept which has the inherent implication of multiple and sometimes contradictory interpretations. The two prominent resilience paradigms that are nested within the scope of environmental resilience, ecological and engineering resilience, can be conflated within policy discussions. However, within the literature, this clear dichotomy and even opposition between the two, manifests itself in differing and counterproductive environmental management goals especially in coastal deltas. Specifically, ecological resilience places emphasis on allowances for multiple ecological states to maintain dynamic stability and engineering resilience emphasizes on anthropomorphic control over these states to maintain functional stability. Utilizing and aggregating indicators to diagnose and rank index the performance of 15 diverse coastal deltas worldwide based on the two resilience management paradigms' goals was hypothesized to yield a negative correlation between the two resilience rankings. The results instead indicated that there was no significant relationship, in either direction, between the two indexes. This null hypothesis would indicate that in some instances, this report's hypothesis holds true, and goes against it within other deltas. While these results are still useful, further research into understanding and addressing certain limitations to this research, such as the lack of data and unclear way to understand complex systems, would help make the results less opaque. Nonetheless, collaboration and dialogue between these two resilience paradigm communities must still be done to address their own limitations and to help better develop a more robust hybrid paradigm such as the socio-ecological resilience-based management model.

8. References

Allen, C.R, Angeler, D.G, Chaffin, B.C, Twidwell, D., and Garmestani, A. (2019). Resilience Reconciled. *Nature; Sustainability*. doi:10.1038/s41893-019-0401-4

Appl, M. (1982). "The Haber–Bosch Process and the Development of Chemical Engineering". A Century of Chemical Engineering. *New York: Plenum Press*. pp. 29–54. ISBN 978-0-306-40895-3.

Baho DL, Allen CR, Garmestani AS, Fried-Petersen HB, Renes SE et al. (2017) A quantitative framework for assessing ecological resilience. *Ecol Soc* 22(3):17. https://doi.org/10.5751/ES-09427-220317

Benton TG, Fairweather D, Graves A, Harris J, Jones A, Lenton T, Norman R, O'Riordan T, Pope E, Tiffin R. (2017). Environmental Tipping Points and Food System Dynamics: Main Report. *Global Food Security*.

Bot, A.J., Nachtergaele, F.O. and Young, A. (2000) Land Resource Potential and Constraints at Regional and Country Levels. *Rome, FAO, World Soil Resources Report No. 90*, ftp://ftp.fao.org/agl/agll/docs/wsr.pdf.

Bureau of Economic Analysis (2020) Gross Domestic Product by State, 4th Quarter and Annual 2019. *BEA*. Accessed at: https://www.bea.gov/system/files/2020-04/qgdpstate0420.pdf

Chaffin, B., & Scown, M. (2018). Social-ecological resilience and geomorphic systems. *Geomorphology*, 305(1), 221–230.

CIA (2017) GDP PPP: Venezuela. *Field Listing - GDP PPP CIA World Factbook* Accessed at: https://www.cia.gov/library/publications/the-world-factbook/rankorder/2001rank.html

Dumont, E., J. A. Harrison, C. Kroeze, E. J. Bakker, and S. P. Seitzinger (2005), Global distribution and sources of dissolved inorganic nitrogen export to the coastal zone: Results from a spatially explicit, global model, Global Biogeochem. *Cycles*, 19, GB4S02, doi:10.1029/2005GB002488.

Dunn F., Darby S., Nicholls R., Cohen S., Zarfl C., Fekete B. (2019) Projections of declining fluvial sediment delivery to major deltas worldwide in response to climate change and anthropogenic stress. *Environ. Res. Lett.* 14 084034

Elvin, Mark & Cuirong, Liu (1998) From the Yellow River to the Huai. Sediments of Time: Environment and Society in Chinese History. Pp 548-552*. Cambridge University Press*. ISBN 0-521-56381-X

Ericson, Jason P, Charles J Vorosmarty, S Lawrence Dingman, Larry G Ward and Michel Meybeck (2006), "Effective sea-level rise and deltas: causes of change and human dimension implications", *Global and Planetary Change* Vol 50, pages 63–82.

Erkens G, Bucx T, Dam R, De Lange G, Lambert J (2014) Sinking coastal cities. *Geophys Res Abstr 16, EGU2014-14606, EGU General Assembly*

Eurostat (2017) Gross domestic product (GDP) at current market prices by NUTS 2 regions. *European Statistical Office*. Accessed at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nama_10r_2gdp&lang=en

FAO (2013) Chapter 3. Fertilizers in Ghana. *Fertilizer Use by Crop in Ghana* Accessed at: http://www.fao.org/3/a0013e/a0013e07.htm#TopOfPage

Folke, C., Carpenter, S., Walker B., Scheffer, M., Elmqvist, T., Gunderson, L., Holling, C.S. (2004). Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. *Annual Review of Ecology, Evolution, and Systematics.* 35:1, 557-581

Folke, C., R. Biggs, A. V. Norström, B. Reyers, and J. Rockström (2016) Social-ecological resilience and biosphere-based sustainability science*. Ecology and Society* 21(3):41.

Fricke AT, Nittrouer CA, Ogston AS, Nowacki DJ, Asp NE, Souza Filho PW (2019). Morphology and dynamics of the intertidal floodplain along the Amazon tidal river*. Earth Surface Processes and Landforms* 44: 204– 218. https://doi-org.proxy.library.uu.nl/10.1002/esp.4545

Frihy, O. E. (2003). The Nile delta-Alexandria coast: vulnerability to sea-level rise, consequences, and adaptation. *Mitigation and Adaptation Strategies for Global Change,* 8 (2), 115-138.

Gebremichael, E., Sultan, M., Becker, R., El Bastawesy, M., Cherif, O., & Emil, M. (2018). Assessing land deformation and sea encroachment in the Nile Delta: a radar interferometric and inundation modeling approach*. Journal of Geophysical Research: Solid Earth* , 123 (4), 3208-3224.

Grafton, R.Q.; Doyen, L.; Béné, C.; Borgomeo, E.; Brooks, K.; Chu, L.; Cumming, G.S.; Dixon, J.; Dovers, S.; Garrick, D. (2019). Realizing resilience for decision-making. *Nat. Sustain.,* 2, 907–913.

Guisan, M.C. (2009) Government effectiveness, education, economic development, and well-being: analysis of European countries in comparison with the US and Canada. *University of Santiago.* Accessed at: http://www.usc.es/economet/reviews/aeid914.pdf

Gunderson, Lance (2000) Ecological Resilience—In Theory and Application. *Annu. Rev. Ecol. Syst*. 2000. 31:425–39

Gustafson, E. J., A. M. G. De Bruijn, R. E. Pangle, J. M. Limousin, N. G. Mcdowell, W. T. Pockman, B. R. Sturtevant, J. D. Muss, and M. E. Kubiske (2014), Integrating ecophysiology and forest landscape models to improve projections of drought effects under climate change, *Global Change Biol*., 21(2), 843–856

Harrison JA, Caraco N, Seitzinger SP. 2005. Global patterns and sources of dissolved organic matter export to the coastal zone: results from a spatially explicit, global model. *Global Biogeochem Cycles 19(4), Art. no. GB4S04*.

Hill, C., Dunn, F., Haque A., Amoako-Johnson, F., Nicholls R., Raju, P., Addo K. (2020) Hotspots of Present and Future Risk Within Deltas: Hazards, Exposure and Vulnerability. In: Nicholls R., Adger W., Hutton C., Hanson S. (eds) *Deltas in the Anthropocene. Palgrave Macmillan, Cham*. https://doi.org/10.1007/978-3-030-23517-8_6

Hogarth, P. (2007). The biology of mangroves and seagrasses. *Oxford University Press*. p. 222. ISBN: 9780198716549

Holling C. S. (1973) Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, Vol. 4 (1973), pp. 1-23

Holling, C.S. (1996) Engineering Resilience versus Ecological Resilience. In: Schulze, P.E., Ed., *Engineering within Ecological Constraints, National Academy Press*, Washington DC, 31-43.

Hooper, D.U., Chapin III, F.S., Ewel, J.J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J.H., Lodge, D.M., Loreau, M., Naeem, S., Schmid, B., Seta¨la¨, H., Symstad, A.J., Vandermeer, J., Wardle, D.A., (2005). Effects of biodiversity on ecosystem functioning: a consensus of current knowledge*.* *Ecological Monographs* 75, 3–35.

IBGE (2014) Regional Accounts 2012. *Brazilian Institute of Geography and Statistics.* [online] Accessed at: https://www.ibge.gov.br/en/home-eng.html

IMF (2019) Real GDP Country Group Tables*, International Monetary Fund*. Accessed [online]: https://www.imf.org/external/pubs/ft/weo/2019/02/weodata/download.aspx .

Keller, J, A Keller and G Davids (1998). River basin development phases and implications of closure. *Journal of Applied Irrigation Science* 33(2):145-164.

Klaghofer, E., Hintersteiner, K., Summer W. (2002)Trends in soil erosion and sediment yield in the alpine basin of the Austrian Danube. *Modelling erosion, sediment transport and sediment yield.* pp. 195-203

Konrad C.P (2003) Effects of urban development on floods. *Fact Sheet 076-03. Reston, VA: US Geological Survey*, 4 pp

Kummu M, Taka M, Guillaume JHA (2018) Gridded global datasets for Gross Domestic Product and Human Development Index over 1990-2015. Scientific Data 5: 180004. https://doi.org/10.1038/sdata.2018.4*. Accessed through Resource Watch. www.resourcewatch.org*

Langdon, P., Dearing, J.A, Dyke, J.G., Wang, R. (2016) Identifying and anticipating tipping points in lake ecosystems. *Pages.* Vol. 24.

Liljeström,I., Kummu, M., & Olli, V. (2012) Nutrient Balance Assessment in the Mekong Basin: Nitrogen and Phosphorus Dynamics in a Catchment Scale. *International Journal of Water Resources Development,* 28:2, 373-391, DOI: 10.1080/07900627.2012.668649

Minderhoud, P. S. J., Coumou, L., Erkens, G., Middelkoop, H., & Stouthamer, E. (2019). Mekong delta much lower than previously assumed in sea-level rise impact assessments. *Nature Communications*, 10(1). doi: 10.1038/s41467-019-11602-1

Nicholls R., Adger W., Hutton C., & Hanson S. (2020) Delta Challenges and Trade-offs from the Holocene to the Anthropocene. *Deltas in the Anthropocene. Palgrave Macmillan, Cham.* Ch.1. pp. 1-17

Nienhuis, J., Ashton, A., Edmonds, D., Hoitinik, A., Kettner, A., Rowland, J. & Tornqvist, T. (2020). Global-scale human impact on delta morphology has led to net land area gain. *Nature.* 577.

Noël, J-F., O'connor, M. (1998). Strong Sustainability and Critical Natural Capital. In : Faucheux, S., O'Connor, M., (Eds.), *Valuation for Sustainable Development: Methods and Policy Indicators. Edward Elgar Publisher, Cheltenham*, pp. 75–99.

OECD (2015). Regional Economy: Millions USD, constant prices, constant PPP*. OECD https://stats.oecd.org/Index.aspx?QueryId=84707*.

Pimm, S.L.; Donohue, I.; Montoya, J.M.; Loreau, M. (2019) Measuring resilience is essential to understand it. *Nature Sustainability*. 2, 895–897.

Quinlan, A. E., M. Berbés-Blázquez, L. J. Haider, and G. D. Peterson. (2016). Measuring and assessing resilience: broadening understanding through multiple disciplinary perspectives. *Journal of Applied Ecology* 23:677-687.

Radtke K., Heintze HJ., Kirch L., Kuppers B., Mann H., Mischo F., Mucke P., Pazdzierny T., Prutz R., Strube F., Weller D. (2018) World Risk Report 2018. *IFHV & BEJ.*

Rahman, M., Penny, G., Mondal, M., Zaman, M., Kryston, A., Salehin, M., Nahar, Q., Islam, M., Bolster, D., Tank, J., et al. (2019). Salinization in large river deltas: Drivers, impacts and sociohydrological feedbacks. Water security, 6:1–8.

Rogers, J. D., Kemp, G. P., Bosworth, H. J., & Seed, R. B. (2015). Interaction between the US Army Corps of Engineers and the Orleans Levee Board preceding the drainage canal wall failures and catastrophic flooding of New Orleans in 2005. *Water Policy*, 17(4), 707-723.

Shindo J (2013) Nitrogen Flow Model as a Tool for Evaluation of Environmental Performance of Agriculture and Effects on Water Environment. *Journal of Developments in Sustainable Agriculture* 8, 1–2.

Scheffer, M., J. Bascompte, W. A. Brock, V. Brovkin, S. R. Carpenter, V. Dakos, H. Held, E. H. van Nes, M. Rietkerk, and G. Sugihara. (2009). Early-warning signals for critical transitions. *Nature* 461: 53–59.

Sills, G., Vroman, N., Wahl, R., & Schwanz, N. (2008). Overview of New Orleans levee failures: Lessons learned and their impact on national levee design and assessment. *Journal of Geotechnical and Geoenvironmental Engineering*, 134(5), 556–565.http://dx.doi.org/10.1061/(ASCE)1090-0241

Smit, B., Wandel, J., (2006). Adaptation, adaptive capacity, and vulnerability. *Global Environmental Change* 16 (3), 282–292.

Smith, W (2013). Agriculture in the central Mekong Delta: Opportunities for donor business engagement. Accessed online (30/7/20): https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/9060.pdf

Solow, Robert M (1992) An almost practical step toward sustainability. Washington, DC: *Resources for the Future*

Stone, Richard (2011) The legacy of the Three Gorges dam. *Science* 333, 817 DOI: 10.1126/science.333.6044.817

Stouthamer E., Berendsen, H. (2001). Avulsion Frequency, Avulsion Duration, and Inter Avulsion Period of Holocene Channel Belts in the Rhine-Meuse Delta, The Netherlands. *Journal of Sedimentary Research.* 71 (4): 589–598.https://doi.org/10.1306/112100710589

Tanner, T., Bahadur, A. and Moench, M. (2017). Challenges for resilience policy and practice. *London: Overseas Development Institute*.

Tockner, K.; Uehlinger, U.; Robinson, C. T.; Siber, R.; Tonolla, D.; Peter, F. D. (2009). "European Rivers". In Lekens, Gene E. (ed.). *Encyclopedia of Inland Waters*. 3. Elsevier. pp. 366–377. ISBN 978-0-12-370626-3.

Tri, H.C, Hens, L., Phuoc, P.M.T, Hung, N.T, Phuong, T.H (2017). A Systematic Approach to the Dilemma Between Flood Vulnerability and Resilience - Review and Concepts. *Vietnam Journal of Science and Technology*.

Tessler, Z. D., Vorosmarty, C. J., Grossberg, M., Gladkova, I., Aizenman, H., Syvitski, J. P. M., & Foufoula-Georgiou, E. (2015). Profiling risk and sustainability in coastal deltas of the world. Science, 349(6248), 638–643. doi: 10.1126/science.aab3574

UNCCD (1994). Article 1 of the Convention text. United Nations Convention to Combat Desertification. *United Nations*. [online] accessed at:

https://www.unccd.int/sites/default/files/relevantlinks/201701/UNCCD_Convention_ENG0.pdf

UN/FAO (2017) Metadata for SDG indicator 6.4.2. *Food and Agriculture Organization of the United Nations*. Access online: https://unstats.un.org/sdgs/metadata/files/Metadata-06-04-02.pdf

UNSDGs (2017) Water Stress Index (%). *UN Statistics Division Database.* Accessed at: https://unstats.un.org/sdgs/indicators/database/

Vitousek, P., H. Mooney, L. Olander, and S. Allison (2002). Nitrogen and nature. *Ambio* 31:97-101.

Volke, M., Scott, M., Cater-Johnson, W., Dixon M. (2015) The Ecological Significance of Emerging Deltas in Regulated Rivers. *BioScience.* Vol. 65 Issue 6. Pp. 598-611, https://doi.org/10.1093/biosci/biv040

Walker, B. Holling, C.S., Carpenter, S.R., Kinzig, A., (2004). Resilience, adaptability, and transformability in social-ecological systems*. Ecology and Society* 9,5.

Walker, B. (2020) Resilience: What it is and is not. *Ecology and Society* 25(2):11.

Wheeler, K. G., Basheer, M., Mekonnen, Z. T., Eltoum, S. O., Mersha, A., Abdo, G. M., Dadson, S. J. (2016). Cooperative filling approaches for the Grand Ethiopian Renaissance Dam. *Water International*, 41(4), 611–634. doi:10.1080/02508060.2016.1177698.

World Bank (2019) World Bank International Comparison Program database: GDP,PPP (Current International $).*World Bank*.

World Bank (2018) Government Effectiveness. *World Bank Database.* Accessed online: https://govdata360.worldbank.org/indicators/h580f9aa5?country=BRA&indicator=388&viz= linechart&years=1996,2018

World Bank (2017) Net Investment in Nonfinancial Assets. *World Bank Database*. Accessed online: https://data.worldbank.org/indicator/GC.NFN.TOTL.GD.ZS

World Bank (2014) Metadata for Net investment in nonfinancial assets. *World Bank.* Accessed online:https://databank.worldbank.org/reports.aspx?source=2&type=metadata&series=GC.NFN.TOTL.GD.ZS

9. Appendix

Ecological Indicator Indexes:

Delta	Country	Basin Area, km2	DIN Load (kg N km-2 yr-1)	Score	Rank	Source
1)Rhine	Netherlands	164,500	2,200.4	0.000	1	Dumont et al., 2005
2)Mississippi	U.S.A	3,191,000	255.6	0.892	8	Dumont et al., 2005
3)Yangtze	China	1,788,000	327.5	0.859	6	Dumont et al., 2005
4)Yellow	China	890,500	120.5	0.954	12	Dumont et al., 2005
5)Po	Italy	70,000	1,053.6	0.526	3	Harrison et al., 2005
6)Nile	Egypt	2,870,000	105.9	0.961	13	Harrison et al., 2005
7)Amazon	Brazil	5,833,000	172.3	0.931	10	Dumont et al., 2005
8)Mekong	Vietnam	2,434,000	304.4	0.870	7	Liljeström, 2012
9)Lena	Russia	2,433,000	21.1	1.000	15	Dumont et al., 2005
10)Danube	Romania	817,000	803.3	0.641	4	Harrison et al., 2005
11)Ganges	Bangladesh	1,050,000	1,139.7	0.487	2	Harrison et al., 2005
12)Indus	Pakistan	1,139,000	136.9	0.947	11	Dumont et al., 2005
13)Krishna	India	228,000	529.8	0.767	5	Shindo, 2013
14) Orinoco	Venezuela	1,100,000	57.4	0.983	14	Harrison et al., 2005
15)Volta	Ghana	407,093	198.6	0.919	9	FAO, Ghana Fertilizer Use 2013

Table 5: DIN Load of the 15 coastal deltas. Utilizing a variety of sources, the annual total kg of DIN (N) was divided by the total basin area (km2). The range-standardization was reversed in this dataset to reflect the highest DIN as the least resilient and the lowest DIN representing the highest resilience in this case.

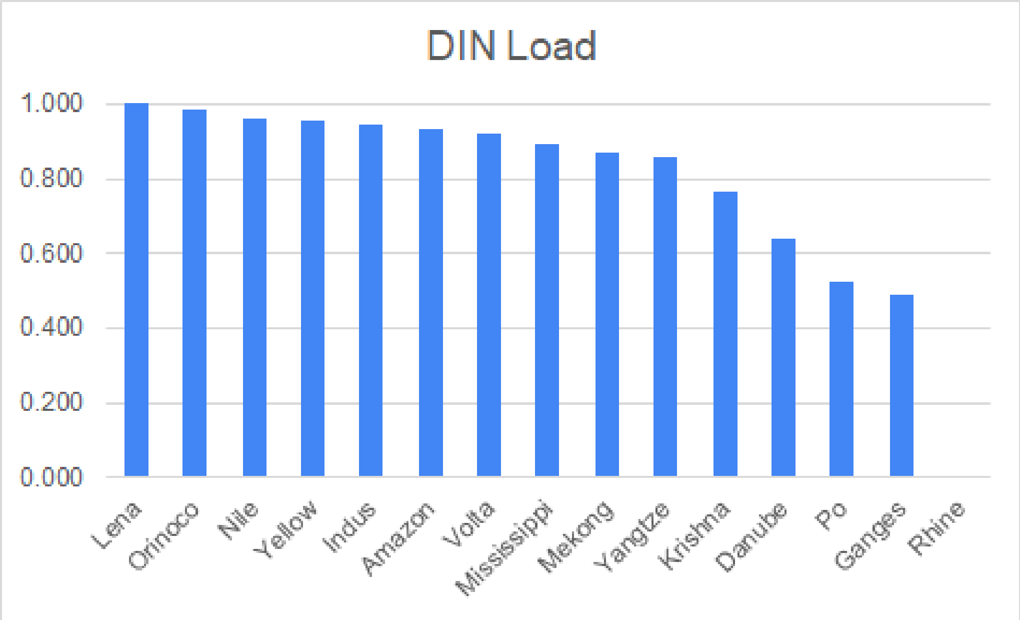
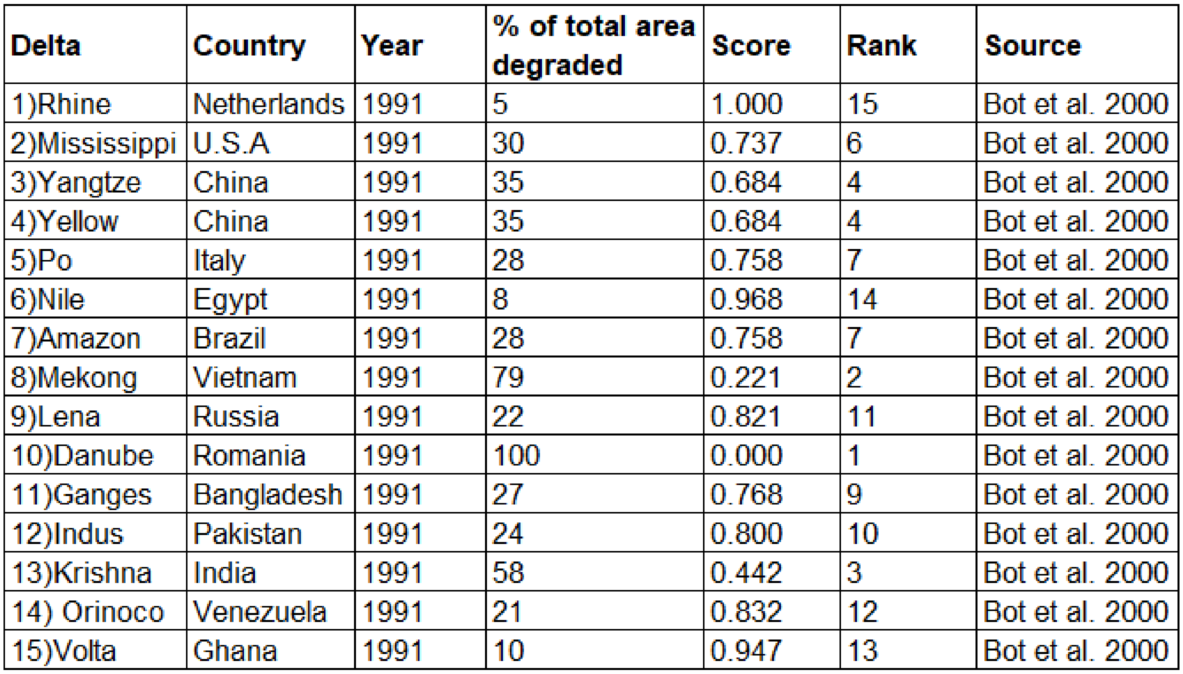


Figure 9: Graph showing the resilience scores of each deltas’ DIN load for each delta.



Delta	Country	Year	% of total area degraded	Score	Rank	Source
1)Rhine	Netherlands	1991	5	1.000	15	Bot et al. 2000
2)Mississippi	U.S.A	1991	30	0.737	6	Bot et al. 2000
3)Yangtze	China	1991	35	0.684	4	Bot et al. 2000
4)Yellow	China	1991	35	0.684	4	Bot et al. 2000
5)Po	Italy	1991	28	0.758	7	Bot et al. 2000
6)Nile	Egypt	1991	8	0.968	14	Bot et al. 2000
7)Amazon	Brazil	1991	28	0.758	7	Bot et al. 2000
8)Mekong	Vietnam	1991	79	0.221	2	Bot et al. 2000
9)Lena	Russia	1991	22	0.821	11	Bot et al. 2000
10)Danube	Romania	1991	100	0.000	1	Bot et al. 2000
11)Ganges	Bangladesh	1991	27	0.768	9	Bot et al. 2000
12)Indus	Pakistan	1991	24	0.800	10	Bot et al. 2000
13)Krishna	India	1991	58	0.442	3	Bot et al. 2000
14) Orinoco	Venezuela	1991	21	0.832	12	Bot et al. 2000
15)Volta	Ghana	1991	10	0.947	13	Bot et al. 2000

Table 6: Percentage of the total land "severe" or "extremely severe" in accordance with the Bot et al., 2000 paper and the GLASOD data. The range-standardization was reversed in this dataset to reflect the highest indicator value as the least resilient and the lowest indicator value representing the highest resilience in this case.

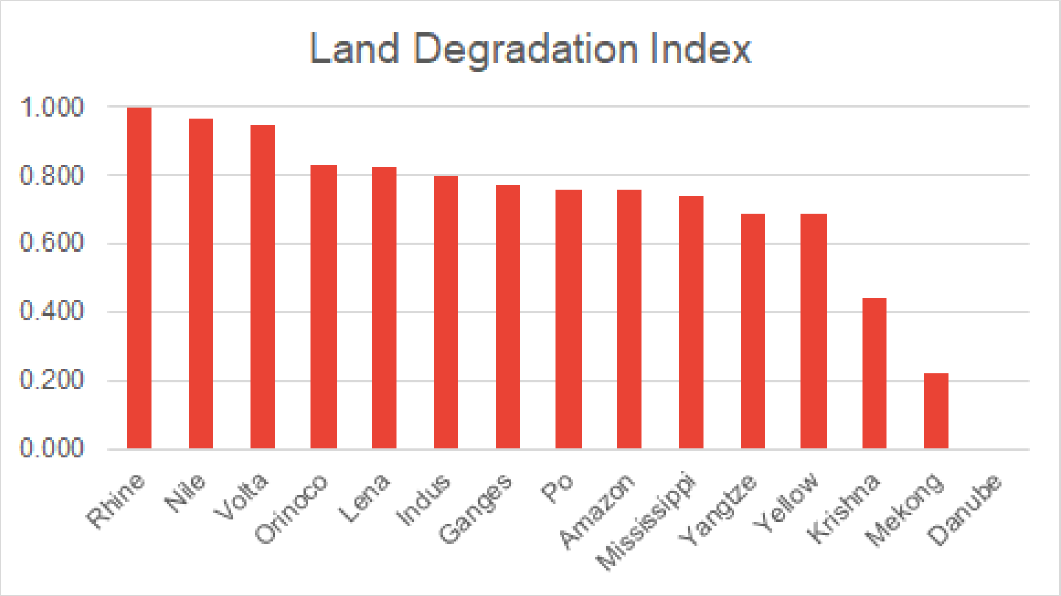
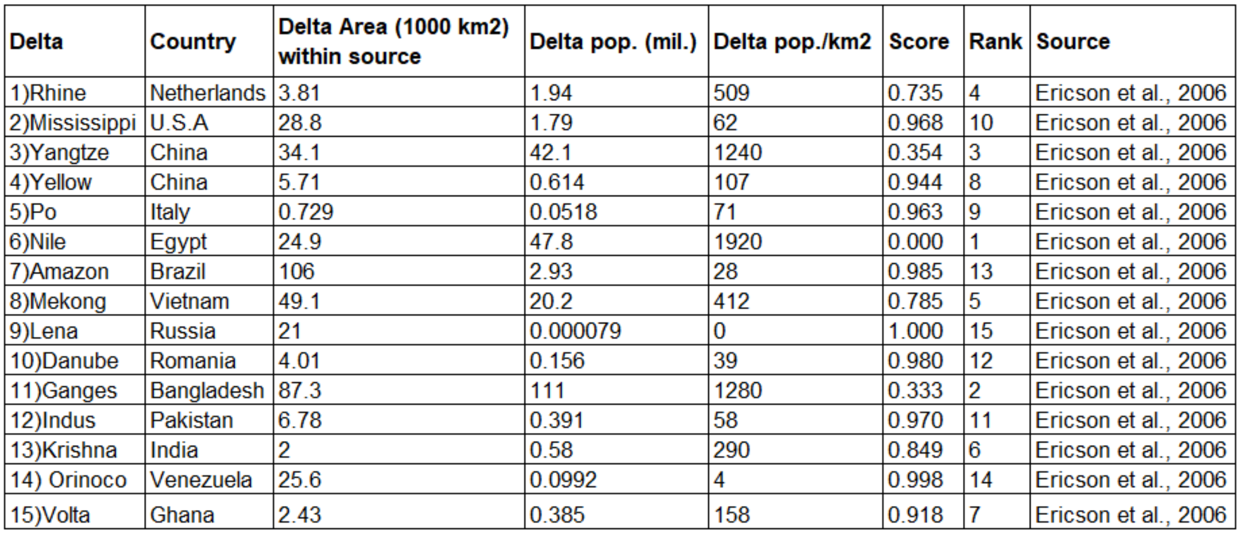


Figure 10: Graph showing the land degradation resilience indicator scores for each delta.



Delta	Country	Delta Area (1000 km2) within source	Delta pop. (mil.)	Delta pop./km2	Score	Rank	Source
1)Rhine	Netherlands	3.81	1.94	509	0.735	4	Ericson et al., 2006
2)Mississippi	U.S.A	28.8	1.79	62	0.968	10	Ericson et al., 2006
3)Yangtze	China	34.1	42.1	1240	0.354	3	Ericson et al., 2006
4)Yellow	China	5.71	0.614	107	0.944	8	Ericson et al., 2006
5)Po	Italy	0.729	0.0518	71	0.963	9	Ericson et al., 2006
6)Nile	Egypt	24.9	47.8	1920	0.000	1	Ericson et al., 2006
7)Amazon	Brazil	106	2.93	28	0.985	13	Ericson et al., 2006
8)Mekong	Vietnam	49.1	20.2	412	0.785	5	Ericson et al., 2006
9)Lena	Russia	21	0.000079	0	1.000	15	Ericson et al., 2006
10)Danube	Romania	4.01	0.156	39	0.980	12	Ericson et al., 2006
11)Ganges	Bangladesh	87.3	111	1280	0.333	2	Ericson et al., 2006
12)Indus	Pakistan	6.78	0.391	58	0.970	11	Ericson et al., 2006
13)Krishna	India	2	0.58	290	0.849	6	Ericson et al., 2006
14) Orinoco	Venezuela	25.6	0.0992	4	0.998	14	Ericson et al., 2006
15)Volta	Ghana	2.43	0.385	158	0.918	7	Ericson et al., 2006

Table 7: Population density of the 15 coastal deltas. The total delta population (mil.) was divided by the total delta area (km2) according to Ericson et al., 2006.. The range-standardization was reversed in this dataset to reflect the highest population density as the least resilient and the lowest population density representing the highest resilience in this case.

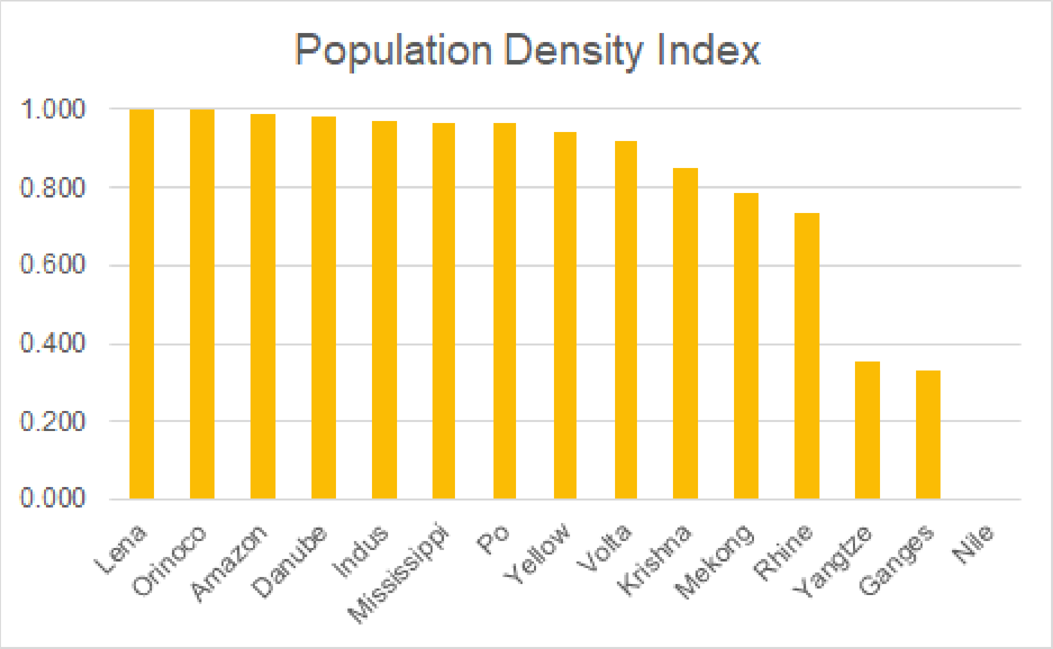


Figure 11: Graph showing the land degradation resilience indicator scores for each delta.

Delta	Country	Year	Indicator 6.4.2	Score	Rank	Source
1)Rhine	Netherlands	2017	15.17	0.899	9	UNSDGs, Water Stress Index (%) 2017
2)Mississippi	U.S.A	2017	28.16	0.791	7	UNSDGs, Water Stress Index (%) 2017
3)Yangtze	China	2017	43.22	0.665	4	UNSDGs, Water Stress Index (%) 2017
4)Yellow	China	2017	43.22	0.665	4	UNSDGs, Water Stress Index (%) 2017
5)Po	Italy	2017	30	0.775	6	UNSDGs, Water Stress Index (%) 2017
6)Nile	Egypt	2017	117.3	0.045	2	UNSDGs, Water Stress Index (%) 2017
7)Amazon	Brazil	2017	3.11	1.000	15	UNSDGs, Water Stress Index (%) 2017
8)Mekong	Vietnam	2017	18.3	0.873	8	UNSDGs, Water Stress Index (%) 2017
9)Lena	Russia	2017	4.1	0.992	14	UNSDGs, Water Stress Index (%) 2017
10)Danube	Romania	2017	6.34	0.973	11	UNSDGs, Water Stress Index (%) 2017
11)Ganges	Bangladesh	2017	5.7	0.978	13	UNSDGs, Water Stress Index (%) 2017
12)Indus	Pakistan	2017	122.69	0.000	1	UNSDGs, Water Stress Index (%) 2017
13)Krishna	India	2017	66.49	0.470	3	UNSDGs, Water Stress Index (%) 2017
14) Orinoco	Venezuela	2017	7.54	0.963	10	UNSDGs, Water Stress Index (%) 2017
15)Volta	Ghana	2017	6.31	0.973	12	UNSDGs, Water Stress Index (%) 2017

Table 8: UN sustainable development goal (UNSDGs) of indicator 6.4.2 or "Water Stress Index (%)" for the countries inhabiting the 15 deltas. The range-standardization was reversed in this dataset to reflect the highest indicator value as the least resilient and the lowest indicator value representing the highest resilience in this case.

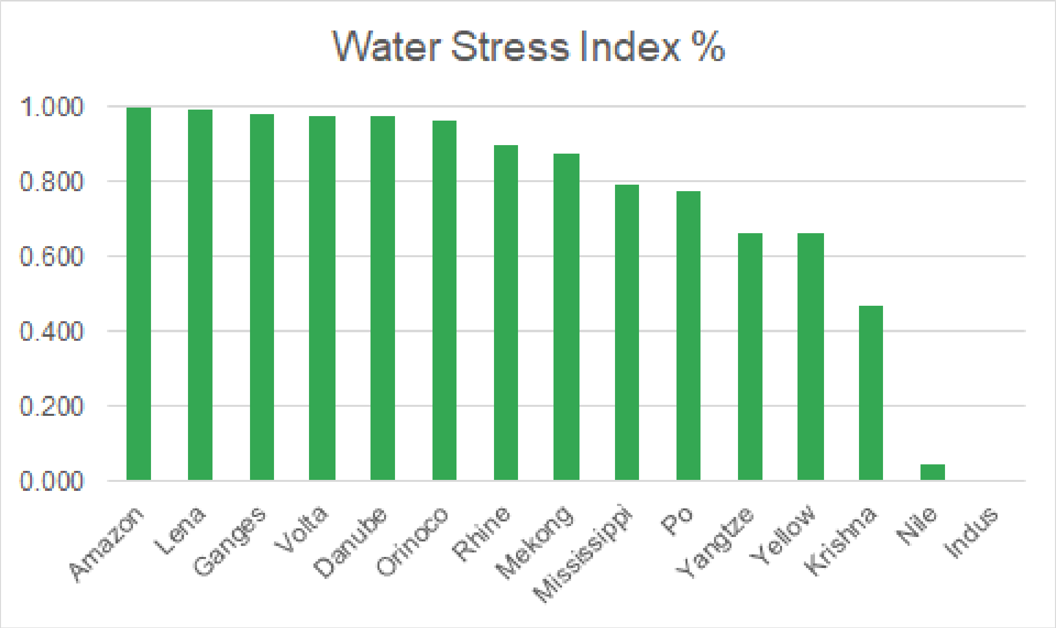


Figure 12: Graph showing the water stress index resilience indicator scores for each delta.

Delta	Country	Year	Change in annual sediment flux (%)	Score	Rank	Source
1)Rhine	Netherlands	1990-2019 to 2070-2099	-33	0.136	3	Dunn et al., 2019
2)Mississippi	U.S.A	1990-2019 to 2070-2099	23	0.773	13	Dunn et al., 2019
3)Yangtze	China	1990-2019 to 2070-2099	-44	0.011	2	Dunn et al., 2019
4)Yellow	China	1990-2019 to 2070-2099	-45	0.000	1	Dunn et al., 2019
5)Po	Italy	1990-2019 to 2070-2099	-31	0.159	4	Dunn et al., 2019
6)Nile	Egypt	1990-2019 to 2070-2099	-27	0.205	5	Dunn et al., 2019
7)Amazon	Brazil	1990-2019 to 2070-2099	-1	0.500	10	Dunn et al., 2019
8)Mekong	Vietnam	1990-2019 to 2070-2099	-22	0.261	6	Dunn et al., 2019
9)Lena	Russia	1990-2019 to 2070-2099	16	0.693	12	Dunn et al., 2019
10)Danube	Romania*	1950-1990	12	0.648	11	Klaghofer et al., 2002
11)Ganges	Bangladesh	1990-2019 to 2070-2099	-9	0.409	9	Dunn et al., 2019
12)Indus	Pakistan	1990-2019 to 2070-2099	-13	0.364	8	Dunn et al., 2019
13)Krishna	India	1990-2019 to 2070-2099	-15	0.341	7	Dunn et al., 2019
14) Orinoco	Venezuela	1990-2019 to 2070-2099	28	0.830	14	Dunn et al., 2019
15)Volta	Ghana	1990-2019 to 2070-2099	43	1.000	15	Dunn et al., 2019
	*=estimated data					

Table 9: Annual sediment flux (%) of the 15 deltas from the period of 1990-2019 to 2070-2099 utilizing data taken from Dunn et al., 2019. Normal range standardization was utilized for the indicator scoring.

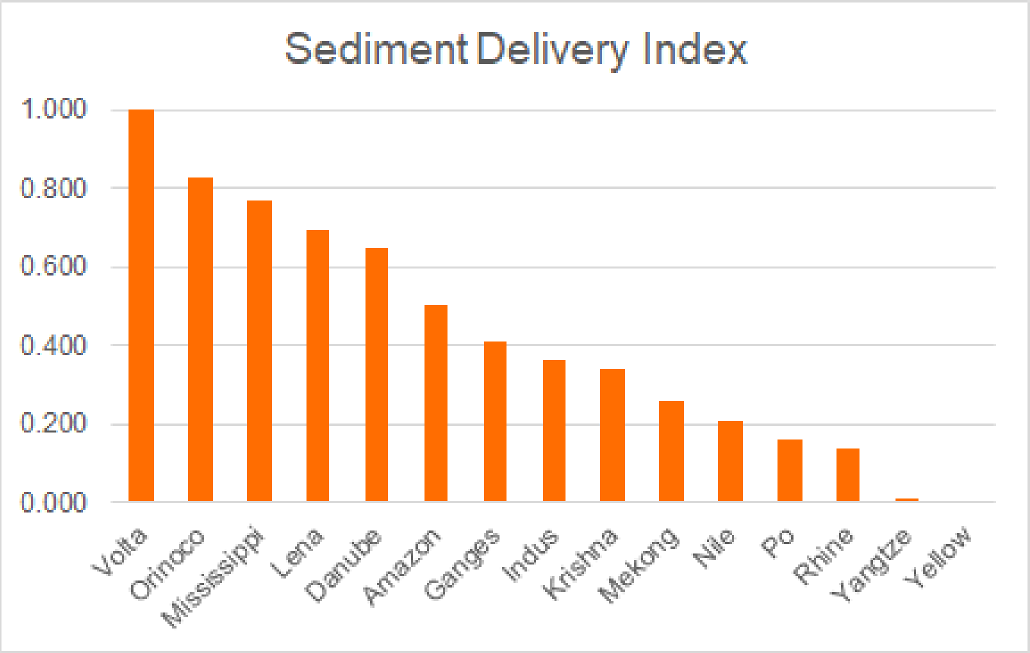


Figure 13: Graph showing the sediment delivery index resilience indicator scores for each delta.

Delta	Country	DIN	Land Degradation	Pop. Density	Water Stress Index %	Sediment Delivery	Resilience Score	Rank
1)Rhine	Netherlands	0.000	1.000	0.735	0.899	0.136	2.770	3
2)Mississippi	U.S.A	0.892	0.737	0.968	0.791	0.773	4.160	11
3)Yangtze	China	0.859	0.684	0.354	0.665	0.011	2.574	2
4)Yellow	China	0.954	0.684	0.944	0.665	0.000	3.247	10
5)Po	Italy	0.526	0.758	0.963	0.775	0.159	3.181	8
6)Nile	Egypt	0.961	0.968	0.000	0.045	0.205	2.179	1
7)Amazon	Brazil	0.931	0.758	0.985	1.000	0.500	4.174	12
8)Mekong	Vietnam	0.870	0.221	0.785	0.873	0.261	3.011	6
9)Lena	Russia	1.000	0.821	1.000	0.992	0.693	4.506	13
10)Danube	Romania	0.641	0.000	0.980	0.973	0.648	3.241	9
11)Ganges	Bangladesh	0.487	0.768	0.333	0.978	0.409	2.976	5
12)Indus	Pakistan	0.947	0.800	0.970	0.000	0.364	3.080	7
13)Krishna	India	0.767	0.442	0.849	0.470	0.341	2.869	4
14) Orinoco	Venezuela	0.983	0.832	0.998	0.963	0.830	4.605	14
15)Volta	Ghana	0.919	0.947	0.918	0.973	1.000	4.757	15

Table 10: Total scores and ranking taken for the 15 deltas over the 6 indicators. A rank of 1 denotes “least ecologically resilient” to 15 denoting “most ecologically resilient”.

Engineering Indicator Indexes:

Delta	Location type	Year	Delta GDP (millions of current Int$)	Delta GDP (Billions of current Int$)	Score	Rank	Reference
1)Rhine	Netherlands/National	2019	1,034,543	1,035	0.362	11	World Bank 2019
2)Mississippi	Louisiana, USA/Regional	2019	267,051	267	0.093	7	Bureau of Economic Analysis,2020
3)Yangtze	Jiangsu,China/Regional	2019	2,849,060	2,849	1.000	15	IMF, Coutnry Goups Tables 2019
4)Yellow	Shandong,China/Regional	2019	2,032,240	2,032	0.713	14	IMF, Coutnry Goups Tables 2019
5)Po	Veneto,Italy/Regional	2016	176,291	176	0.061	5	Eurostat 2017
6)Nile	Egypt/National	2019	1,229,832	1,230	0.431	12	World Bank 2019
7)Amazon	Para,Brazil/Regional	2016	39,501	40	0.013	2	IBGE 2016
8)Mekong	Mekong Delta,Vietnam/Regional	2009	85,200	85	0.029	3	Shrestha et al., 2013
9)Lena	Far Eastern Federdal Distrcit,Russia/Regional	2018	219,826	220	0.076	6	IMF, Coutnry Goups Tables 2019
10)Danube	Tulcea,Romania/ Regional	2015	3,305	3	0.000	1	OECD 2015
11)Ganges	Bangladesh/National	2019	807,200	807	0.282	10	World Bank 2019
12)Indus	Sindh,Pakistan/Regional*	2018	373,379	373	0.130	8	World Bank 2019
13)Krishna	Andhra Pradesh,India/Regional*	2019	1,470,587	1,471	0.516	13	World Bank 2019
14)Orinoco	Venezuela/National*	2017 est.	389,400	389	0.136	9	CIA World Factbook, Venezuela Economy 2017
15)Volta	Ghana/National*	2019	171,464	171	0.059	4	World Bank 2019
	* = Data Incomplete or Estimate						

Table 11: Real GDP PPP for each region/country where the 15 deltas reside. Normal range standardization was utilized for the indicator scoring.

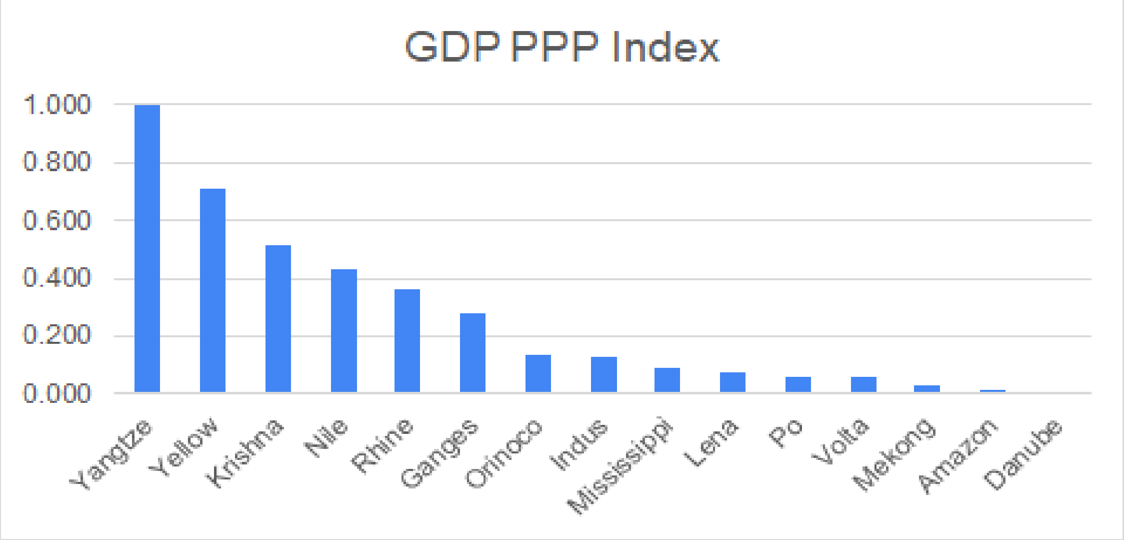


Figure 14: Graph showing the GDP PPP index resilience indicator scores for each delta.

Delta	Country	Year	Type	GDP per cap PPP (2011 USD)	Score	Rank	source
1)Rhine	Netherlands	2015	National	52,283.15	1.000	15	Kummu et al., 2018
2)Mississippi	U.S.A	2015	Delta region	48,586.52	0.924	14	Kummu et al., 2018
3)Yangtze	China	2015	Delta region	31,040.43	0.561	12	Kummu et al., 2018
4)Yellow	China	2015	Delta region	17,012.88	0.272	10	Kummu et al., 2018
5)Po	Italy	2015	Delta region	38,552.94	0.717	13	Kummu et al., 2018
6)Nile	Egypt	2015	Delta region	10,557.99	0.139	8	Kummu et al., 2018
7)Amazon	Brazil	2015	Delta region	8,602.79	0.098	7	Kummu et al., 2018
8)Mekong	Vietnam	2015	Delta region	6,033.97	0.045	4	Kummu et al., 2018
9)Lena	Russia	2015	Delta region	30,971.43	0.560	11	Kummu et al., 2018
10)Danube	Romania	2015	Delta region	15,339.09	0.237	9	Kummu et al., 2018
11)Ganges	Bangladesh	2015	National	3,849.11	0.000	1	Kummu et al., 2018
12)Indus	Pakistan	2015	Delta region	5,600.90	0.036	3	Kummu et al., 2018
13)Krishna	India	2015	Delta region	6,940.27	0.064	6	Kummu et al., 2018
14)Orinoco	Venezuela	2015	Delta region	6,459.72	0.054	5	Kummu et al., 2018
15)Volta	Ghana	2015	Delta region	3,953.21	0.002	2	Kummu et al., 2018

Table 12: Real GDP PPP per capita for each region/country where the 15 deltas reside. Normal range standardization was utilized for the indicator scoring.

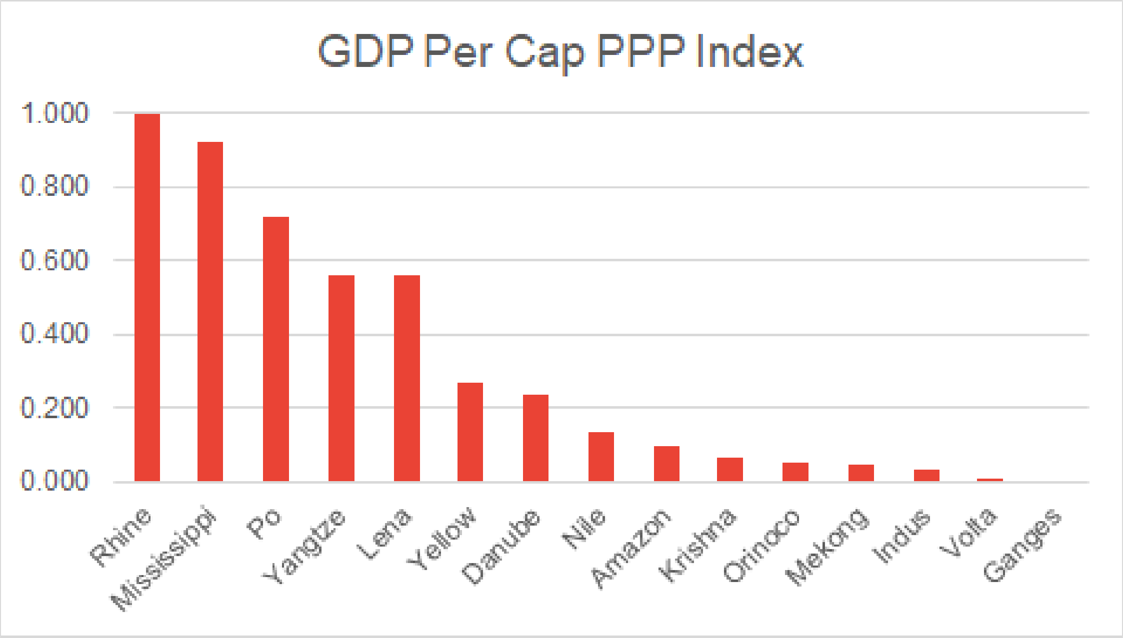
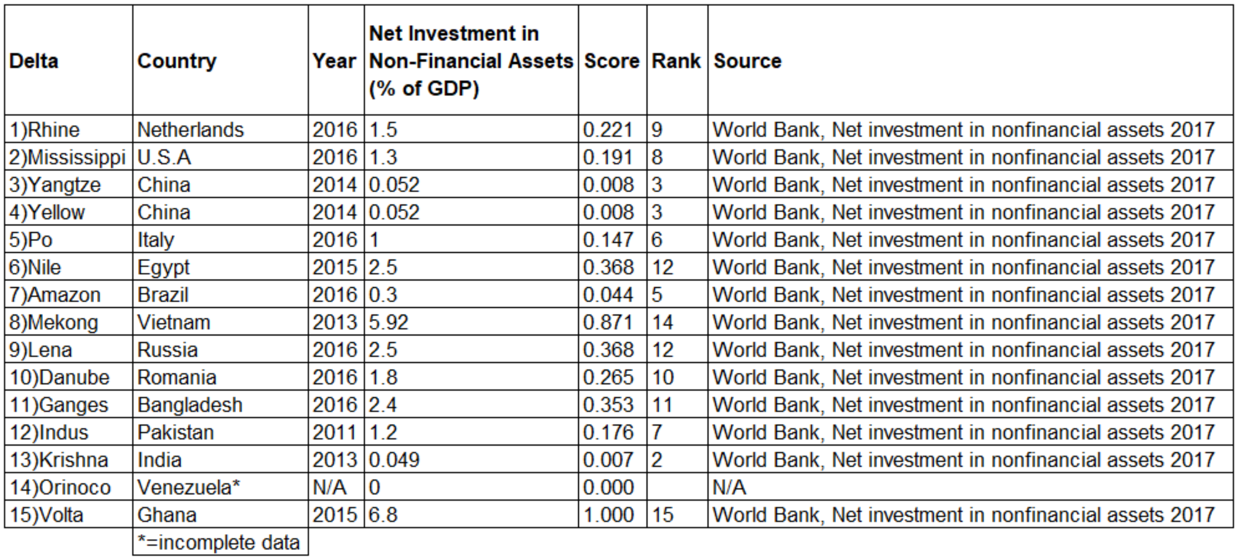


Figure 15: Graph showing the GDP per cap PPP index resilience indicator scores for each delta.



Delta	Country	Year	Net Investment in Non-Financial Assets (% of GDP)	Score	Rank	Source
1)Rhine	Netherlands	2016	1.5	0.221	9	World Bank, Net investment in nonfinancial assets 2017
2)Mississippi	U.S.A	2016	1.3	0.191	8	World Bank, Net investment in nonfinancial assets 2017
3)Yangtze	China	2014	0.052	0.008	3	World Bank, Net investment in nonfinancial assets 2017
4)Yellow	China	2014	0.052	0.008	3	World Bank, Net investment in nonfinancial assets 2017
5)Po	Italy	2016	1	0.147	6	World Bank, Net investment in nonfinancial assets 2017
6)Nile	Egypt	2015	2.5	0.368	12	World Bank, Net investment in nonfinancial assets 2017
7)Amazon	Brazil	2016	0.3	0.044	5	World Bank, Net investment in nonfinancial assets 2017
8)Mekong	Vietnam	2013	5.92	0.871	14	World Bank, Net investment in nonfinancial assets 2017
9)Lena	Russia	2016	2.5	0.368	12	World Bank, Net investment in nonfinancial assets 2017
10)Danube	Romania	2016	1.8	0.265	10	World Bank, Net investment in nonfinancial assets 2017
11)Ganges	Bangladesh	2016	2.4	0.353	11	World Bank, Net investment in nonfinancial assets 2017
12)Indus	Pakistan	2011	1.2	0.176	7	World Bank, Net investment in nonfinancial assets 2017
13)Krishna	India	2013	0.049	0.007	2	World Bank, Net investment in nonfinancial assets 2017
14)Orinoco	Venezuela*	N/A	0	0.000		N/A
15)Volta	Ghana	2015	6.8	1.000	15	World Bank, Net investment in nonfinancial assets 2017
	*=incomplete data					

Table 13: Net investment in non-financial assets (% of GDP) for each country where the 15 deltas reside. Normal range standardization was utilized for the indicator scoring.

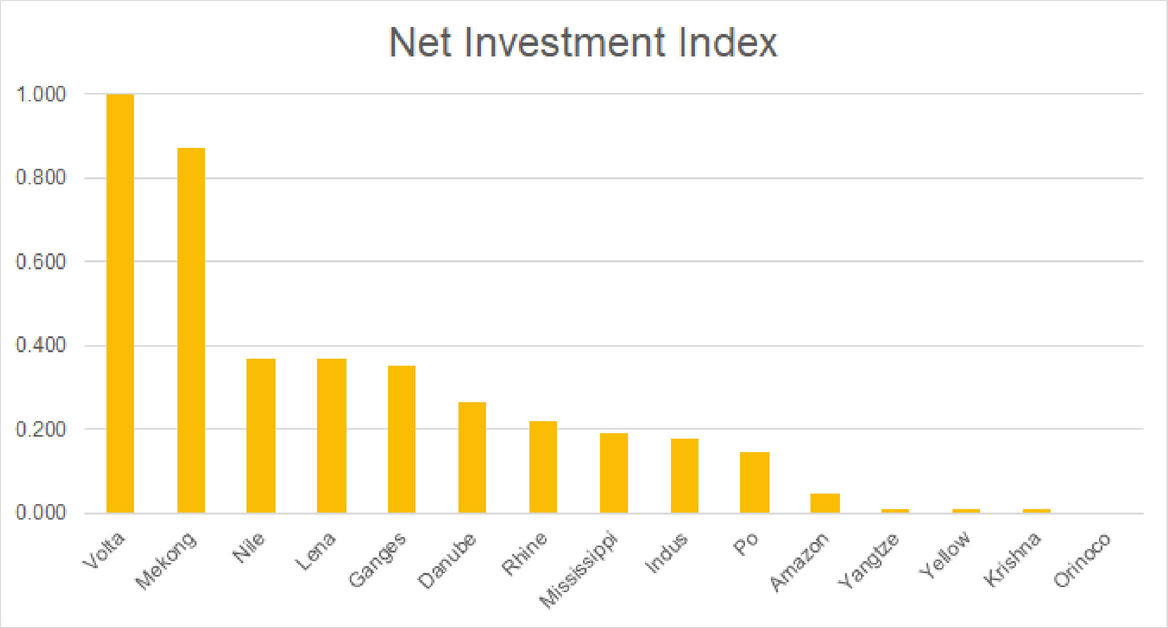
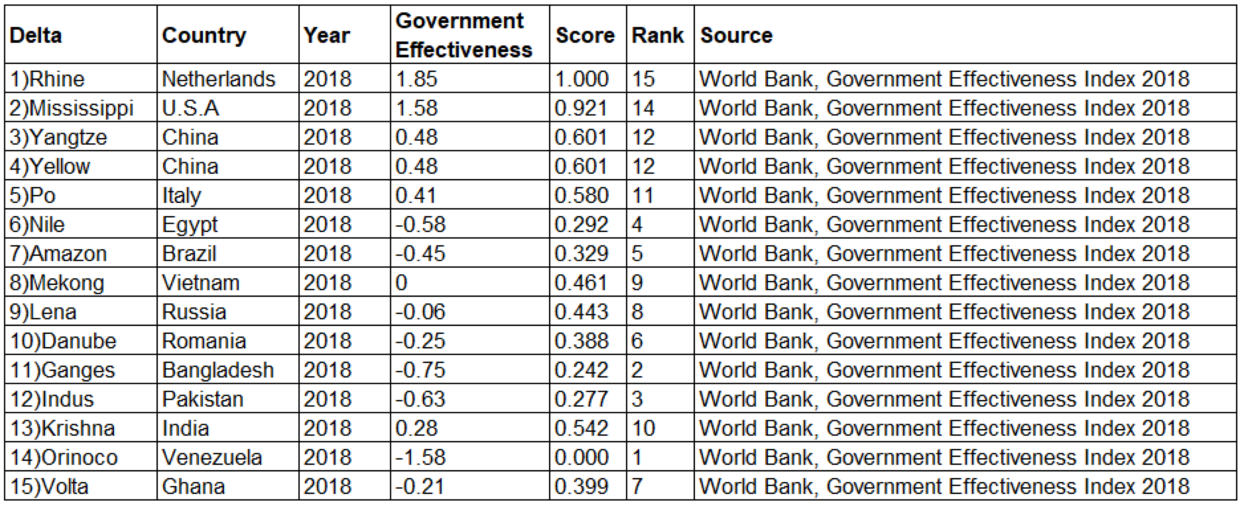


Figure 16: Graph showing the net investment index resilience indicator scores for each delta.



Delta	Country	Year	Government Effectiveness	Score	Rank	Source
1)Rhine	Netherlands	2018	1.85	1.000	15	World Bank, Government Effectiveness Index 2018
2)Mississippi	U.S.A	2018	1.58	0.921	14	World Bank, Government Effectiveness Index 2018
3)Yangtze	China	2018	0.48	0.601	12	World Bank, Government Effectiveness Index 2018
4)Yellow	China	2018	0.48	0.601	12	World Bank, Government Effectiveness Index 2018
5)Po	Italy	2018	0.41	0.580	11	World Bank, Government Effectiveness Index 2018
6)Nile	Egypt	2018	-0.58	0.292	4	World Bank, Government Effectiveness Index 2018
7)Amazon	Brazil	2018	-0.45	0.329	5	World Bank, Government Effectiveness Index 2018
8)Mekong	Vietnam	2018	0	0.461	9	World Bank, Government Effectiveness Index 2018
9)Lena	Russia	2018	-0.06	0.443	8	World Bank, Government Effectiveness Index 2018
10)Danube	Romania	2018	-0.25	0.388	6	World Bank, Government Effectiveness Index 2018
11)Ganges	Bangladesh	2018	-0.75	0.242	2	World Bank, Government Effectiveness Index 2018
12)Indus	Pakistan	2018	-0.63	0.277	3	World Bank, Government Effectiveness Index 2018
13)Krishna	India	2018	0.28	0.542	10	World Bank, Government Effectiveness Index 2018
14)Orinoco	Venezuela	2018	-1.58	0.000	1	World Bank, Government Effectiveness Index 2018
15)Volta	Ghana	2018	-0.21	0.399	7	World Bank, Government Effectiveness Index 2018

Table 14: Government effectiveness scores of the countries where the 15 deltas reside utilizing data taken from the World Bank. Normal range standardization was utilized for the indicator scoring.

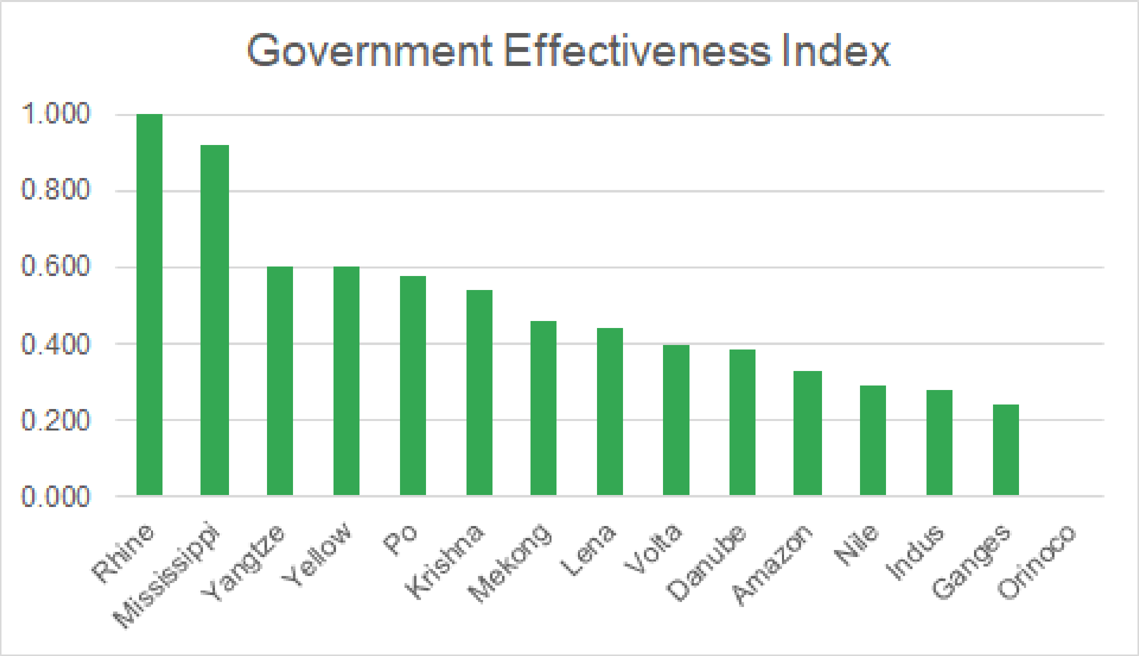
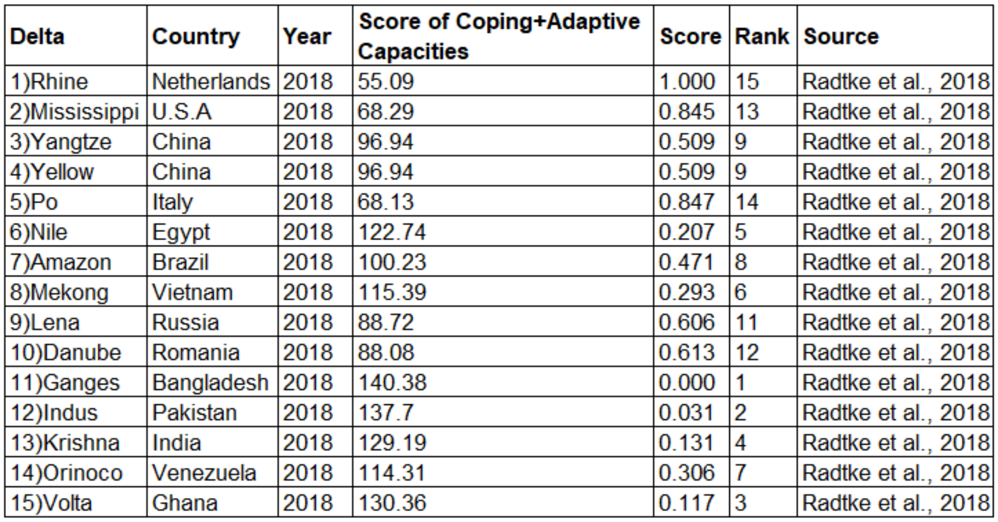


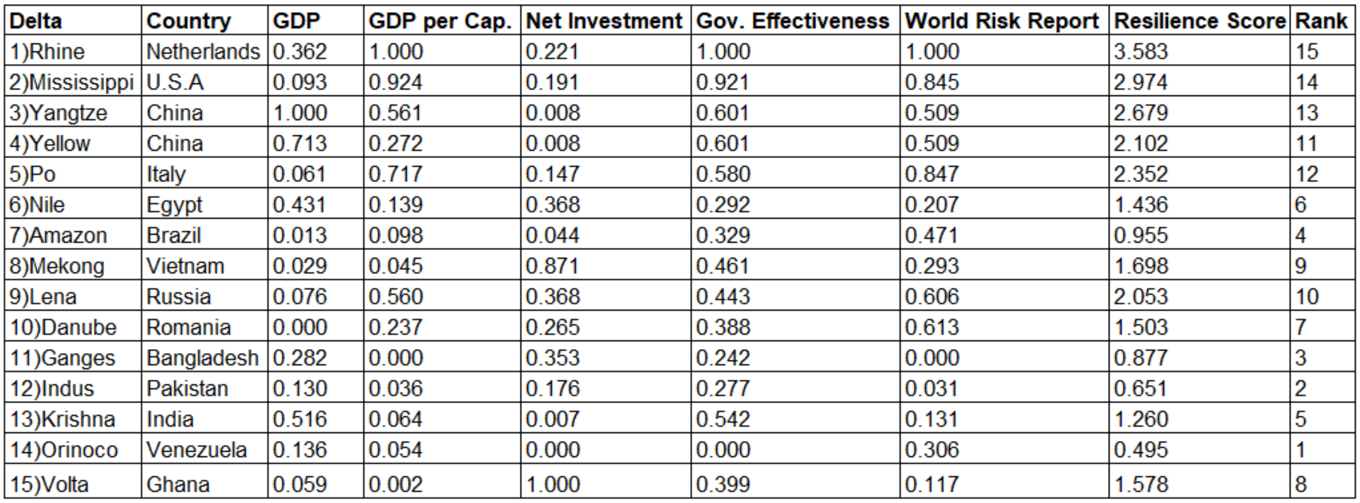
Figure 17: Graph showing the government effectiveness index resilience indicator scores for each delta.



Delta	Country	Year	Score of Coping+Adaptive Capacities	Score	Rank	Source
1)Rhine	Netherlands	2018	55.09	1.000	15	Radtke et al., 2018
2)Mississippi	U.S.A	2018	68.29	0.845	13	Radtke et al., 2018
3)Yangtze	China	2018	96.94	0.509	9	Radtke et al., 2018
4)Yellow	China	2018	96.94	0.509	9	Radtke et al., 2018
5)Po	Italy	2018	68.13	0.847	14	Radtke et al., 2018
6)Nile	Egypt	2018	122.74	0.207	5	Radtke et al., 2018
7)Amazon	Brazil	2018	100.23	0.471	8	Radtke et al., 2018
8)Mekong	Vietnam	2018	115.39	0.293	6	Radtke et al., 2018
9)Lena	Russia	2018	88.72	0.606	11	Radtke et al., 2018
10)Danube	Romania	2018	88.08	0.613	12	Radtke et al., 2018
11)Ganges	Bangladesh	2018	140.38	0.000	1	Radtke et al., 2018
12)Indus	Pakistan	2018	137.7	0.031	2	Radtke et al., 2018
13)Krishna	India	2018	129.19	0.131	4	Radtke et al., 2018
14)Orinoco	Venezuela	2018	114.31	0.306	7	Radtke et al., 2018
15)Volta	Ghana	2018	130.36	0.117	3	Radtke et al., 2018

Table 15: Combined score of the lack of coping capacities of the nations that the 15 deltas reside utilizing data from the World Risk Report (Radtke et al., 2018). The range-standardization was reversed in this dataset to reflect the highest indicator value as the least resilient and the lowest indicator value representing the highest resilience in this case.

Figure 18: Graph showing the World Risk index resilience indicator scores for each delta.



Delta	Country	GDP	GDP per Cap.	Net Investment	Gov. Effectiveness	World Risk Report	Resilience Score	Rank
1)Rhine	Netherlands	0.362	1.000	0.221	1.000	1.000	3.583	15
2)Mississippi	U.S.A	0.093	0.924	0.191	0.921	0.845	2.974	14
3)Yangtze	China	1.000	0.561	0.008	0.601	0.509	2.679	13
4)Yellow	China	0.713	0.272	0.008	0.601	0.509	2.102	11
5)Po	Italy	0.061	0.717	0.147	0.580	0.847	2.352	12
6)Nile	Egypt	0.431	0.139	0.368	0.292	0.207	1.436	6
7)Amazon	Brazil	0.013	0.098	0.044	0.329	0.471	0.955	4
8)Mekong	Vietnam	0.029	0.045	0.871	0.461	0.293	1.698	9
9)Lena	Russia	0.076	0.560	0.368	0.443	0.606	2.053	10
10)Danube	Romania	0.000	0.237	0.265	0.388	0.613	1.503	7
11)Ganges	Bangladesh	0.282	0.000	0.353	0.242	0.000	0.877	3
12)Indus	Pakistan	0.130	0.036	0.176	0.277	0.031	0.651	2
13)Krishna	India	0.516	0.064	0.007	0.542	0.131	1.260	5
14)Orinoco	Venezuela	0.136	0.054	0.000	0.000	0.306	0.495	1
15)Volta	Ghana	0.059	0.002	1.000	0.399	0.117	1.578	8

Table 16: Total scores and ranking taken for the 15 deltas over the 6 indicators. A rank of 1 denotes “least engineered resilience” to 15 denoting “most engineered resilience”.

10. Acknowledgements

I would like to thank my thesis supervisor, Dr. Murray Scown of the UU Geosciences Department, immensely for all his time, support, and guidance towards this research. His feedback on my tasks and our periodic meetings inspired me to narrow down the key aspects in this report. He went above and beyond his role as a supervisor and I will forever be grateful. I would also like to thank Dr. Jaap Nienhuis of the UU Geosciences Department for giving me key insights on the geophysics of deltas. Lastly I would like to thank my parents, David and Helen Wada, for supporting me emotionally and financially through this master's program.