Rethinking Fluvial Flood Control:
Analyzing Wide-Scale Impacts of Engineered and Nature-Based Measures

Supervised Research Project

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Abstract

Historically, many cities have been built on the banks of rivers due to the host of services they provide. However, fluvial cities and settlements are under increasing flood risk, particularly in the face of climate change. In order to safeguard the interests of the city and its dwellers, flood control measures – ranging from engineered to nature-based solutions – are widely being implemented. While these measures have allowed cities to remain where they are and reduce flood risk, it is now becoming evident that flood control has widespread ecological and economic impacts, especially at the larger catchment-basin level. Flood control measures are also at growing risk of failure given hydrological changes in recent years which in turn increases risk to lives and livelihoods of nearby residents. Thus, this study looks at the wide-scale social, economic and environmental impacts of engineered (dikes) and nature-based (floodplain restoration and river renaturation) flood control measures in a bid to improve future fluvial flood control approaches. For each approach, a qualitative analysis of flood control case studies from different parts of the world, with in-depth examination of one or two cases, has been conducted. The report also examines the environmental and social impact assessments that are an integral part of flood control planning in most regions; as conventionally used, they fail to capture the full extent of impacts. Flood control practices in Quebec, a region where both engineered and nature-based solutions are being implemented, are then briefly explored. The findings of this study emphasize the need for a more holistic and wide-lensed approach to flood control planning. This research is intended to give planners and other multi-disciplinary actors a broad and simplified look at the long-term and wide-scale positive and negative impacts of flood control measures.

Resumé

Historiquement, de nombreuses villes ont été construites sur les rives des rivières en raison de la multitude de services qu'elles offrent. Cependant, les villes et agglomérations fluviales sont soumises à un risque d'inondation croissant, en particulier face au changement climatique. Afin de sauvegarder les intérêts de la ville et de ses habitants, des mesures de gestion des inondations - allant des solutions artificielles aux solutions basées sur la nature - sont largement mises en œuvre. Bien que ces mesures aient permis aux villes de rester là où elles sont et de réduire les risques d'inondation, il devient maintenant évident que la gestion des inondations a des impacts écologiques et économiques généralisés, en particulier au niveau des bassins versants. Les mesures de gestion des inondations courent également un risque croissant d'échec compte tenu des changements hydrologiques de ces dernières années, ce qui augmente les risques pour la vie et les moyens de subsistance des résidents à proximité. Ainsi, cette étude examine les impacts sociaux, économiques et environnementaux à grande échelle des mesures de gestion des inondations artificielles (digues) et naturelles (restauration des plaines inondables et renaturation des rivières), dans le but d'améliorer les futures approches de contrôle des crues fluviales. Pour chaque approche, une analyse qualitative est menée sur des études de cas de gestion des inondations dans différentes parties du monde, avec un examen approfondi d'un ou deux cas. Le rapport examine également les études d'impact environnemental et social, qui font partie intégrante de la planification de la gestion des inondations dans la plupart des régions ; telles que traditionnellement utilisées, ces études ne permettent pas de saisir toute l'étendue de ces impacts. Le cas Québécois des pratiques de lutte contre les inondations est ensuite exploré, la région étant un lieu de mise en œuvre de solutions artificielles et basées sur la nature.

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CHAPTER 1 Introduction

1.1 Contextualizing the problem

Water is one of the most essential elements for the survival of any living being. Humans consume water directly and use it for food production, sanitation, industrialism and transportation, among other activities. Thus, it comes as no surprise that humans have settled near sources of water since time immemorial. Rivers have historically been the centre of many civilizations (Macklin and Lewin, 2015): ancient Mesopotamia rested within the Tigris-Euphrates river system; the Indus Valley Harappa civilization spanned the Indus River and its tributaries; the Huanghe or Yellow River civilization that flourished between 7000 and 5000 BC was located in modern day China’s Yellow River basin; the ancient Egyptian civilization developed around the Nile River; and Mesoamerican civilizations like Maya, Toltec, and Aztec, were all serviced by waters from the rivers Usumacinta, Motagua, and Coatzacoalcos (see Figure 1). The preference for settlement near major bodies of water is also apparent during the period of European settler-colonialization of the 16th-18th centuries; Spanish settler-colonizers established colonies in Asia and America in accordance with the Laws of the Indies which directed new settlements to be strategically built near water. The intent behind this directive, as laid out in the body of laws, was for settlers to have access to water for consumption, sanitation, food production and transportation. Havana (Cuba), Lima (Peru) and Manila (Philippines) are some modern-day cities established by the Spanish on the banks of rivers.

Figure 1 Ancient riverside civilizations of the world
Source: Sherry David, blendspace.com

In addition to being a source of water, rivers and riverine systems serve another key purpose which makes its surrounding regions a prime choice for habitation: fertile soil. As a river flows over rocks and soil in its path, the sheer velocity causes erosion. The eroded material gets carried down as sediments and silt, which then gets deposited on river banks forming fertile alluvial soil. This fluvial phenomenon becomes spatially widespread during seasonal flooding when water and silt volumes exceed the natural path of the river, and temporary inundation of surrounding areas occur. As alluvial soil builds up through silt deposition over the years, land becomes increasingly fertile, which is ideal for cultivation of crops and other plants (Chapman and Darby, 2016). Thus, river systems contribute broadly to production of food and generate means of livelihoods for the people living nearby.

While river systems and seasonal flood regimes can be highly beneficial (for drinking, agriculture, sanitation, transportation, etc.), it is becoming increasingly risky to live near rivers. Climate change and expanding human activities on rivers are leading to higher than historically usual levels of rainfall, a rise in sea-level, changes in tidal dynamics, changes in snow melt, and other shifts that contribute to an increase in the volume of runoff water in rivers. In many locales, such changes have turned mild, beneficial seasonal inundations into aggravated, disastrous episodes of flooding (Bronstert, 2003; Devkota & Bhattarai, 2018). In South-East Asia alone, flood related damages between 1990 and 2009 amounted to a hefty 161,979 billion USD (Huu, 2011). The 2013 fluvial flood disaster in Calgary incurred over 6 billion Canadian dollars in economic losses, with 78% of Canadian federal disaster assistance in the last 50 years having been spent on flood related property damage (Alexandre, 2019). Although historically civilizations have abandoned their settlements over disastrous flood events (Kidder et al., 2012), given increased urbanization such a move is unfeasible.

As the costs of flood events continue to increase exponentially, there is growing pressure on governments globally to invest heavily in flood control measures. Between 2014 and 2017, approximately 56.86 billion USD was combinedly invested by twelve of Asia's largest economies - China, Japan, Republic of Korea, India, Philippines, Indonesia, Thailand, Taiwan, Vietnam, Malaysia, Bangladesh, and Pakistan - in flood protection measures, accounting for an average of 0.26% of the region's GDP (Ishiwatari, 2019). There are myriad approaches to managing fluvial flood effects including controlling fluvial waters through physical measures, or reducing the damage caused by flooding through land-use planning, to name a couple. Measures range from hard-engineered interventions like dams, dikes, levees, and storm basins to nature-based solutions like renaturation of rivers, beaver dams, restoring alluvial floodplains, and more.

Given the large and multi-dimensional scale (i.e., spatial, temporal, economic, social, environmental) of costs and benefits of flood control measures, such projects are often accompanied by officially sanctioned impact assessments. These impact assessments generally focus on the effects of flood control projects on the local region. Effects on communities and biodiversity further upstream/downstream are not typically assessed. For example, studies like Richter et al. (2010), Beck et al. (2012), and Obour et al. (2016) highlight how construction of dams upstream can have many negative impacts on downstream fluvial conditions, but as Erlewein (2013) points out in the context of hydroelectricity dam construction in India, standard Environmental Impact Assessments (EIAs) have scopes limited to the local project area and fail to consider the large-scale impacts.

The findings of this study can help inform planners, engineers, policy makers, funding agencies and the wider public of the variety of flood control measures that exist today, and inform them of the positive and negative impacts of a sample of engineered (one) and nature-based (two) flood control measures. The concluding chapter provides recommendations on reshaping flood control approaches and impact assessment methodologies for future fluvial flood control projects.

1.2 Objectives

This project looks at the wide-scale social, economic and environmental impacts of engineered and nature-based fluvial flood control measures as a way to better inform future planning for flood control. Within the scope of this report, one engineered measure (dikes/levees) and two interrelated nature-based measures (floodplain restoration and river renaturation) are selected and assessed in depth. The project attempts to uncover how engineered and nature-based measures perform in comparison, whether one approach is superior, and how both approaches perform in the long run particularly in light of climate change.

The study also analyses the efficacy and reliability of conventional project impact assessments in capturing the true extent of social, economic, and more importantly, environmental impacts of fluvial flood control projects. Are these assessments unbiased and representative of all the impacts? If not, what are the shortcomings, what causes them, and how can these weaknesses or gaps be rectified for future projects?

Finally, the study looks at the case of a region where both engineered and nature-based approaches have been and are being implemented to manage and control fluvial flooding as a way to identify key drivers for choosing one measure over the other.

1.3 Methodology

Research Design

As discussed above, rivers and river water contribute to communities in many different ways, affecting human lives, livelihoods, transportation, local and national economy, and more. In fact, flood control measures are almost always implemented to protect these different, yet interrelated, interests. Yin (1981, 2011) emphasizes that case studies are an effective way to derive an in-depth understanding of "cases" set in their real-world context. Case studies also help uncover various interactions between social, economic, environmental, cultural, political and technical factors which are integral to large-scale infrastructure projects like flood control. Therefore, this study employs the method of studying cases and the contexts in which they are set.

To achieve the above objectives, this study will analyse cases of regions where engineered and/or nature-based flood control measures have been implemented with a focus on answering the following key questions:

(1) What is the capacity of flood control provided by the particular measure? What factors lead to the selection of one type of flood control approach, be it engineered or nature-based, over the other?
(2) What short-term and long-term impacts does the measure have on ecology and river hydrology both locally and at the wider catchment-basin level?
(3) How does implementation of the measure affect human lives and livelihoods in the region? Does the flood control approach contribute to or detract from the local economic development?

Furthermore, the study also tries to uncover details about the planning process behind the implementation of each measure. Does the planning process take a top-down or bottom-up approach? Are environmental and social impact assessments officially carried out? What are the gaps and/or shortcomings in the impact assessment process?

Planning for flood infrastructure often entails collaboration between local residents, engineers, sociologists, environmental groups and activists, politicians, funding agencies, and others. As an urban planner with a background in engineering, I recognize that it is important to present information, particularly when intended for pan-disciplinary stakeholders, in a way that is easily interpretable and understandable. Additionally, the quantification of impacts varies greatly based on the context in which an event occurs. For example, a densely populated settlement is likely to suffer from greater economic losses and infrastructural damage during a flood than a low-density settlement facing floods of the same intensity and frequency. Thus, this analysis is qualitative in nature such that policy-makers and other actors can be informed of the wide range of impacts implementation of engineered and nature-based flood control measures can have, following which they may choose to exert more focused efforts into quantifying impacts in their specific contexts.

Literature Review

Academic and non-academic literature has been used to explain key concepts, document cases and develop ideas throughout this report. A review of old and more recent literature is used to outline the evolution of fluvial flood control mechanisms and flood management goals, shortcomings of conventional project impact assessments, and the several case studies. The articles are drawn from planning, engineering, economics, hydrology, environment and water resource journals from across the globe for a multi-disciplinary understanding and pan-global perspective of flood control measures and their impacts.

Case Studies

This study employs illustrative case studies to uncover the social, economic, and environmental impacts of engineered and nature-based solutions to flood control. Gerring (2004) defines a case study as the intensive study or analysis of a single example or unit of a particular phenomenon or concept with the intention of generalizing the findings across a larger set of similar units. In contrast, Feagin et al. (1991) and Flyvbjerg (2011) opine that a single case study may not be representative of all similar units and are therefore effective only during the preliminary stages of a study. My approach is to use secondary data to document an illustrative primary case. To address the critique, I situate that case within similar ones elsewhere.

To assess the impacts of an engineered flood control solution, the case of dike/levee construction in Vietnam's Mekong River delta was selected. The Mekong is a good case for study because it highlights the impacts of dike construction along a trans-national river in a developing, primarily agricultural economy where planning for flood control typically is via a top-down approach. To document economic, social and environmental impacts of dike construction in the delta, literature authored by environmentalists, planners, sociologists, and other scientists on the various impacts was reviewed. A PhD thesis by Huu (2011) titled *'Planning and implementation of dike systems in the Mekong Delta, Vietnam'* served as a rich source of information. Drawing on existing academic and non-academic literature, findings from the Mekong case were then compared with similar cases in other parts of the world.

For nature-based fluvial flood control solutions, the case of floodplain restoration and river renaturation in the downstream city of Leuven in Belgium's Dijle basin was selected. The case of Leuven is a good one to study as it was proposed as an alternative to an engineered flood control solution. The areas around Leuven where the project was implemented are also incredibly rich in biodiversity and has been declared protected by organizations such as the European Bird Directive and European Habitat Directive. Although the majority of literature relevant to this case was in Dutch, information was accessed via translation to English using GoogleTranslate. Dr. Francis Turkelboom, a professor at KU Leuven who has extensively studied impacts of flood management in the region, was also contacted for additional information and clarifications. Impact assessment reports published by the government could not be found as most official documents were in Dutch and keyword searches were not fruitful; it is unclear whether extensive official impact assessments were conducted in advance of the projects, or if only assessments by researchers at KU Leuven were considered.

Lastly, the case of historical and current flood control practices in Quebec has been explored based on the insights of Chapters 3 and 4. Quebec has been selected as an appropriate case to study as it is a region where both engineered and nature-based flood control approaches have been implemented. Relevant academic and non-academic literature was reviewed to identify the patterns and trends of flood control planning in Quebec, as well as determine what factors influence the selection of one type of measure of the other.

The case studies were selected primarily on the basis of quality and availability of relevant academic and non-academic literature online. The search for literature was done using keywords like *engineered to nature-based flood control, impacts of engineered flood control measures, impacts of nature-based flood control, dike construction in Mekong, impacts of dike construction, dike failure, floodplain restoration, impacts of floodplain restoration, Dijle nature-based flood control, flood control in Quebec, history of flood control in Quebec,* and more. When searching for literature related to dike construction, synonymous terms – dykes, levees – were also used. Given the limited scope of this project as well as restriction owing to the COVID-19 global pandemic, the analysis depends entirely on secondary data, and no interviews (except for a few email exchanges with Dr. Turkelboom) or site visits were conducted.

1.4 Structure of report

Chapter 1 of this report briefly introduces the context and relevance of this study in planning and engineering practices, followed by a description of the methodology undertaken to conduct the study.

Chapter 2 reviews existing literature to explain two broad concepts foundational to this study: (1) engineered and nature-based solutions for fluvial flood management, and (2) shortcomings of conventional project impact assessments.

Chapter 3 explores dike construction as an example of engineered flood control solution. The chapter presents the case of dike construction in the Mekong River Delta in Vietnam, and its social, economic and environmental impacts at the local and catchment level. The findings are substantiated by numerous examples of dike construction and their impacts from regions across the world. A comparison is made between project impact assessments and actual project impacts of dike construction in the context of cases discussed in this section. The chapter concludes with a summary of the social, economic and environmental advantages and disadvantages of dikes as an engineered measure to control fluvial flooding.

Chapter 4 discusses the case of an alluvial floodplain restoration and river renaturation project in Belgium's Dijle River basin as an example of nature-based solutions to flooding. As literature on nature-based fluvial flood management measures remain limited, the findings of the case study will be substantiated by fewer examples of similar projects. A brief analysis of nature-based flood control project impact assessments and their reliability is then presented. Finally, a summary of the social, economic and environmental advantages and disadvantages of nature-based solutions is presented.

Chapter 5 briefly looks at the current and historical flood control practices in Quebec as it is a region where both engineered and nature-based flood control approaches have been implemented. This section attempts to uncover what factors drive the decision of choosing one type of measure over the other.

Chapter 6 is the conclusion of this report. Key findings from the study are presented, followed by discussions regarding the current trends of fluvial flood control, and recommendations on how to manage fluvial flooding going forward.

CHAPTER 2 What do we know about flood control planning approaches?

This chapter presents pertinent concepts and discourse as a basis for the analytical chapters that follow. The first section discusses fluvial flooding, various approaches to controlling fluvial floods, and common tensions in flood control planning. The section that follows outlines the history, relevance, and challenges of conventional impact assessments which are a key component of flood control planning in many parts of the world.

2.1 Fluvial flooding and its management

The term “fluvial” is commonly used in geography and earth sciences, and pertains to rivers, streams, and riverine systems. It is also used when referring to processes and phenomenon occurring in or near rivers such as erosion, transportation, depositing, flow dynamics, geomorphic action, etc. (Neuendorf, 2005). Although rivers contain less than 0.005% of continental water at a time (Knighton, 2014), they have the potential to highly support, but also disrupt, human habitation near it by the means of fluvial flooding.

Hydrologically, fluvial flooding occurs when water discharge exceeds the volumetric capacity of the river channel and overflows the river bank thereby inundating its surroundings. Higher than normal river discharge can be caused by (a) increased water volumes flowing into the river through glacial melt, heavy rainfall, large-scale surface runoff, etc., and (b) large volumes of silt, sand and debris collected by the waters as it flows over and erodes the riverbed. While fluvial flooding in itself is natural and normal, increased urbanization near riverbanks has caused fluvial flooding to become destructive and a high-risk disaster (Luo et al., 2015). Despite this risk, cities continue to flourish near rivers with many efforts being made to control and manage fluvial flooding and its effects.

2.1.1 Classifying flood solution approaches

De Bruijn (2004) broadly defines two approaches to coping with flooding in a region by a community facing risk of floods – resistance and resilience. The resistance approach aims to *prevent* flooding typically through structural measures that has the “ability to let discharge waves pass without causing floods” up to a certain threshold (de Bruijn, 2004). Resilience, in contrast, focuses on “living with floods” and mitigating the social (human lives and livelihoods) and economic risks of flood events. Bruijn also explains that resilience can be “strategies that allow floods, but aim at minimizing the flood impacts, maximizing the graduality of the increase of flood impacts with increasing discharges and maximizing the recovery rates for all possible discharge waves". Douven et al. (2012) similarly defines the resistance strategy as one that "aims to prevent and regulate floods" and resilience as a strategy that "aims to minimise the consequences of floods". Douven et al. (2012) further goes on to refer to resistance and resilience strategies as flood *protection* and flood *adaptation* approaches, respectively. By this definition engineered or structural measures like dams and dikes (further discussed in section 2.1.2) can be classified as a resistance approach, and nature-based measures like the *Room for Rivers* concept (further discussed in section 2.1.3) come under the resilience approach.

Although de Bruijn (2004) and Douven et al. (2012) distinguishes the two, many scholars (Restemeyer et al., 2015; Holling, 1966; Holling, 1973; Davoudi et al., 2012; de Bruijn, 2004) point out that the two are not mutually exclusive and distinct. These authors explain that resilience is often a system's ability and capacity to resist the impacts of a disaster (a flood event in this case), and the time the system takes to bounce back to equilibrium (i.e., pre-disaster) conditions. In the case of flooding, the system could refer to the city, its people and infrastructure, local and wider-scale ecology and ecological functions, and economy, to name a few. If we consider this broader definition, the resilience approach can include more resilient management of engineered resistance measures in the context of adaptation to floods.

Contrastingly, Yevjevich (1994) classifies both engineered and nature-based flood control measures as physical/structural interventions. Yevjevich (1994) does however distinguish them as *intensive* and *extensive* physical interventions, respectively. Intensive physical measures largely consist of interventions like "levees, dikes and walls; reservoirs, retention and release basins; increase of channel capacity, parallel and diversion flood channels; and flood plain polders and platforms", while extensive physical measures include "forest, grass and arable land controls, soil conservation, snow management, and urban flood control."

While the above authors take a rather binary approach to classifying flood control and flood risk mitigation measures, Van der Nat et al. (2016) employs a broader, and more scalar, classification. They define five categories of engineered to nature-based coastal flood control approaches which have been adapted from Berry et al.'s (2013) paper. These approaches, ranked in the order of ecosystem services that they offer, are: hard engineering, soft engineering, ecologically enhanced engineering, ecological engineering adaptation, and ecosystem conservation adaptation. Hard engineering measures are typically built structures which alter or disrupt natural hydrological processes like flooding and include measures like dike, dam and embankment construction. Soft engineering measures are "human-mediated" efforts to "maintain the dynamic equilibrium" of natural systems, such as shore nourishment in the case of coastal erosion (Van der Nat et al., 2016) and dredging of sediments from the riverbed to increase discharge capacity. Ecologically enhanced engineering interventions aim "to improve ecological functioning of artificial [hard engineered] structures and to mitigate their negative influence on ecosystem resilience". An example of ecologically enhanced engineering would be incorporating fish ladders/fish steps in the design of dams to allow fish to migrate freely across a river. Similar, yet different, is the ecological engineering adaptation method, which "uses the ability of ecosystem engineering species to modify local environmental conditions and create structures that have flood protection value". Introducing beavers to an area to build beaver dams which act as a "natural" flood control measure is an example of the ecological engineering approach. Finally, the ecosystem conservation adaptation approach aims to "derive the desired flood protection capacity entirely from the ecosystem" with efforts to conserve and restore ecological spaces. Popular nature-based flood control solutions like restoration of floodplains/wetlands, river renaturation, and conservation of mangrove forests are some "interventions" that come under this approach.

Within the scope of this study, we look at approaches from two ends of the spectrum – hard engineered and nature-based approaches to fluvial flood control. Sections 2.1.2 and 2.1.3 below delve deeper into the history and conceptual details of these two approaches.

2.1.2 History of flood control: Engineered solutions

Flood control and management is not a new concept for humankind. Excavations from the mid-19th century in Mohenjo-daro of the Harappan Indus Valley civilization ruins uncovered that settlers of this ancient civilization (3300 – 1300 BCE) had built a twenty-five feet high mud-brick wall along the edge of the city's mound which archeologists and historians postulate was a measure to raise the city's elevation level in response to flood threats (Dales, 1965). In ancient Rome as far back as 6th century BC, extensive networks of open-air canals and drainage systems were employed to divert water from streams to the Tiber River, to drain marshes to make low-lying lands habitable, and eventually to drain flood waters from the low-lying Roman Forum (Hopkins, 2007). Under Roman Emperor Augustus, engineering works such as clearing the riverbed of debris, building embankment walls and maintaining the main drainage system was carried out to reduce flood-risk (Long, 2008). Following the 1557 flood event, military engineer Antonio Trevisi and physician Andrea Bacci were employed by the Catholic church to tackle future floods in Rome. Their solutions required engineering efforts and included dredging of the river, keeping drains clean and constructing trenches (Long, 2008). In more recent Roman history, between 1875 and 1910, very high embankment walls similar to those in London and

Paris were constructed along the Tiber and continues to protect Rome from most flood events till today (Di Baldassarre, 2017). Further west, taking after practices from their native land, European settlers in New Orleans constructed some of America's first levees along the Mississippi River between 1718 and 1727 (Kusky, 2008).

Thus, for centuries we have seen engineered efforts to deal with floods. A common term that is used when referring to engineered or structural measures is 'grey infrastructure'. Grey infrastructure is human-made and engineered structures which are employed to control, remove or manipulate ecosystems (Rosenbloom, 2018). They are often built using concrete, metal, pipes, mud and other construction material, and are designed to meet a set of performance criteria like discharge volume, wave height, geological conditions, etc. (Rosenbloom, 2018). Chiu et al. (2021) write that traditional engineered flood control measures follow three basic operational principles – (a) using structures to restrict water overflow, (b) employ structures to consume or dampen the power of flowing water, and (c) build structures that rapidly drain water out from floodplains and other vulnerable regions. Structural measures are typically effective in controlling flood risk at a specific local region and not at the large-scale catchment level. There are numerous kinds of engineered flood control and management measures, some of which are briefly described in Box 1 below. This study focuses on dike construction as an example of engineered flood control measures.

Dikes, or levees, are earthen embankments built along the course of a river or riverbank which acts as a physical barrier that prevents the river from meandering off of its course, and as a flood barrier during peak discharge or flow periods. The term 'dike' or 'dyke' is most commonly used in the Anglo-Saxon regions of England, Netherlands, Germany, etc., whereas the term 'levee' derives from the French word *levée* and is now commonly used in America and France. They are one of the most commonly used fluvial flood control measure and are amongst the oldest structural tools to controlling floods. Evidence of some of the earliest dikes/levees can be found in the ruins of the Indus Valley civilization, ancient Egypt, China and Mesopotamia (Baba et al., 2018; Lander, 2014). Depending on the peak flow height of river water, low- or high-dikes may be built. A dike is classified as 'low' when its crest is at a maximum height of 4 meters, and when it is greater than or equal to 4 meters, it is called a high-dike (Vu et al., 2021).

Although dikes are built to resist flood waters, they are susceptible to failure, i.e., breakage or toppling over. Some common causes of dike failure are (a) when water discharge levels in the channel far exceed the retaining capacity of the dike, (b) when flow velocity of discharge exceeds the design capacity of the dike, and (c) when excessive soil erosion destabilizes the dike. Kundzewicz et al. (2005) discusses cases of flood events in Central Europe where two out of three times dikes sustained some degree of damage. They also illustrate how dike failure rates are going up as precipitation patterns are becoming growingly unpredictable owing to climate change and peak flow levels in rivers have increased. Failure of dikes also result in high damages to property and lives.

Chapter 3 discusses more on dikes in the context of Can Tho City and the Mekong Delta.

2.1.3 Advent of nature-based solutions to flooding

Cohen-Shacham et al. (2016) define nature-based solutions as “actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges (e.g., climate change, food, and water security or natural disasters) effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits”. Thus, NBS aims to provide social, economic and environmental benefits whilst also fulfilling flood protection goals. The three main principles of NBS, as summarized by Chiu et al. (2021), are: (a) provide more room for water to flow, (b) use and replicate nature and natural processes, and (c) increase water absorption capacity and natural storage facilities.

For the longest time in history, flood control was achieved through engineered structural measures and focused on protecting an individual area. As the frequency and intensity of flood events worsened, notably in the 1900s, societies had to resort to more structural interventions like raising the heights of dikes/levees, build sturdier dams, divert rivers using structural measures, etc. (Chiu et al., 2021). These infrastructures required regular maintenance and monitoring, and were proving to be less and less effective against increasing flood risks, particularly in light of climate change (Kavvada and Held, 2018). The late 19th and 20th centuries also saw the introduction of terms like “ecology” and “ecosystem” which signalled a shift towards acknowledging the environment as dynamic and impactable (Chiu et al., 2021).

The Industrial Revolution and the years following it drew global attention to environmental pollution and its effects (Markham, 2019). This instigated widespread efforts to reverse pollution resulting in the 1972 US Clean Water Act, which was the culmination of over 100 years of state and federal negotiations and regulations (Foster and Matlock, 2001). Between the 1970s and 1980s, river restoration projects were undertaken to improve water quality and fluvial ecology. It was only in the late 80s and early 90s, after the UN put forward the concept of sustainable development, that river restoration practices were employed for flood protection efforts (Chiu et al., 2021).

Box 1: Examples of common engineered flood control measures

Detention dams

Flood control detention dams are dams built on rivers or streams with the intent of regulating the volume and speed of water that flows downstream to a non-risky level. River water collects on the upstream side of the dam and is released through the floodgates in a controlled manner, thereby reducing flood risk downstream. They are typically made of concrete, masonry or earth, and often contains metal reinforcement. The design specifications such as breadth, width, height, floodgate location and position, are determined through studies of the local topography, soil conditions, fluvial hydrology and flow path, etc. On average, physical construction of a dam takes about 8.6 years with several more years of planning and design preceding it (Ansar et al, 2014). Excessive rainfall, snowmelt and surface runoff can increase the volume of water in a dam's reservoir which increases risk of dam failure and consequent flood risk past a certain point.

Weirs

A weir is a structural barrier built across the width of a river for the purpose of controlling flow velocity and height of river water. They look similar to a low-dam, however they vary in functionality. Unlike dams, water does not collect behind the weir but rather flows over the head/crest of the weir. The amount of water flowing over the crest can be adjusted by raising or lowering the weir crest, or through the use of sluice gates. Weir failure is commonly caused by destabilization of the structure through either excessive uplift pressure which occurs when water seeps through the bottom of the weir and/or wave action of river water, or erosion of riverbed on the upstream or downstream side of the weir.

Canals or channels

One way of managing or controlling fluvial flooding is by redirecting excess river discharge from its desire path. This can be achieved through a network of canals, channels or drainage networks which act as an alternate path through which a certain volume of river water can travel, often to a designated catchment basin, thereby reducing the amount of water flowing downstream to a non- or low-flood level. Doing so can minimize or eliminate flood risk and flood related damages to settlements downstream. These channels or canals can either be trenches dug into the earth or be more pucca with cemented or concrete walls. For optimal functioning, these alternate pathways are built with a slope to enable flow of water. Canals need to be regularly cleared of debris and sediments to ensure unobstructed flow of water.

Flood walls

Flood walls are large vertical walls/structures installed near buildings or settlements to keep floodwaters out. They are commonly made of pre-fabricated concrete elements and are typically deployed in areas with too little space to construct dikes or levees. These barriers do not have as high of a flood resistance capacity as dams or levees and work best against low-intensity seasonal flooding.

Flood barrier

A flood barrier is a large metal, concrete or stone-fill structure installed parallel to the river's cross-section to regulate the volume of water flowing downstream. It is synonymously called a surge barrier as it restrains excess water from flowing downstream during a storm or tidal surge, and slowly releases the backed-up water once the surge has passed. They can be movable like the Thames Barrier (built across the Thames River in London which protects the city from flooding) or immovable like the Foss Barrier in York, England (Horner, 1979). Flood barriers are often built in combination with floodwalls or dikes/levees for increased flood protection. The term may also refer to small-scale barriers deployed around individual homes or buildings as an additional layer of flood protection, and are growing increasingly popular in flood prone regions.

While nature-based solutions (NBS) to fluvial flooding have been around for a long time, they have become popular as publicly funded projects only as recently as the 21st century. In 2006, the Dutch cabinet proposed the 'Room for the River' project with a budget of €2.2 billion. The project includes interventions like moving existing dikes further away from the river bank, increasing the depth of flood channels, reducing the height of groynes, and removing obstacles from the course of the river, which would all contribute to a greater cross-sectional area for the unimpeded flow of water in the Rhine, Meuse, Waal and Ijssel Rivers (van Herk et al., 2015). The 2007 Flood Directive passed by the European Union was another key milestone in promoting nature-based flood solutions as a mainstream flood control practice. The directive mandated flood risk assessments that considered the social, economic, environmental and cultural impacts of floods, and also pushed for 'prevention, protection, and preparedness' when dealing with floods (Directive, 2007).

NBS focuses on flood management at the larger catchment scale and are hence also referred to as 'catchment-based flood management' (Dadson et al., 2017). As a relatively new concept that may be limited by existing governance structures, NBS is frequently implemented in combination with traditional engineered flood control measures. NBS solutions are rarely an isolated intervention; they often are a series of interventions specific to the context where they will be implemented. Therefore, there may be considerable overlap between measures and no two solutions will be the same. Some common nature-based fluvial flood control measures and concepts are described below in Box 2. This study focuses on the case of floodplain restoration and river renaturation as a combined intervention, and is discussed in greater detail in Chapter 4.

Historically, many urban settlements have been built on floodplains – such settlements have degraded the environment and increased flood risks to the population settled there. Restoration of floodplains are now being done in many parts of the world, most commonly in Europe. Land-use policies are used to relocate urban settlements farther away from fluvial floodplains, and to restrict further urbanization on them. This relocation creates more room for rivers to flow during peak discharge periods without risking the lives and livelihoods of people living nearby. Floodplain restoration also entails allowing native vegetation to naturally grow back in the region, which further contributes to attenuation of floods.

A complementary approach is renaturation or renaturalization of rivers wherein the riverine system is restored to its natural state by removing obstructions; restoring natural floodplains, wetlands and marshes; creating new streams or small rivers that connect to the main river; developing an efficient flood map; and implementing land-use regulations that minimise impediments to river flows.

Box 2: Examples of common nature-based flood control measures

Room for rivers

As the name suggests, this type of solutions aims to create more room or net area for the river to flow such that waters do not exceed the river's designated flow area (or flood zones) during peak discharge (van Herk et al, 2015). This can be achieved through some of the following interventions: (1) clearing obstructions like fallen trees, debris and engineered structures in the waterway to allow fluvial waters to flow unimpeded, (2) increasing the depth of the river channel by clearing the riverbed of wastes, and/or removing some of the silt deposits from the riverbed to create a greater cross-sectional area for flowing water, (3) moving river infrastructure like dikes or levees further away from the river bed to create a larger floodplain, and implement land-use changes to limit year-around human activities on to reduce flood risk, and (4) remove or reduce the height of groynes (hydraulic structures constructed perpendicular to the shore or riverbank in order to interrupt the flow of water, and to limit the movement of sediments) so that river water may flow more smoothly. The focus of this type of effort is to enable greater mobility to fluvial waters (Biron et al, 2014). Through such efforts, the river would have more area to flow through while also greatly reducing flood risk.

Beaver dams

Beaver dams are dam-like structures built naturally by beavers out of trees, branches, logs, grass, mud and rocks. Beaver's build these dams to ensure higher and more stable waters for their habitation. They act much like traditional engineered dams in how they store and slow down the flow of water. However, they are much smaller in scale and thus don't impact the surrounding ecosystems as gravely as a dam would. The freeboard above the water level allows excess water behind the dam to be discharged naturally during peak flow. The dam also allows water to flow through it at a retarded rate. Neumayer et al (2020) conducted a modeled analysis of beaver dams and concluded that their flood control ability can withstand some of the strongest rainfall events. Recognizing its many benefits, many regions around the world have been reintroducing beavers in floodplains where they're extinct, and protecting them in regions where they're endangered (Rosell et al, 2005).

Restoration of wetlands

Similar to floodplain restoration, efforts to restore wetlands, which were historically drained to accommodate urban growth, are now being made. Wetlands serve as surface water storage facilities during high precipitation periods, which help to attenuate flood risks by regulating peak discharge water volumes (Pattinson-Williams et al., 2018). Mitsch and Gosselink suggest that "3-7% of temperate-zone watersheds should be in wetlands to provide adequate flood control and water quality values for the landscape". In addition to flood control, wetlands have been found instrumental to carbon sequestration which is essential in combatting climate change and its effects.

The renaturation method also entails reconnecting streams, rivers, brooks, wetlands, etc. in a way that mimics pre-development conditions. Biron et al. (2014) sum up that the main focus of this method is on fluvial flood mechanisms, meanwhile, Kuks (2002) says “river renaturalization is seen as the best way to achieve more water buffering capacity given the future climate expectations.” This approach is also known by other names like freedom space for rivers or river corridors.

2.1.4 Flood control and geopolitical tensions

Rivers are inherently transboundary entities, i.e., they often flow through different geopolitical regions. Effective and sustainable planning of flood control measures is somewhat tricky where rivers cross municipal, provincial, state and/or national boundaries. Studies like Triet et al. (2017), Duc Tran et al. (2018) and Thanh et al. (2020) illustrate how construction of embankment-like flood control measures upstream increases volume and velocity of discharge downstream, which increases flood risk as a consequence. However, flood control planning is largely confined to geopolitical boundaries. STÉPHANIE (2009) points out that although France and UK have national flood risk management plans, severe challenges surround the implementation of such plans. Firstly, the plans are drafted and passed at the higher central or national level, to be implemented by local provincial or municipal level authorities. Such a top-down approach hinders context-specific flood control planning. Second, there are numerous other official stakeholders involved, which blurs the lines of hierarchy and order in planning efforts, thereby reducing clarity and further complicating the planning process. Thirdly, the social and economic interests of residents and their elected representatives vary even across regions within the same country. Therefore, a flood management plan at the national level may not be representative of the interests of some communities who then resist the implementation of plans. STÉPHANIE (2009) also highlights how, oftentimes, local residents and authorities are not educated as to advancements in flood control practices and research; top-down flood management plans may be received, and rejected, as revolutionary ideas of unproven effectiveness. Moreover, the personnel in charge of implementing such measures may not have the necessary skillset to do so.

The challenge of transboundary interests gets even more difficult when a river flows through different countries. For decades now, tensions between the upstream Ethiopia and downstream Egypt and Sudan have been rife owing to disputes over water from the Nile River and its tributaries (Swain, 1997). Matters have only escalated since Ethiopia announced the Renaissance Dam project, which, although intended to boost Ethiopia’s economy, is perceived as a threat to the lives and livelihoods of residents in Egypt and Sudan (Abtew, 2022). The conflict has also forced other countries like China and the USA to take sides, which highlights the sensitive interactions of multi-national interests when it comes to planning of water infrastructure.

Owing to the various implications and interactions at play in fluvial flood control projects, official project impact assessments such as Environmental Impact Assessments (EIA) and Social Impact Assessments (SIA) are required to be carried out. The following section looks at the history and evolution of impact assessments, as well as their major shortcomings, as discussed in popular literature.

2.2 Impact assessments and their (lack of) efficacy on the grand scale

Development projects, like flood control infrastructure, require considerable capital and impact the local and global community in many ways. For the implementation of such projects to make sense, cost-benefit analyses are often carried out. Traditionally, the 'costs' were a measure of monetary investment whereas benefits included safeguarding of people, service provision, economic benefits, etc. The late 1900s saw a great deal of interest in environmental concerns, particularly after the creation of the United Nations Environment Programme (UNEP) in 1972. It was around this time that the first Environmental Impact Assessment (EIA) was formulated in the US, which then rapidly spread to other nations worldwide (Hironaka, 2002). An Environmental Impact Assessment has now become a prerequisite to most development projects and details the predicted environmental consequences and effects of the project (Gilpin, 1995). In addition to predicting the immediate and long-term environmental effects of a project, an EIA typically lays out project alternatives that will have lower environmental impact; they are essential tools in carrying out public consultations (Hironaka, 2002).

The global popularization of environmental impact assessments can be traced back to rising pressure on the UNEP and world banks to respond to growing environmental concerns, particularly from activists in the developed western nations. In fact, an EIA became mandatory for approving funding from entities like the World Bank, Asian Development Bank and the African Development Bank (Hironaka, 2002). As EIAs require the efforts of educated members from scientific communities, they are given the status of legitimate and fully accurate. However, in recent years, many studies have highlighted the major shortcomings of EIAs, key among them being the failure of EIAs to capture the full extent of negative effects of large-scale development projects.

2.2.1 Challenges and shortcomings of conventional EIAs

One of the biggest concerns with employing EIAs as an environmental management tool is the fact that not all projects require an EIA (Noble, 2011). Small-scale projects or those which are perceived to not have any significant impact assessments are often not subject to elaborate environmental impact assessments. Noble (2011) calls this step the "Screening" stage of project planning and EIAs.

Singh et al. (2020) in their paper analysing EIAs for projects in British Columbia (Canada), California (United States), Veracruz (Mexico), Brazil, England and Wales, Queensland (Australia) and New Zealand, found that impacts listed as 'significant' were consistently low across all cases studied, suggesting that either (a) only projects with low/benign impacts are seriously considered for implementation, or (b) the analysis methodologies "contribute to bias against finding significant adverse impacts". Flyvbjerg (2009) in his controversial piece point out how costs are very often underestimated and benefits are hyper-inflated when assessing infrastructure projects during the planning phase. This results in the implementation of less-than-ideal projects with huge ramifications in the future. The deforestation of forest or wetlands for agricultural purposes is one such project where cost-benefit analyses have been grossly misrepresented. Studies have found that deforestation and increased agricultural activities can disrupt natural precipitation patterns (Leite-Filho et al., 2021), cause severe degradation of soil and nearby water sources, and contribute directly to climate change. Unpredictable rain patterns and rising global temperatures negatively impact agricultural productivity (Felter & Robinson, 2021). However, these negative impacts are often downplayed with the short-term agricultural productivity touted to be a big gain, particularly by politicians who aim to safeguard their interests through actions which can reap immediate positive results. Noble (2011) writes that EIAs are "rarely value-free or complete, and is frequently constrained or shaped by political factors and societal interests".

Such distortions and gaps in the narrative of an impact assessment is not limited to environmental impact assessments. Every project has an impact on the local and national economy in some way. Infrastructure projects also require space which can have considerable ramifications on the local residents, and this social impact would be higher in more densely populated areas like urban centers. Phillips and Edwards (2000) outline the various challenges, constraints and shortcomings of carrying out impact assessments in the context of one of their slum-revival projects. The project was funded by an international donor agency and implemented by a local government partner. During this project, they found themselves in a tough position of tailoring their questions and relaying their findings in a way that would be acceptable to the various stakeholders, i.e., the funding agency, local government, and the residents. They struggled to balance the interests of the officials who hired them whilst also staying true to the findings of their assessments. Phillips and Edwards (2000) cite the Terms of Reference, which is a contract between the assessor and the agency hiring them, oftentimes regulate what may or may not be asked. They also point out that authors of impact assessments are likely to be influenced by their own backgrounds and prerequisite knowledge which would frame their narrative in a certain way (Wilkins, 2003).

As Pendse et al. (1989) point out, there are various methodologies in which impact assessments can be carried out. Some are very brief and address only certain obvious criteria, whereas the more comprehensive assessment methods entail time-consuming extensive research and quantification. Many projects are planned and executed within time constraints owing to funding schedules, political interests, contract periods, etc., thus leaving inadequate time to carry out a detailed project impact assessment. While assessment methodologies are not standardized, there is the likelihood that a certain method is employed by an agency for all types of projects, even when the specific method or checklist is incompatible with the project at hand. There also arises the possibility of limited funding which would prevent assessors to undertake a more elaborate and effective assessment method (Wilkins, 2003). The lack of a standardized assessment method results in EIAs that follow the narrative of the assessor. Furthermore, as impact assessments attempt to capture impacts to various systems (hydrological, geological, meteorology, social, etc.), it is critical to have multi-disciplinary teams to carry out project impact assessments (Noble, 2011). However, it may not be financially feasible to have such teams, particularly in developing countries where technical expertise may be limited.

Most of the EIAs or Environmental Impact Statements assessed by Singh et al. (2020) employed different methods for analyses. For a comprehensive assessment of project impacts, assessors would require a full range of pre-project data. Many developing regions lack advanced data collection systems that record precipitation patterns, humidity levels, soil conditions, ecosystem studies, etc., all of which are imperative to quantifying the impacts a project can have (Wilkins, 2003). According to Pendse et al (1989), the simplest method of carrying out an EIA is the ad hoc method. Such an assessment does not assure that all relevant impacts would be identified and could give rise to inconsistencies across the board. Further, it was observed that most EIAs only vaguely captured cumulative impacts; even when cumulative impacts were addressed, the methodology employed was not clearly defined (Singh et al., 2020). Ortolano and Shepherd (1995) even go on to say that cumulative impacts are often not fully addressed in EIAs.

In transboundary cases like fluvial projects, impacts can be observed far and wide over the course of time. Richter et al. (2010), Zhang et al. (2010), Mohamed (2012), and Sileet et al. (2013), among other studies, have shown how water projects in different parts of the world cause negative impacts downstream following implementation. Singh et al. (2020) also critiques conventional impact assessments for their somewhat myopic spatial and temporal scales. Their study found that EIAs typically assess impacts over spatial boundaries that do not correlate to the complete habitat of impacted wildlife populations. Furthermore, EIAs, specifically for mining projects as identified by Singh et al. (2020), were found to consider impacts of projects and mitigation measures only for a period of 0 to 4 years post project completion. Monitoring of impacts post project implementation are also rarely, if ever, conducted (Ortolano and Shepherd, 1995), even when recommended in the project's EIA. Additionally, Ortolano and Shepherd (1995) point out that sometimes, mitigation measures proposed in EIAs are not implemented. Singh et al. (2020) concurs by writing that "some mitigation proposals were worded in such a way that it was unclear if they would even be implemented" in the case of EIAs for mining projects.

Finally, it is imperative to engage the public and all concerned stakeholders in the EIA process as it can help "(1) access a wide range of information, including traditional knowledge; (2) identify socially acceptable solutions; (3) ensure more balanced decision making; (4) minimise conflict and potential costly delays; (5) reduce the possibility of legal challenge; and (5) promote social learning" (Noble, 2011, p. 5). However, public participation in EIAs has almost consistently been inadequate (Ortolano and Shepherd, 1995; Singh et al., 2020). Ortolano and Shepherd (1995) point out that although many countries "have mandated some level of public participation in EIA", the public's involvement either occurs too late to have any meaningful impact in the planning process, or is conducted simply as a way of informing local residents of the project plan without creating room for their input. A similar observation was made by Singh et al. (2020) in the case of numerous EIAs conducted across 7 regions. They found that in some cases "local stakeholders were simply provided with information about a planned development without an opportunity to voice concerns", but more commonly "local stakeholder concerns were documented (without follow-up) or responded to in facilitated meetings without further opportunity to influence the design of the project or determination of significance". Singh et al. (2020) also found biases in the stakeholder groups that were consulted; consultations of stakeholders "disproportionately failed to include environmental, Indigenous and community groups even when these groups had a stake in a proposed development". It is important to note that exclusion of indigenous and local residents can be detrimental as they "often have dependencies on and histories linked to the environment not shared by others" and thus perpetuates a power-imbalance which has led to the erasure of indigenous culture world-wide (Singh et al., 2020; Banerjee, 2000; Ward, 2001).

2.2.2 Advantages of EIAs

Despite the many shortcomings, EIAs are still viewed as "a means to aid decision making through which concerns about the potential environmental consequences of proposed actions, public or private, are incorporated into decisions regarding those actions" (Noble, 2011, p. 1). It is the most widely employed environmental management tool worldwide and is used in more than 100 countries (Sadler, 1996; Noble, 2011). EIAs have made environmental considerations a vital part of project planning which has benefitted, however minutely, the planet and its various ecosystems. In Belgium's Dijle Valley, nature-based solutions to flood control were proposed as a more environmentally friendly alternative to an engineered solution after environmental impact assessments and research were initially carried out. Thus, EIAs have forced project stakeholders to rethink project planning approaches, and facilitated discourse around environmental issues in correlation to large-scale infrastructure projects.

When carried out effectively, EIAs also have the potential to engage stakeholders at all levels like officials, funding agencies, technical contributors, activists, and local residents, which can help foster long-term relations, and bring in more cooperative and collaborative action in planning (Wilkins, 2003). This kind of public engagement also pushes communities to think beyond the individual interest and look at the collective good which contributes to better communal relations. Wilkins (2003) refers to this shift in perspective as "social learning".

As funding from many international agencies is dependent on project impact assessment reports, even developing countries are being forced to consider the environmental and social ramifications of large-scale infrastructure projects (Gilpin, 1995; Noble, 2011). Whereas in the lack of such a mandate, economic development would have likely taken priority in these countries. Therefore, EIAs are an instrument for the public good, albeit one in need of serious improvement.

CHAPTER 3 Engineered solutions: The case of Dike construction in Can Tho City in Vietnam's Mekong River Delta

In chronicled history, dikes/levees have been used as a flood control and water retention measure since as far back as 70 CE in Rome. An example is the Devil's Dikes stretching between modern day Serbia, Romania and Hungary which are a series of fortifications built by the Romans along the Tisza River. Closer to home, the USA and Canada have also employed dike and levee systems for riverine and coastal flood control for centuries. This chapter explores the case of flood control and its impacts on Can Tho City and the section of the Mekong River Delta in Vietnam at large. The region has a long history of employing engineered measures to manage fluvial flooding which more recently includes an extensive network of dikes and water channels. The following sub-section illustrates how the findings of the Mekong Delta case are not exclusive to the Mekong region by briefly discussing similar examples from across the world.

3.1 A background of flood protection dikes in Can Tho City and the Mekong Delta

Can Tho City is the fourth largest city in Vietnam with a population of approximately 1.3 million as of 2018 (Statistical Yearbook of Vietnam, 2018). It is the largest settlement in the Mekong River Delta. The city, and the province at large, is located on the southwestern banks of the Bassac River which is a distributary of the Mekong and Tonle Sap rivers (see Figures 2 and 3). The lower section of the Mekong River lies roughly 30 km northeast of the city, and is a major source of water for the region. The Mekong River Delta is home to around 22% of Vietnam's population with a growth rate of 2.4%. The Bassac and Mekong River systems play a large role in making the delta highly fertile, which has allowed the region to produce about half the country's total food volume. Though 52% of Can Tho City's inhabitants can be classified as urban residents, 63% are employed in agricultural activities, with rice production being the main economic activity.

3.1.1 Flooding in the region

The Mekong Delta primarily experiences two seasons: the dry season spans from December to May, and the wet monsoon lasts from June to November. During the monsoon, the Bassac and Mekong rivers carry high volumes of water as a result of heavy rainfall which peaks between September and early October (Huu, 2011). This annual increase in discharge causes silt carrying waters to overflow the river banks and flood the surrounding areas. Owing to the delta's low topography, these annual floods inundate about two-third of the Mekong River Delta every year, leaving behind silt deposits. These deposits then form alluvial soil which, as discussed previously, leaves the delta fertile and wellsuited for agriculture and food production. Thus, historically, local residents depend on annual flooding to sustain their life in the region. More recently, however, the flood events have grown more severe and generates more damage than benefits. In the year 2000, during one of the regions worst flood events, flood related damages in Can Tho City amounted to over 600 billion Vietnamese dong (roughly 40 million USD) (Table 1). Inundation depths in Can Tho City are typically between 0.5 m to 1 m, as discussed in Xuan and Matsui's 1998 paper, which is considered high. Figure 4 below illustrates the inundation depths across the Mekong River Delta.

Numerous studies, by both private researchers and those commissioned by official entities like the Vietnamese government and the Mekong River Commission, have uncovered various causes for this drastic change in the hydraulics of the Bassac and Mekong Rivers. One of the most significant causes is the increase in volume of runoff water in the river. Globally, precipitation patterns have been changing in recent years (Dore, 2005). Research has found that climate change and global warming have caused an increase in average annual rainfall in the Mekong River basin owing to increased rates of evaporation from nearby water bodies and evapotranspiration as regional temperatures rise (Eastham et al., 2008). Climate change has also accelerated the melting of glaciers and snow in the mountains in the Tibetan plateau where the Mekong River originates, thereby increasing the amount of water flowing into the river upstream. As these waters flow downstream, they gain momentum and collect more stormwater that runs off from impermeable urban surfaces.

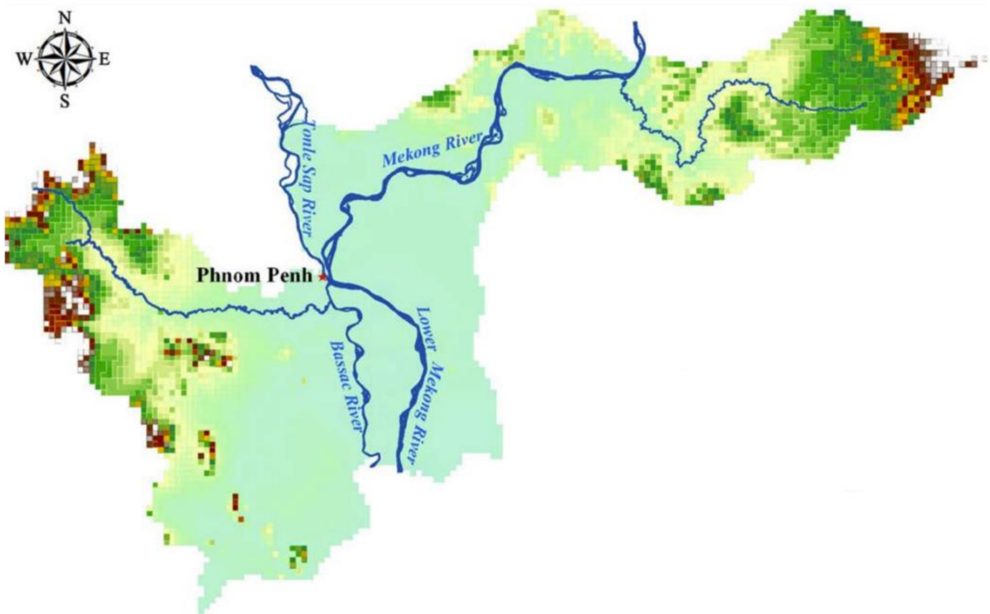

Figure 2 Bassac and Mekong rivers in Vietnam's Mekong River Delta
Source: Xu et al. (2020)

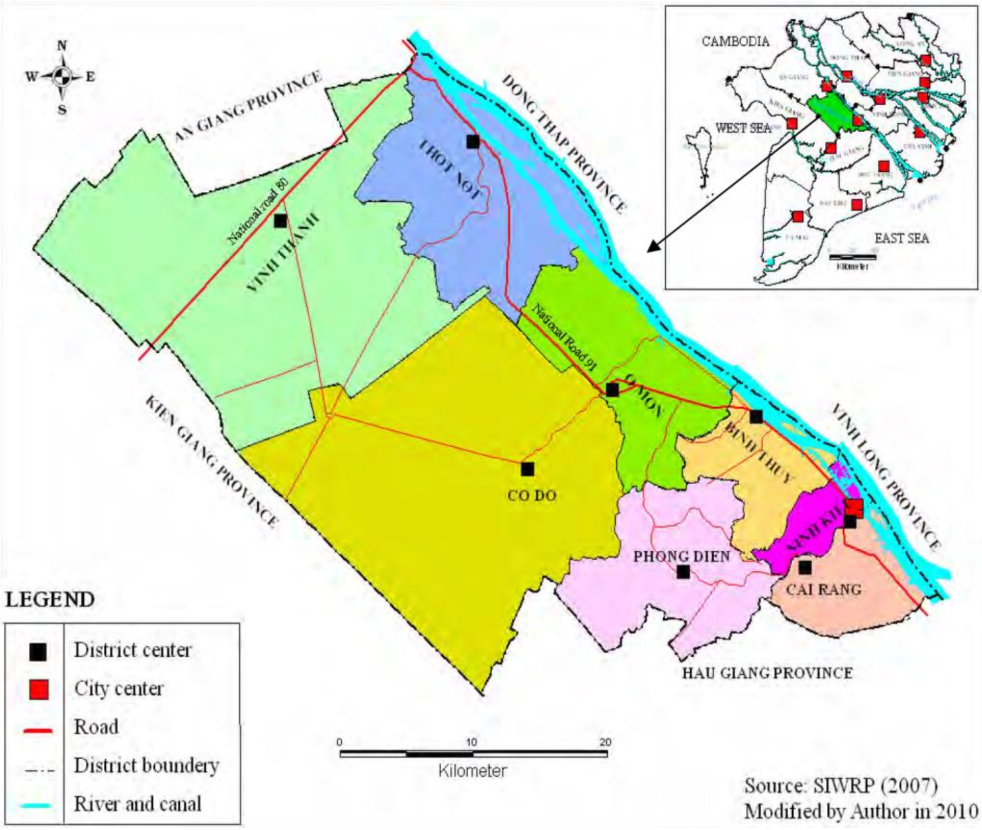

Figure 3 Location of Can Tho province and city near the Bassac River

Source: Huu (2011)

Table 1 Flood damage costs in Can Tho City 1991-2001

Unit: VND billion (USD 1 = VND 15,000)

Items of damages	1991	1994	1995	1996	2000	2001
Rice production	38.70	52.18	7.00	27.20	86.25	21.50
Vegetable and industrial plants	13.71	15.50	2.00	5.00	15.60	4.60
Fruit tree	147.50	242.66	28.80	60.06	206.40	58.65
Fishery	6.50	8.20	2.16	0.03	1.25	0.50
Transport and irrigation	72.50	38.32	26.25	40.40	138.60	38.28
Education	3.50	8.46	0.15	2.90	6.90	2.60
Health care	1.70	1.50	0.03	0.14	1.50	0.70
Housing and others	35.00	21.37	1.20	65.80	145.80	55.20
Total	**319.11**	**390.19**	**67.59**	**201.53**	**602.30**	**182.03**

Source: Huu (2011). Data from Southern Institute for Water Resources Planning (2005)

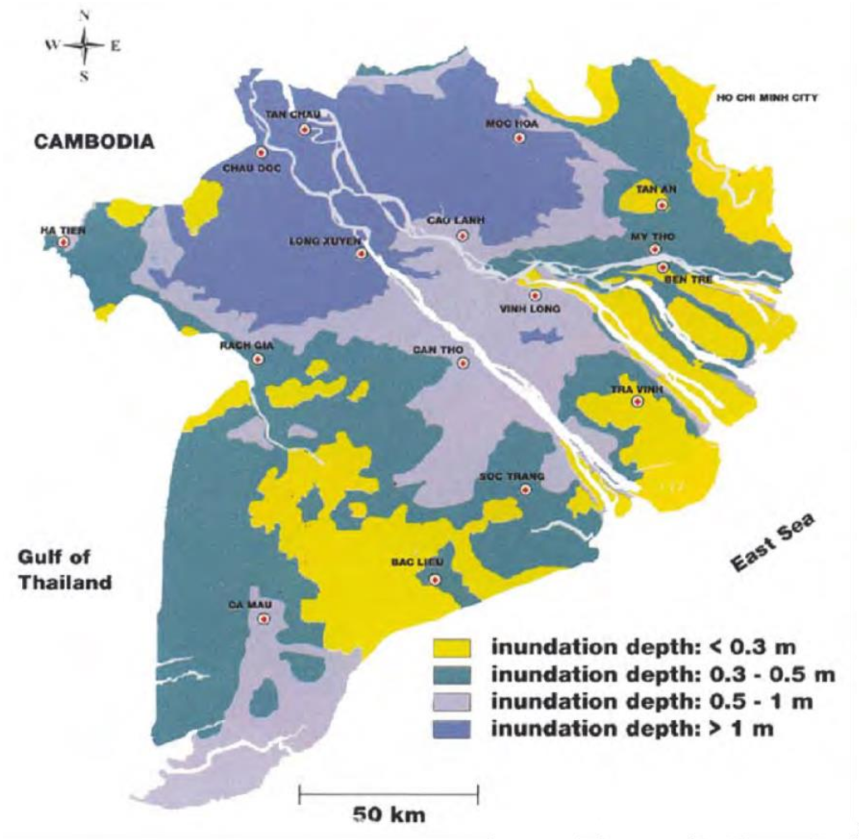

Figure 4 Flood levels in the Mekong River Delta
Source: Xuan and Matsui (1998)

Higher discharge volumes alone are not very detrimental; however, combined with the effects of manmade infrastructure like dams, the velocity of water as it reaches the Mekong Delta and Can Tho province become perilous. In China alone, there are eleven dams that straddle the Mekong River (Eyler, 2020) with many more being planned or under construction as the river makes its way through Laos, Thailand and Cambodia before eventually draining into the South China Sea through Vietnam. These dams, while a vital source of hydroelectricity, prevent the passage of sediments and silt leading to degradation of the riverbed which further accelerates the velocity the flow of river water (Vaidyanathan, 2011). These large volumes of water traveling at high velocity are more likely to veer off course, inundate wider regions more deeply, and cause greater damage than in the past.

Another effect of climate change on water regimes in the delta is the rise in sea-levels, notably the South China Sea where the river ends, and associated changes in tidal patterns. The Bassac and Mekong Rivers, and the delta at large, are low-lying regions with an average elevation of 0.8m above sea level (Minderhoud et al., 2019). As sea levels rise, drainage of flood waters from such a low-lying area takes longer, which in turn contributes to greater risk of flood related damages. Saltwater intrusion, coastal flooding and coastal erosion are other phenomena that can increasingly be observed in the region as a result. These effects, along with less sedimental depositing occurring around the delta and prolonged groundwater extraction, has contributed to rising land subsidence in the region (Minderhoud et al., 2020) which results in higher flood water levels and longer inundation periods.

3.1.2 Water management and flood control infrastructure in the delta

As mentioned earlier, the Mekong River Delta is a region dominated by agricultural activities. In pursuit of higher agricultural productivity, many public works were undertaken from 1930 onwards which entailed draining of marshes, swamps and forests and their conversion to agricultural land. Following the formation of modern-day Vietnam in 1975, a more systematic approach was taken towards the development of the country and its economy, and switches were made to higher-yield crop varieties and farming practices (Huu, 2011). To facilitate greater agricultural output, water management and flood control measures were adopted in the Can Tho City region. Extensive networks of artificial canals were built linking various arms of natural rivers in the delta. These canals served the dual purpose of freshwater distribution to Can Tho City and its neighboring districts, and drainage of floodwaters from areas west of the Bassac and Mekong Rivers (Thanh et al., 2020; Huu, 2011). Between 1996 and 2001, based on the country's Five-Year Development Plan, more comprehensive low-dike systems and hydraulic structures were built to better manage flood waters from the Mekong River (Triet et al., 2017). Low dikes, as the name suggests, are low in height with crests that reach the maximum water level during the early monsoon month of August. The intent of low dikes is to hold off seasonal fluvial inundation long enough to harvest the summer-autumn crops, after which the delta can be renourished with silt laden floodwaters during the peak discharge period (Huu, 2011).

In 2000, Can Tho City and the delta experienced a disastrous flood which inundated over 97% of the Mekong River Delta and caused millions of dollars worth of damage (Balica et al., 2014). This flood instigated the large-scale construction of high dikes, ones with crests 0.5m higher than the 2000 maximum flood level (Triet et al., 2017; Huu, 2011). The high dikes were designed to completely keep flood waters out and was touted by the government as a measure to protect its citizens and their agricultural livelihoods. Construction of high dikes also helped improve rural-urban accessibility in the region with National Roads 80 and 91 being constructed on the main dikes that controlled floodwaters from the Bassac River. As holds true for any manmade intervention, there are a myriad of economic, environmental and social impacts associated with the construction of dikes, particularly high dikes, in the Mekong Delta. These positive and negative impacts are discussed below (Table 2).

3.1.3 Economic impacts of high-dike construction

The implementation of dike systems has benefitted the economy of the Mekong River Delta and its residents in many ways. Construction of dikes along with systemic draining of marshes and wetlands in the delta has helped transform more land area into arable agricultural land. The dikes prevent unfavorable levels of water from entering and inundating the plains of the delta where farming activities are carried out. Prolonged inundation and/or violent flooding can be detrimental to the viability of crops farmed, and thus dikes have played a big role in safeguarding farming in the region. With increased protection from flooding, farmers in the delta have been able to diversify their crop types, agriculture and farming patterns. The adoption of triple-rice-cropping systems has increased rice production outputs in the delta which has allowed the agricultural economy of the region to improve. Integrated rice-fish farming techniques have been implemented by many farmers in the delta and the Can Tho province, which has resulted in an increase in commercial production and fish sales. Farming of vegetables, perennial fruits and aquaculture has also now become viable which further contributes to the economy and national food production at large (Huu, 2011).

As the delta becomes increasingly urbanized with roads, schools, hospitals, etc., and a rapidly growing population, there is now more to be lost in flood related damages. Flood preventive dikes like those in the Mekong Delta protect residents and their property, as well as public property, by controlling annual inundation in the delta to levels deemed manageable. Thus, short term risk of floods and flood related damages to the regional and national economy can be averted. However, as discussed in other sections of this paper, construction of hydrological infrastructure like dams, dikes and levees, upstream causes increased discharge in the downstream regions of the Mekong and Bassac Rivers, which threaten the integrity of flood protection dikes (Thanh et al., 2020). With increased land subsidence in the delta and changing hydrological regimes in the rivers, dike breaches occur each year during peak flood periods. The costs for repairing the broken dikes are borne by local residents and authorities. Together, initial implementation, maintenance and repair costs, constitute a heavy economic toll on the local farmers and residents (Nguyen, 2014; Huu, 2011).

In addition to the costs associated with construction and maintenance of dikes, local residents have incurred other losses (Nguyen, 2014). The yearly seasonal flooding allowed native fish species from the rivers to migrate into the floodplains, which served as breeding grounds for them. Construction of dikes has obstructed this migration, with possible fishing revenues lost to residents. Furthermore, the floodwaters played a vital role in fertilizing soil in the delta. The flood preventative action of high dikes reduced soil fertility, prompting farmers to spend money out of pocket for fertilizers and agrochemicals. When reporting the economic impact of high-dike construction, the government correlates improved agricultural output to flood control. Meanwhile independent researchers internationally point out that it is the use of fertilizers that has led to the increased agricultural production in the country (Manh et al., 2014).

3.1.4 Environmental impacts of high-dike construction

The major motive behind dike construction in Can Tho province and the Mekong Delta was to protect the lives of residents and to safeguard crops and agriculture in the region. While these goals were largely achieved, there have been environmental repercussions to the implementation of high dike systems. Numerous hydrological studies over the past two decades have uncovered that upstream dike systems, and other hydrological infrastructure, have increased the volume and velocity of waters downstream causing higher peak discharge water levels (Triet et al., 2017; Duc Tran et al., 2018; Thanh et al., 2020). Hydrological simulations and modelling have shown that in Can Tho City and province maximum water levels have increased by 9-13cm after dike construction and the annual inundation period has also increased by 15 days (Triet et al., 2017). As explained above, the combined action of climate change, land subsidence, land use change and dike construction related alterations in hydrological regimes of the Bassac and Mekong River systems have increased flood risk in the region. The increase in flow velocity of river water is also causing greater erosion of the riverbed and earthen dike systems which in turn affect groundwater levels and the integrity of dike systems respectively.

Another impact of implementation of dike systems is its negative effects on the sustainable reproduction of native fish species. Dikes act as a physical barrier to fluvial flood waters which carry mature fish into the floodplains. Typically, fish in the Mekong and Bassac River systems migrate to the floodplains to breed but conversion of the floodplains to agricultural land and prevention of fish carrying floodwaters from entering the plains has deprived native fish from its breeding grounds which in turn has caused a decline in their numbers (Huu, 2011). Dike construction related loss in soil fertility further encourages farmers to use fertilizers and agrochemicals which are leading causes of water and soil pollution. The chemicals leach through the soil into groundwater and negatively affect the health and wellbeing of locals. Fertilizer and agrochemical residues also wash off the field into the rivers which poison fish, wildlife and other aquatic beings (Kiet et al., 2021).

The implementation of dike systems across the Mekong River Delta was accompanied by drainage of floodplains, wetlands and marshlands. This was done in order to increase land available for agriculture, the leading contributor to Can Tho and other provinces' economy. Large swathes of forest land were also cleared for this purpose (Huu, 2011). Forests are major regulators of the earths water, energy and carbon cycles, and deforestation has been found to be a significant contributor to climate change and global warming (Ellison et al., 2017). Wetlands, swamps and marshlands are also rich in biodiversity and contribute to carbon sequestration. The destruction of such lands for agricultural purposes exacerbates the global climate change crisis.

3.1.5 Social impacts of high-dike construction

Construction of flood control and irrigation infrastructure in the Mekong Delta has positively affected the regions agricultural economy. The diversification and intensification of agricultural practices have generated more employment opportunities for local residents and has enabled them to earn more income. This has allowed the socio-economic scenario in the region to advance and has drawn in more people and businesses. The growing population is also increasingly urbanizing. With the stability offered by planned flood control measures, Can Tho City has been on an astounding journey of urbanization. National Roads 80 and 91, built following high-dike construction, improved access to schools, hospitals, and other services. Better and faster transportation also led to an expansion of trading within and outside the region. Can Tho now aims to become the region's first Smart City by 2025 (VNA, 2020). Plans for e-governance, IT integration in transportation and traffic management, IT enabled city planning and management measures, etc. are currently underway as part of this transformation.

However, as explained above, dike construction has led to changes in the hydrological regime of the Mekong and Bassac Rivers. The rivers and its tributaries now experience greater levels of riverbed erosion than in the past, potentially lowering groundwater levels (Gilja et al., 2010) and threatening potable water supply in the region. The erosive action also threatens the integrity of dike systems that were built to keep residents and their livelihoods safe. Given present water levels and flow velocity in the river, dike failure could catastrophically flood parts of the delta. Flood currents could destroy crops, damage infrastructure, and take the lives of the growing population. Huu (2011) documented resulting fear and apprehension among residents even a decade ago. Furthermore, the costs of construction, repair and maintenance of dikes are being borne by the farmers the dyke system is intended to directly benefit which takes a huge financial toll on the farmers. This can be especially challenging to poorer farmers, particularly in case of poor yields during a season.

Dike system planning in the region has been undertaken via a top-down approach with responsibility assigned, in the 2000s, to the Ministry of Agriculture and Rural Development (MARD) and other official agencies (Huu, 2011). The flood control dike system for Can Tho City was planned almost exclusively based on input from political organizations and Vietnam's Sub-Institute for Water Resources Planning (SIWRP). The plan focused solely on flood control and hence did not wholly reflect the interests and practical needs of different social groups in the community. This process led to dissent amongst the local population, many who had years of experiential knowledge about living in harmony with the floods. In fact, many rural residents in the province said that dike construction has done more harm than good, citing aggravating flood risks and degraded natural resources to name a few (Huu, 2011).

3.2 Dike/levee construction impacts: A wider global issue

A look at case studies and reports of dike construction in various regions show that the observations made in the Mekong River Delta are not isolated. Similar dynamics are found globally, from the United States and Latin America, to Europe. Construction of dikes has lessened immediate flood risks but generated a range of other social, economic, and environmental impacts.

The Mississippi River Basin in USA has seen intensive dike construction by both official agents and private parties. Following a devastating flood in summer 1993 which saw the failure of about 70% of dikes/levees in the Midwest, American flood management practices were called into question (Tobin, 1995). Studies that followed uncovered that in the Mississippi Basin, dike construction led to changes in the hydrological regime of rivers which put unanticipated pressure on the dikes and threatened their structural integrity through the waters erosive action (IFMRC, 1994; Huthoff et al., 2013). Myers and White (1993) postulated that the levees suffered structural damage through prolonged exposure to high water levels leading to seepage of moisture. Numerous changes in environmental conditions were also identified in relation to dike implementation in the region, including an increase in deforestation, urbanization, and destruction of wetlands (Tobin, 1995). Dike construction in the Mississippi basin created a sense of safety and security amongst people, which encouraged intensive habitation, industrial development and urbanization of the region; when dikes later failed across the region, there was human and economic losses. Several nationally sanctioned studies later uncovered that most privately constructed dikes/levees did not meet design and safety standards which resulted in calls for better monitoring and regulation of dike construction in the country.

In densely populated Bangladesh, dikes constructed along the Jamuna River have enabled large numbers of people to inhabit riverbank areas. However, the risk of dike failure is growing, events which would lead to the loss of lives of many along with millions, if not billions, of dollars' worth of property and infrastructure damage (Ferdous et al., 2019).

Dike construction along the banks of Danube and Tisza Rivers in Hungary spanned a total length of 792km in 1840 (Nagy, 2006). Between 1945 and 1993, over 84 levee failures occurred making the dike/levee failure rate in the country quite high. Structural and engineering related causes for failure include overtopping, hydraulic soil failure, loss of stability owing to embankment saturation, and leakage along structures. Hydrological and meteorological causes, such as increased snowmelt and storm floods, were also found to trigger dike failures. These failures led to massive losses.

In the nearby Dutch delta, intensive dike and levee construction has been found to accelerate land subsidence and related issues (van Staveren & van Tatenhove, 2016). A reduction in silt deposition in the delta was also observed. Meanwhile, sediments on the riverbed raised river water levels, which in turn meant strengthening and raising of embankments was required, thus locking the delta into a cycle of dike dependency.

Changes in hydrological regimes and consequent impacts on local ecosystems are a consequence of dike construction in Venezuela and Germany as well (Smith et al., 2006; Leyer, 2005). In Germany, the spatial distribution and species composition of plants were negatively affected owing to changes in water level fluctuation patterns. Flood regimes and downstream water flows in Venezuela were affected by implementation of dikes in the Llanos de Orinoco region resulting in changes in proportions of different ecosystems in the area.

The environmental impact assessment authored by Hassan et al. (2006) of dike systems between Bor and Malakal along the White Nile in South Sudan highlighted that dike construction would lead to increase in flood depth and duration, significant changes in vegetation distribution and plant species, decline in wildlife numbers, reduction in aquatic biodiversity and native fish species, salination and agrochemical related pollution of water and soil, and increased future flood risk. Vancouver's infamous Seawall near Stanley Park is essentially a dike-like embankment built to shield the region from coastal effects. As Lee (2019) observes, coastal dikes, much like fluvial dikes, can contribute to degradation of land and marine life over time.

3.3 Conventional impact assessments vs. actual impacts

The above sections illustrate how there has been a long history of dike/levee construction across the globe. Much of it has occurred with strong political backing. Despite the fluvial flood control capacity of dikes/levees, they have numerous negative impacts on local and catchment-level ecological functions, local economic well-being, and social security.

A common theme across all the cases discussed above was how dike construction upstream had negative influences on downstream hydrology of river water. This relationship highlights how water infrastructures have transboundary impacts; most rivers pass through two or more countries. As observed in the Mekong Delta, despite efforts to manage the river and its waters collaboratively, construction of water infrastructure along the Mekong River and its tributaries are undertaken by local level authorities with little to no consultation with authorities in other regions. One contributing difficulty is that most conventional project impact assessments look at the effects of the project within its immediate vicinity or within the region's bureaucratic boundaries alone. Such an assessment is inherently flawed; project impacts transcend these arbitrary boundaries.

Although research has found dike and engineered infrastructure to be detrimental to the ecology and hydrology of the river and its floodplains, as of 2015, proposals were made for further construction of engineered flood control measures along the Can Tho River in the Mekong Delta's Can Tho City. Component 1 of the Can Tho Urban Development and Resilience Project (CTUDR) entails construction of a 5.5km embankment along the Can Tho River behind which roads and parks are proposed, as well as reinforcement, rehabilitation and reconnection of existing and new canals in the region. In compliance with the World Bank's requirement of conducting an environmental and social impact assessment for large-scale projects, a 322 page Environmental and Social Impact Assessment (IAC Vietnam, 2015) was jointly published by the People Committee of Can Tho City and their consultants IAC Vietnam and Sinh Thai Cice. While one would expect the document to outline all the negative environmental impacts of such a project, little to no mention has been made regarding long-term project impacts on the river hydrology, aquatic life and local ecosystems. The environmental evaluation for the selected embankment intervention alternative reads - "Ensuring urban landscape because of matching with old embankment system and increasing elevation in the future and ensure beautiful, durable and modern" (IAC Vietnam, 2015, p. 114). The selected alternative is also highlighted to be the least expensive option with the strongest potential to improve the social and economic scenario in the region, and is projected to have "No Impact" on "forests, natural habitats, fish and aquatic life". In fact, the report reads as a strong proponent for the project rather than a neutral assessment of actual project impacts. This advocacy resonates with Flyvbjerg's (2009) finding that costs are often underestimated, and benefits overinflated, in conventional impact assessments. Furthermore, a report that spans over 300 pages is less likely to be read by ordinary citizens, even though they are the ones who have lived experience of the locale and are the most likely to be affected. This case thus begs the question – are impact assessments truly reliable?

While dike construction is slowly waning in Europe and the USA, it is still being implemented as a flood control measure in the Global South. While it may be difficult to identify all the causes for such a trend, it is possible that one reason is the low cost associated with dike construction, particularly in densely populated regions where people have strong ties to their land and homes, as is common in many Global South countries. Another cause may be a lack of data and technical expertise, which forces impact assessors to resort to standardized assessment methodologies that may often fail to capture the true extent of impacts (Phillips and Edwards, 2000). Political interests may also play a role as older western practices of engineering are viewed to be superior by many in developing nations, so a government that implements infrastructural projects is more likely to be perceived as a harbinger of progress, which can then improve political standing. Funding for projects in such regions are also often obtained from international investors and lenders whose vested interests may be reflected in the impact assessments. Lastly, as climate change, globalization, the COVID-19 pandemic, and inflation further deflate the economies of developing nations, it is simply possible that short-term social and economic needs are prioritized over long-term effects on the environment. These conflicting interests influence the framing of official impact assessments which then fail to represent the truth about a project's impact on the society, economy and environment (Phillips and Edwards, 2000).

3.4 Key takeaways

- Dikes/levees are embankments; physical barriers that, when built along the course of the river, attenuate the flow of river discharge. They have long been used as engineered fluvial flood control measures in different parts of the world.
- The Mekong Delta case showed that while dike construction can promote local agriculture and reduce flood risks, it can be detrimental to local and catchment-basin area's ecological systems. Some examples include changes in river hydrology, disruption of fish breeding and migration patterns, and decline in local biodiversity (summarized in Table 2 below).
- The identified impacts are not only found in Vietnam's Mekong Delta case. Similar findings have been observed in dike construction projects in USA (Mississippi River basin), Bangladesh (Jamuna River), Hungary (Danube and Tisza Rivers), Netherlands (Dutch delta), Venezuela (Llanos de Orinoco region), and South Sudan (White Nile River), to name a few.
- Despite studies criticizing dike construction for their negative impacts, conventional project impact assessments fail to highlight the long-term and wide-scale negative impacts, and instead seem to perpetrate the notion that dikes are the most ideal flood control measure. There is however a shift away from engineered flood control approaches in the Global North, as discussed in the next chapter.

Table 2 Engineered solution summary table

	ADVANTAGES	DISADVANTAGES
Economic	1. Changes in traditional farming patterns leading to a stronger and larger agricultural economy 2. Large scale fish farming has now been made possible 3. Reducing short term risk of floods and flood related damages	1. Loss of soil fertility requires farmers to use more fertilizers which have economic implications. 2. High costs of repairing broken dikes fall on residents and local authorities
Environmental		1. Upstream dike systems have increased downstream flood peaks and water levels, increasing future flood risk 2. Flood regime and inundation levels in the region have been significantly altered. 3. Increased erosion of river banks as flow velocity increases 4. Native fish species have declined as (i) dike systems prevent migration of fish during breeding season, and (ii) conversion of fish breeding habitats to commercial agricultural land impede fish reproduction. 5. Reduction in soil fertility as silt transfer is prevented by dike barriers 6. Increased water and soil pollution as farmers use more fertilizers 7. Retention of flood waters encourages agricultural activity which entails clearing of floodplains, wetlands, forests, marshland, etc.
Social	1. Agricultural diversity to generate employment opportunities and income for local people 2. Improved social security from flood related damages and losses 3. Improved rural infrastructure (eg. roads) and better living standards for rural residents including better access to education for children.	1. Delayed drainage of floodwaters from paddy and rice fields which disrupts traditional ways of living in the region 2. Erosion of the riverbed would cause lowering of groundwater levels which threaten potable water supply for the residents. 3. Longer and violent inundation periods, particularly in case of dike failure, would cause damage to property, contaminate freshwater sources through interaction with sanitation services, and threaten food security. 4. Costs of repairing broken dikes are a burden on low-income farmers 5. Local residents and farmers feel excluded from the top-down planning process
Others	1. Somewhat replicable as long-established design standards exist.	1. Technical expertise required 2. High construction cost

CHAPTER 4 Nature-based solutions: The case of Floodplain Restoration and River Renaturation in Belgium’s Dijle River Valley

With global warming and climate change becoming a pressing issue, there has been a global shift to environmental awareness and the impacts of human activities on nature and its various natural processes. Recent studies have also uncovered the numerous negative environmental, social and economic impacts of engineered flood control infrastructure. As a response to the effects of engineered fluvial flood control, nature-based flood control approaches were adopted. There is limited literature on nature-based approaches, as it has been a formalised practice of only the last three decades. This chapter first explores in depth the case of the Dijle River nature-based flood control project in Flanders, Belgium, where the various projects impacts are addressed. The following section positions the findings from this case on the global scale with several similar cases in other parts of the world. The third section discusses the reliability of conventional project impact assessments in the context of nature-based flood control projects. A summary of key takeaways and findings concludes the chapter.

4.1 A background of floodplain restoration and river renaturation in Belgium’s Dijle Valley

The Dijle or Dyle River is a perennial river flowing northwards through central Belgium. It originates in Houtain-le-Val in the Belgian province of Walloon Brabant and flows past major cities like Leuven, Mechelen (Dijlestad), Wavre, Ottignies, Antwerp, etc. The Dijle extends for about 86 kilometres in length before merging with the Nete River to form the bigger river Rupel which then joins the Scheldt River. The Scheldt River flows through parts of France, Belgium and Netherlands before eventually draining into the North Sea past the Antwerp seaport.

The Dijle is a strongly meandering river with several sharp curves along its course (see Figure 5). It has carved out a valley that is roughly 60-70 metres deep and 1 kilometre wide (De Becker et al., 1999). While the Dijle used to be a constant base flow river, widespread and intensive deforestation during the early medieval times has resulted in a shift in the river’s hydrological regime to a frequently flooding alluvial one (Turkelboom et al., 2021). The deforestation has also lent to greater erosion upstream, which gets deposited in the valley as sediments and silt, making the valley and the Dijle’s catchment area fertile; agriculture (hay making, poplar tree cultivation, livestock grazing, etc.) has been practiced there for decades. The region also has high nature value and aesthetics, attracting many leisure homes.

Despite the dominance of agriculture and other human activities, there is an abundance of biodiversity, including rare species of birds, plants and animal. In the 1970s, the valley and its surroundings were designated as a “nature area” by the Regional Destination Plan. At the same time, the valley floor was designated as a European Bird Directive Area, a designation expanded to a large proportion of the region in 1992. Upstream, to the south of Leuven, are two nature reserves – the Vijver van Oud-Heverlee, operated by the Flemish Agency of Nature and Forestry (ANB); and the Doode Bemde, operated by a local NGO. The river itself is managed by the Flanders Environment Agency (VMM) who have initiated flood management efforts on the Dijle (Turkelboom et al., 2021; Flanders Environment Agency, 2011).

Figure 5 Meandering course of Dijle River
Source: Yves Adams/Vildaphoto (Turkelboom et al., 2021)

4.1.1 Leuven city and its flood management efforts

Leuven is the eighth largest city in Belgium and is the capital of the country’s Flemish Brabant province. It has a population of over 100,000. Many residents are international students, attracted by Belgium’s largest university, KU Leuven. The city has been threatened by large flood events on multiple occasions, inundations attributed to prolonged periods of heavy rainfall and excessive snowmelt. The January 1891 flood is said to have inundated about a third of the Leuven city centre. Flood risk has further increased following the expansion of the city onto the floodplains of the Dijle River after the second world war (Turkelboom et al., 2021). Floods like those that occurred in March (1947), August (1996) and September (1998) had the potential to cause widespread damage to lives and property, but damages were controlled through active flood management efforts such as locking a flood barrage around the city center, diverting excess water rapidly through canal systems, and activating other flood control structures on the Dijle itself.

In the 1970s and 1980s, there was growing demands for governments and the public water administration to mitigate social and economic flood risks (Turkelboom et al., 2021). Over 125 hectares of urban area in Leuven – including zones of historic significance and critical infrastructure such as roads, a hospital and university campus – were, and are, at risk of floods. Construction of multiple storm basins to store excess water during flood periods were proposed but blocked by a nature conservationist NGO that saw the construction as a threat to the local environment. For nearly 25 years, the NGO and affiliated environmentalists negotiated with government agencies and other stakeholders associated with this project to adopt a more "nature-oriented flood control approach" (Turkelboom et al., 2021). They engaged newspapers and other media outlets to raise awareness regarding the sensitive nature of the Dijle and its surroundings and the threats of gray infrastructure construction. By 1993, following legislation that mandated environmental impact assessments to be conducted for such projects, the NGO was recognized as a legitimate stakeholder/discussion partner, and the administration was forced to consider more environmentally-friendly alternatives for flood management in the region. Finally, in the year 2000, it was decided that an upstream alluvial floodplain (south of Leuven) would be restored and a single emergency storm holding basin would be constructed in Egenhoven (immediately south of Leuven) for emergency flood control (Demeyer and Turkelboom, 2013).

The nature-based solution entails several (non)-interventions, as elucidated by Turkelboom et al. (2021). They are as follows:

(a) *Using the storage capacity of the full natural floodplain:* One of the major "interventions" of this nature-based solution is to allow the Dijle to flood its natural floodplain upstream of Leuven city. A large portion of this area lies within the Doode Bemde nature reserve where the natural flooding would have little consequence on human habitation (Demeyer and Turkelboom, 2013). During peak discharge periods, sediment laden water from the Dijle will now exceed its natural banks in the upper sections of the river course onto its natural floodplain which will consequently reduce the volume of discharge as the river draws closer to Leuven, thereby reducing flood risk in Leuven.

(b) *'Zero management' of the river and its banks:* Another measure to regulate the flow of water in the Dijle is to naturally increase the roughness of the riverbed, particularly in the Doode Bemde and regions upstream of Leuven. Prior to the implementation of the nature-based solution, the Dijle was periodically cleared of fallen trees, silt, and other obstructions (Demeyer and Turkelboom, 2013). Fallen trees are no longer cleared and the riverbanks are not mowed along most parts of the Dijle. As a result, the watercourse has become rougher, slowing the flow of water downstream, and small floods, which affect the natural floodplain, are allowed to occur; these shifts reduce flood risk downstream (Turkelboom et al., 2021).

(c) *Reconnecting the rivers Leighracht and IJse:* The Leigracht is a watercourse that runs fairly straight near the upstream section of the Dijle. It joins the IJse River, which is a tributary of the Dijle, about 50m upstream of where the IJse joins the Dijle near Doode Bemde nature reserve (see Figure 6). Until 2002, there existed a siphon in the Leigracht just before it joined the IJse which prevented the regulation of water levels in the Leigracht. Since the siphon has been removed, the water level in the Leigracht varies with the water level in the Dijle (owing to their proximity and connectivity). This in turn allows for natural flooding of the river system's floodplains in the Neerijse basin (La Rivière, 2015).

(d) *Minimal infrastructure works:* It was decided that little to no infrastructural interventions would be included in the nature-based solution. Exceptions include, a single emergency storm basin at Egenhoven (in case of extreme rainfall in regions south of Leuven), and some small structures at the fringes of the floodplain. Levees in the Grootbroek region are also slowly being lowered to utilize the storage capacity in Florival (Demeyer and Turkelboom, 2013). The idea is to allow the Dijle and its floodplain to operate in the most natural way as possible.

What is particularly interesting about this case is that it was proposed as an alternative to engineered flood control measures. Therefore, many of the reports and literature related to this project is comparative in nature where the costs and benefits of the nature-based solution are juxtaposed to those of an engineered solution. Given that the project was debated for 25 years, several studies were examined flood control efficacy as well as environmental, economic and social impacts, as discussed in the following sections. The flood control effectiveness and impacts were assessed using different computer modelling methods, advancements in which helped establish the nature-based solution as the superior option. While the four main (non)-interventions have largely been implemented, the project can be considered as ongoing since the riverbed roughening through zero-management is a long-term undertaking and efforts to expand the floodplain capacity is still underway (Demeyer and Turkelboom, 2013; Turkelboom, 2021).

Figure 6 Leigracht joining Neerijse and Dijle
Source: Piessens and Vanvelk (n.d.)

4.1.2 Economic impacts

Adoption of a nature-based flood control solution in the Leuven area was eased by the presence of two nature reserves upstream of the city that reduced the economic costs of implementation. While returning the floodplain to its natural state was a shared goal for the nature reserves, the water agency, and many other stakeholders, the lands that were to be restored to a natural floodplain were already a part of the two nature reserves (particularly the Doode Bemde). Human habitation, property ownership, and business operations were minimal, which kept the often large financial and social burdens of expropriation and land acquisition to a minimum. Even outside the reserves, housing had never been very dominant in the valley owing to its waterlogged soils (Turkelboom et al., 2021). About 50 to 60 hectares of land were ultimately expropriated. These lands were identified as at risk of flooding more than once every 25 years in the nature-based scenario, although the one-time expropriation costs were far lower than the sum of post-disaster recovery and compensation costs (Demeyer and Turkelboom, 2013).

Engineered infrastructure projects also usually have high capital costs for design and construction. As the nature-based solution on the Dijle entails minimal construction of infrastructure (the one emergency storm basin at Egenhoven), implementation costs are far lower than the proposed multiple basin alternative. Demeyer and Turkelboom's (2013) report for VMM notes that operation and maintenance costs will be lower but "nature management" costs higher for the nature-based approach than the engineered scenario. "Nature-management" here includes annual or bi-annual mowing and maintenance of the grasslands in the floodplain and valley at large. With more frequent natural flooding of the floodplains and higher groundwater levels, the proportion of wet grasslands is higher in the nature-based scenario, which also requires more frequent mowing and specialized equipment. The cost of maintaining a hectare of wet plot of grasslands is higher than that of a dry plot which is more dominant in the holding basin scenario. Nonetheless, the overall project cost over a 30-year period is much lower in the nature-based scenario as opposed to the alternative. As the sediments are spread out over a larger area now, dredging of sludge from the riverbed is no longer needed, and is thus another cost saving.

In the run-up to having the nature-based solution chosen over the engineered one, local environmentalists and NGOs ran media campaigns and organized nature-walks to build closer relations between people and nature. These efforts resulted in implementation of nature-oriented recreational activities in the area upon residents' requests. All of this has contributed to an increase in local tourism, which, inadvertently, has aided the local economy.

The nature-based project has many ecological and social benefits of high inherent monetary value. For every tonne of carbon sequestered in soil, there is a monetary benefit of €220, which results in a gain of €61,759 – €71, 850 per year (Demeyer and Turkelboom, 2013). Similarly, the monetary value of denitrification ranges between €5 - €74 per kilogram of nitrogen, and the project is estimated to denitrify about 4,233,000 kilograms of nitrogen over a project lifespan of 30 years.

4.1.3 Environmental impacts

Not restricting waters from the Dijle and allowing the river to naturally and frequently flood its floodplains has helped increase soil fertility in the region. Even distribution of sediments over a much larger area is an additional benefit; when large quantities of sediments get deposited over local flora – such as often occurs with sediment catchment basins, the deposits can cause anaerobic degradation, choking and killing the plants (Demeyer and Turkelboom, 2013).

Natural roughening of the riverbed, which the nature-based approach promotes through non clearance of river obstructions, has several environmental benefits. As the riverbed becomes shallower from “zero-management” of the river, the river water flows more freely and overflows more uniformly and frequently during peak storms. Shallow and deep pools, small beaches, and non-vegetated banks, are formed. The different types of pools are home to a wider variety of aquatic beings thereby increasing aquatic biodiversity in the floodplains. Vegetation-free banks, such as those that now form in the Dijle floodplains, are excellent breeding grounds for bird species like the kingfisher. More frequent flooding has altered some of the characteristics of the floodplains, which can serve as favorable habitats to a host of new plant, animal, bird and insect species. As de Nooij et al. (2006) highlights, species diversity is greater in an area where a wider gradient of flood characteristics can be found.

Since the implementation of the nature-based solution, the river channel has roughened and, importantly, water quality has improved. Pollution control and water cleaning efforts undertaken all along the Dijle may be the cause of improved water quality, but so to may be increased environmental awareness. Fish quantities and diversity in the Dijle are also increasing. Less polluted and oxygen rich waters are naturally more favorable to aquatic life. The roughened river channel contributes to the formation of sloped banks, bank vegetation and aquatic plants, which all serve as good habitats for different aquatic species. Nonetheless, frequent flooding poses the threat of contamination of nearby sources of drinking water. To prevent such contamination, low dikes have been constructed around these sources which keep flood waters out.

Improvement in the Dijle water quality can also be owed to the higher rate of denitrification in the nature-based scenario (Demeyer and Turkelboom, 2013; Turkelboom et al., 2021). Denitrification is the process by which nitrates (NO_3) in water gets converted to nitrogen (N_2) by the chemical action of bacteria which is then released into the air. Denitrification capacity of swamps, terrestrial and wet ecosystems and running water is higher than dry soils, and the total area of such lands are higher in the nature-based scenario. Frequent flooding also allows denitrification to occur in larger volumes of water. Demeyer and Turkelboom (2013) calculates that a total of 4,233 tonnes of nitrogen is denitrified over a span of 30 years.

Another key factor that has aided the increase in biodiversity is the rise in groundwater levels. The floodwaters inundate the floodplains and naturally replenish the local aquifers more frequently, thereby increasing the height and depth of groundwater, as validated by data collected and studied by De Becker and De Bie (2013). Higher groundwater levels have enabled wet vegetation species like reed and meadowsweet to prosper in the restored floodplains and has shifted dry grasslands to locations further away from the riverbank (Turkelboom et al., 2021). The overall rise in vegetation cover is expected to improve local air quality and serve as noise pollution reducers. Plants have the capacity to filter pollutants like ozone, nitrogen oxides, and various particulate matter. Based on preliminary calculations, Demeyer and Turkelboom (2013) estimate that the nature-based scenario can capture between 14,329 – 28,819 kg of particulate matter each year. Plants also capture carbon dioxide and other greenhouse gases, and replenish the atmosphere's supply of oxygen (which slows down global warming). The increased tree cover also acts as a greenbelt which attenuates noise from the E40 motorway which runs through the Dijle valley (Demeyer and Turkelboom, 2013; Islam et al., 2012).

The nature-based solution is more efficient in combatting climate change as it contributes to higher carbon sequestration capacity in the study area. Frequent flooding and higher groundwater levels result in moister soils and an increase in swamps in the region. These conditions are more favorable to soil carbon sequestration. Demeyer and Turkelboon (2013) calculated that an additional 542 to 554 tonnes of carbon would be stored in soils each year in the nature-based scenario. However, more carbon is found to be stored in trees and plants that grow in drier soils. Thus, a decrease in carbon sequestered in vegetation can be observed in this scenario.

4.1.4 Social impacts

The Dijle valley ecosystem is one of the richest and most dominant in the whole Flanders region of Belgium (La Rivière, 2015). The nature-based interventions improvements to the environmental quality of the region have created opportunities for nature-enthusiasts, local residents and tourists to access nature. Paths and boardwalks for biking and walking connect key areas of environmental interest along the Dijle. The naturally formed beaches attract avid birdwatchers trying to get a glimpse of kingfishers and other birds. Based on a study conducted in association with KU Leuven (Coucke, 2013), about 77% of the respondents favored the nature-based scenario and were willing to pay €8 per month per household on average to access the "experience and recreation" ecosystem service.

As stated above, local environmentalists and NGOs engaged extensively with the public to raise awareness of the valley's nature value in the lead up to the approval of the nature-based alternative. Media campaigns, nature-walks and events were largely successful in building stronger ties between people and nature. Guided tours of Doode Bemde are offered frequently for groups of up to 25 at a time. Visitors have easier access to the therapeutic effects of nature. And, with increased use, there is now also more incentive to preserve and enhance the aesthetic and functional values of nature in the region.

As discussed above, the nature-based scenario has contributed to improved water and air quality, carbon sequestration, and reduced noise pollution, which are all beneficial for human health. High levels of nitrates in the blood stream, often absorbed through nitrate-rich water, can affect one's health in many ways like causing weakness, dizziness, fatigue, excess heart rate, etc. (Ward et al., 2005). Excess carbon and smoke emission not only pollutes the air we breathe, but also accelerates climate change which has been found to disrupt weather patterns and cause irregular precipitation leading to flash floods. The nature-based scenario is thus viewed as a multi-faceted solution to flooding and the impacts of human activity on the environment at large.

4.2 Floodplain restoration and river renaturation efforts and challenges globally

Ecological, social, and economic benefits of floodplain restoration and river renaturation are seen in diverse locales. Following devastating floods in the 19th and 20th century owing to repeated dike failure, implementation of the Yolo flood bypass project was launched on California's Sacramento River. The project includes redirection of river discharge during large floods into two floodplains which are bounded by dikes/levees. The floodplains are inundated less frequently and for shorter periods of time than in its natural state but offers considerable downstream flood mitigation services during peak discharge periods (Serra-Llobet et al., 2022). Extensive farming activities are now carried out on the floodplains during the dry season which are fertilized through sediment deposition during periods of inundation. During the spring and winter, it serves as rearing habitat for native fish species and foraging habitat for waterbirds (Katz et al., 2017; Strum et al., 2013). The floods have also been found to recharge groundwater and provide other ecological benefits.

The Isar River Restoration Project in Munich, Germany, is a successful illustration of how nature-based solutions can be implemented even in densely populated urban areas if there is adequate will to do so. The project interventions include removal of lateral concrete obstructions like weirs and levees, relocation of levees, widening of the river channel by up to 50-90 meters, etc. In addition to flood risk reduction, the project has resulted in restoration of aquatic habitats like those of the Danube salmon, improved water quality, and access to quality recreational space (Serra-Llobet et al., 2022). Local water quality was further improved by deploying a sewage treatment plant to treat effluents from towns upstream, which allowed the river water to become safe for human contact. The newly formed gravel banks are now accessible to the public for picnics, barbecues, sunbathing, etc. and recreational infrastructure including public toilets have been installed. These opportunities have garnered wider public support for the Isar restoration project (Serra-Llobet et al., 2022).

One of the biggest challenges of employing nature-based flood control solutions is that its flood control capacity is limited to smaller flood events. The Kissimmee River Restoration Project (KRRP) in Florida exemplifies this. The KRRP was launched as a corrective measure to restore biodiversity and the river's natural hydrological regime after decades of engineered flood control practices caused wide-scale ecological damages in the region. The project, costing around USD 1 billion, is divided into several phases and entails backfilling of a portion of existing canals, levee and canal modifications, removal and modification of water control structures and obstacles, etc. and acquisition of land to restore the floodplains to its 1954 level in terms of hectares of floodable area (Koebel Jr and Bousquin, 2014). What started off as an ecological project offers some flood mitigation benefits, however, engineered measures are still employed in tandem to complement the flood attenuation abilities of the restored river and floodplain. The project received considerable opposition from local residents who were at risk of being displaced. A successful land acquisition program in the 1980s managed to mitigate this opposition, which was followed by planning efforts that acknowledged the opposing social and cultural sensitivities of all concerning stakeholders (Whalen et al., 2002). As of 2021, around 25,000 acres of wetlands have been restored in the basin which hosts at least 159 species of birds and other wildlife (Cox, 2021).

4.3 Conventional impact assessments vs actual project impacts

Nature-based flood control solutions are the most recent approach to flood control and adaptation. The cases discussed above have all been responses to the negative effects of engineered flood control measures that were implemented in the preceding decades. One of the main objectives of most, if not all, nature-based interventions is environmental restoration and long-term environmental goals. Thus, such projects tend to have elaborate environmental impact assessments covering environmental costs and benefits at the local and catchment basin scales. In the case of the Dijle River nature-based project, numerous impact studies were carried out by local, national, and international environmentalists in association with researchers at KU Leuven. Raising environmental awareness and garnering public support was a key action that led to the success of the project. The project was also proposed as an alternative to asolution which led to many comparative studies being carried out. Therefore, it can be said that impact assessments for nature-based projects tend to capture wide-scale and long-term environmental and social impacts of the project.

That said, there are some doubts about the reliability of these assessments, some even voiced by the assessors themselves. A major challenge is the accuracy of computer modelling based assessment approaches. Demeyer and Turkelboom (2013, p. 74) write, "In general, we used actually measured data for the nature development scenario and modelled data, data of 20 years ago or expert estimates for the holding basin scenario. At present, this is the only possible approach due to the lack of more accurate data, but it includes a risk of incorrect estimates”. Similarly, Dadson et al. (2017, p. 3) in their paper on catchment-based natural flood management say that “While the benefits are well understood in principle, uncertainty around the quantitative predictions of the potential for CBFM/NFM interventions to reduce local and downstream flood hazards remains high, especially in large catchments and for major floods”. Hence, even if extensive assessments are carried out, one cannot say with certainty that the actual outcomes of nature-based projects would be as ecologically favorable as the assessment report may state. Most flood control projects around the world fail to carry out post-implementation measurements and evaluations which is necessary to quantify the actual success or failure of the project (Bernhardt et al., 2005; Koebel and Bousquin, 2014). This challenge is even greater for projects in regions with poor data collection practices where atmospheric, soil, hydrologic, and ecological measurements are irregularly or never recorded and made available, such as in the global south.

Studies by researchers like Pendse et al. (1989), Phillips and Edwards (2000), and Flyvbjerg (2009) point out that impact assessments are often informed by assessment methodologies and approaches taken for other similar projects, and their long-term outcomes. As nature-based approaches to flood control are relatively recent and few in number, it can be difficult to ascertain what the actual long-term impacts of such projects may be. Further, nature-based projects are often very context specific and no two projects are the same, which makes assessing by drawing comparisons difficult. One also cannot help but wonder if nature-based flood control solutions are yet another attempt at “greenwashing”, where negative outcomes of an intervention could plausibly be covered up by the idea of a green approach being better ecologically and in the context of sustainability. Ultimately, the reliability of conventional impact assessments of nature-based fluvial flood control projects can only be determined in due course as rivers and their floodplains first (if ever) return to their natural, pre-construction baseline conditions, and then respond to the nature-based intervention.

4.5 Key Takeaways

- In recent years, there has been a shift towards nature-based approaches to flood control like river renaturation and floodplain restoration. These approaches aim to restore the rivers natural hydrological behavior such that residents can safely "live with the floods" in a manner that is sustainable for not only the human species, but also all other living beings with whom we share the planet.

- As ecological conservation is a primary goal in most nature-based projects, they are projected to have a high level of environmental benefits which subsequently contributes to economic and social gains. These approaches, however, are not devoid of negative impacts (as summarized in Table 3 below).
- Since nature-based projects are still in their infancy, their actual impacts are still unknown and can only be fully assessed in due course of time. As of now, conventional impact assessments of nature-based projects may inaccurately estimate or quantify potential positive and negative impacts due to poor data availability, paucity in more advanced and accurate measurement techniques, lack of experience with similar projects, etc.

Table 3 Nature-based solution summary table

	ADVANTAGES	**DISADVANTAGES**
Economic	1. Lower cost of implementation, operation and maintenance (eg. sludge removal) 2. Improved and preserved nature, and nature-oriented activities, aid local tourism. 3. High monetary value of increased ecosystem services like carbon sequestration, denitrification and recreational services.	1. Greater land requirement than an engineered solution which can result in higher expropriation and land acquisition costs. 2. Higher cost of mowing and maintaining grasslands.
Environmental	1. Sediments are spread out over larger area leading to more fertile soil which results in greater agricultural productivity, and less fatal burial of vegetation. 2. Small beaches and steep banks are naturally formed. 3. Restoration of natural habitats which serve as breeding grounds for species like the kingfisher (in the Dijle case), and other rare birds and fish. 4. Increased aquatic, plant and bird biodiversity and numbers. 5. Ground water level rises closer to the surface which aids growth of vegetation.	1. Dry grasslands will decrease owing to higher ground water levels. 2. Flooding could contaminate nearby sources of drinking water. 3. Decrease in carbon sequestered in vegetation.

Table 4 (continued) Nature-based solution summary table

	ADVANTAGES	**DISADVANTAGES**
Environmental	6. Increase in vegetation improves air quality, control noise pollution, water purification, carbon sequestration, urban heat mitigation, etc. 7. Wetter soils lead to higher carbon sequestration in soil and higher rate of denitrification. 8. Greater environmental awareness leading to less pollution and better water quality overall.	
Social	1. Opportunity for recreational activities 2. Building relations between people and nature, and raise awareness about effects of human activities on the environment. 3. Preserve and enhance the aesthetic values and therapeutic effects of nature. 4. Improved water quality and environmental conditions directly contribute to better health.	1. Displacement of residents and businesses in the project area.
Others	1. Provides wider catchment-level flood protection/mitigation benefits. 2. Adaptable over time to achieve greater ecological and flood control benefits.	1. Non-replicable as the design is very context specific. 2. More effective against smaller, frequent flood events than large floods. 3. Often implemented in tandem with engineered measures for higher flood control capacity. 4. Ecological benefits are gauged using computer modeling and statistical evaluation methods during the planning phase, but only 10% of such projects conduct post-implementation evaluations to assess whether project goals are met. 5. Probability of inaccuracy in quantifying projections of project benefits.

CHAPTER 5 From Engineered to Nature-based flood control: Cases from Quebec

The province of Quebec is home to about 2% of the world's total fresh water supply, with over a million lakes and 4,500 rivers of varying sizes. Many communities have settled by the banks of these rivers, and many now have implemented some form of flood defense strategy. From the findings of the previous two chapters, it is evident that both engineered and nature-based flood control solutions have their strengths and weaknesses. One approach may be more fitting in certain conditions than the other. For example, in regions with low space availability and high urbanization, an engineered measure may be the better solution. Cases reviewed above also indicated the use of combined approaches to pursue risk mitigation together with environmental objectives.

Quebec is a province where both engineered and nature-based solutions to flood control have been/are being implemented. The following section briefly explores the past and present approaches to flood control in the province to identify flood control planning practices, conditions that have led to the selection of engineered, nature-based or mixed approaches, and trends emerging towards flood management.

5.1 Engineered flood control in Quebec

The history of planning for flood control in Montreal throughout the 19th century illustrates the prominence of engineering in flood control in the province. Following successive devastating floods in the 1830s and 1841, a stone revetment wall was built by the Royal Engineers to stand 30 centimeters above the highest recorded water level at the time (Boone, 1996). The wall provided the city and its dwellers with protection against floods until 1848; that year, another flood inundated the city. In the years that followed, particularly between the 1860s and 1880s, several flood events wreaked havoc on the city. After the 1884 flood, a committee was formed to develop a flood control policy for Montreal. The committee deliberated and researched for over two years before recommending that the river channel be widened and obstructions be removed along a long section of the Saint Lawrence River. Indecision surrounding funding for such projects resulted in little action.

The most devastating flood in the history of Montreal occurred in 1886 and pushed officials to implement protective measures such as: constructing clay dams; and installing pumping stations to prevent backing up of the city's sewers during future floods. The committee viewing these as a temporary solution, recommending that the most vulnerable streets be elevated, dikes/levees be constructed around Pointe St. Charles and a new taller revetment wall be constructed. Once again, disputes arose among the city's municipality, Montreal's Harbor Commission and the Canadian Federal Government over funding responsibilities, leading to further inaction (Boone, 1996). Meanwhile, Montreal's port catapulted in popularity and, with renewed pressure from the commission and the city's elite, some funding from the federal government was secured to upgrade the harbor and to take actions to mitigate risks of another devastating flood. Most of the proposed interventions were blocked due to opposition from the francophone dominant neighborhoods who stood not to gain much from the implementation of these measures (Boone, 1996). Over half a century of unsuccessful planning later, a 1,561-meter-long flood-wall – the Mackay Pier/ Jetée Mackay (later renamed Cité du Havre) - was built in 1899 (Boone, 1996; Montpetit, 2017). In 1965, the pier was widened and connected to the two islands off the coast of Montreal – Île Sainte-Hélène and Île Notre-Dame – by the Concorde bridge; it remains one of the most notable flood control structures in the city.

Many reservoirs and hydro-electric dams have been constructed on the Ottawa River, which originates in Quebec, just past Montreal, and flows through the province of Ontario. Much like the Saint Lawrence River, the Ottawa River also has a long history of flooding which recurrently affects residents in both provinces. Although not built for flood control purposes, the dams and reservoirs are used to control seasonal flooding, for instance through collaborative planning and management, such as emptying the reservoirs prior to the start of the spring flood to increase storage capacity (Nix, 1987). The Montreal region, which is disproportionately affected by the floods owing to its location at the confluence of the Ottawa and Saint Lawrence Rivers, has seen an increase in dike construction in the last several decades to combat flood risk. The boroughs of Île-Bizard and Pierrefonds-Roxboro have been erecting temporary dikes each year at a cost several million dollars as flood defense while mayors of both boroughs lobby for the implementation of permanent dikes ("Are there enough", 2019). Similar calls for permanent dikes in Montreal's neighboring municipality of Deux-Montagnes have also been made in recent years ("Deux-Montagnes anxious", 2018). To limit flooding along Montreal's norther banks, a dam was also built at the mouth of the Mille Iles River in 1985 (Nix, 1987).

5.2 From engineered to nature-based flood control: The case of Saint Charles River

The case of renaturation of the Saint Charles River near Quebec City is exemplary of a rise in engineered measures of river management in favor of nature-based approaches. The Saint Charles River basin which spans about 550 km^2 was among the first areas in the region to be colonized be European settlers. It is an "urban river" that originates in the Saint Charles Lake and joins the Saint Lawrence River through Quebec City. The 19th and 20th century saw a rise in trade and industrialism in the region which led to the Saint Charles being named as one of the most polluted rivers in the province. In response, during the last half of the 20th century, with intensification of development in mind, large-scale projects − including construction of a river embankment (1957), concreting of the riverbanks (1969-1974) and erection of tidal dam (1970s) − were carried out (Brun, 2015). Although the objectives of these projects were to improve the river's water quality and make it more attractive, the results were far from achieved, which then resulted in the conception of redevelopment plans for the Saint Charles centering on the river and its ecological quality. The Kabir-Kouba plan was the first; costing CAD 115 million, the project developed a variety of fauna habitats and encouraged development of riverside vegetation, accompanied by large efforts to divert and modernize rainwater and wastewater networks along with construction of storage facilities. While the interventions were ambitious, they did not produce the full extent of desired outcomes. In the spring of 2000, with interest from the provincial government, a project to depollute and renature the Saint Charles River was launched. Hundreds of meters of concrete structures have now been replaced with vegetation, revitalized parks, urban furniture, and better water management (Brun, 2015), much like in the case of nature-based interventions in Belgium's Dijle River Valley. The downstream renaturation efforts have also resulted in the return of several fish species to the river. The latest *Plan de mise en valeur des rivières* (2020-2040) aims to restore the rivers Cap Rouge, Saint Charles, Beauport and Montmorency, as well as create a 30 km^2 natural park with the intent of protecting and enhancing ecology in the province. In the case of the Saint Charles, fluvial flood control is still largely managed through engineered efforts, however, there is a growing consciousness of the ecological value of river basins and the impact of human activities on them.

5.3 A shift towards nature-based flood control in the province

Major flood events in 2011, 2017 and 2019 in the Lake Champlain and Richelieu River basin has renewed calls for better and sustainable flood control measures. The basin encompasses parts of Quebec, Vermont, and New York. As such, the International Joint Commission (IJC), wh an international organization established under the 1909 Boundary Waters Treaty that oversees and manages water-issues in the shared basin, addressed the flooding, undertaking studies that will inform a renewed water and flood management plan for the basin. While the final proposal is set to be published later in 2022, some "white papers" that have been released that call for floodplain restoration in viable areas and contextual planning in the different municipalities that lie along the basin (Alberti-Dufort, 2022; Henstra, 2022). Given that ther are urban settlements, buildings of heritage value and stated governmental "desire to densify metropolitan areas", relocation of built structures and restoration of the full floodplain remains impossible (Alberti-Dufort, 2022). Alberti-

Dufort (2022) highlights the need for co-management and collaborative governance to tackle transboundary issues like fluvial flood control; the example of Saint-Raymond municipality in Quebec is cited, where a committee of elected officials, municipal employees, residents and other stakeholders was created to deal with the flooding of the Saint-Anne River.

Another example of nature-based flood management in Quebec is the Grand parc de l'Ouest project in Montreal, which is still in its infancy. The project aims to connect existing parks in the west end of the island such as Anse-à-l'Orme, Bois-de-L'île-Bizard, Bois-de-la-Roche, Cap-Saint-Jacques and Rapides-du-Cheval-Blanc, areas which are home to some rare wetlands and water bodies. Around 175 hectares of land were acquired by the city in 2019, and the region is expected to function as a floodplain to mitigate flood risks from the Saint Lawrence River (Alberti-Dufort, 2022).

5.4 Key Takeaways

- Quebec, like many other places, has a long history of engineered flood control approaches.
- In recent years, nature-based approaches are becoming more mainstream as governments at all three levels – municipal, provincial, and federal – are growingly concerned with environmental integrity.
- Despite this transition, in densely populated areas like Montreal, officials in boroughs that are at high risk of flooding are rallying for implementation of permanent dike systems. Structural/engineered flood control measures are considered to be the most fitting solution in these regions perhaps because of spatial or temporal constraints, past experience with dike-based flood control, pressures from funding agencies, or other factors. It can also be said that in the face of climate change and growing urbanization, engineered measures are viewed by some as a more reliable approach to fluvial flood control.
- Nonetheless, nature-based approaches are increasingly being implemented as a way to mitigate present and future flood events in the province.

CHAPTER 6 Conclusions

This study illustrates how there has been a long history of resistance-based flood response (de Bruijn, 2004), i.e., flood control, in fluvial regions across the world and documents some of the impacts such measures have had over time. Engineered or structural measures have traditionally been employed as publicly funded flood control solutions. Case studies of dike construction highlight that although engineered measures provide flood control up to the design-specific threshold, there are a host of wider impacts on the environment and subsequently the local society and economy. Dikes alter the rivers hydrological regime by physically restricting the area through which river water can flow thereby increasing flow velocity, which then increases risks of dike failure and inundation downstream. In addition to being a barrier to water, dikes prevent the lateral transport of silt, the deposit of which makes floodplains fertile for agriculture. After dikes and other engineered flood control measures are implemented, a marked decrease in soil fertility and increase in use of fertilizers has been recorded. Dike failure, such as occurred in the Mississippi River basin, inflict millions of dollars' worth of damage to those settled in the region, which has led to a scaling back of dike construction. With increasing unpredictability in precipitation patterns owing to climate change, it is becoming harder to design engineered flood control measures as they are usually designed for a factor of 100-year peak flow. Nonetheless, calls for dike construction as a flood control measure still prevail even in developed regions like Quebec, Canada, since they effectively help limit floods; they are seen as particularly suitable for dense neighborhoods where space is limited.

Recognizing the ecological damage linked to engineered flood control measures, nature-based solutions are e being proposed as alternatives to engineered solutions. They are employed in publicly funded responses to flood risk, such as the floodplain restoration and river renaturation in Belgium's Dijle basin. Nature-based solutions are considered *extensive* flood control measures (Yevjevich, 1994); they entail recreating nature's natural flood attenuation properties through restoration activities and consider flood control impacts at the wider catchment-basin level. In doing so, flood control capacity is achieved without disrupting the indigenous ecosystem and ecological functions. In fact, most restoration projects have reported a marked increase in local vegetation cover and biodiversity, subsequently creating opportunities for recreational activities and improved human-nature connections. They are also lauded for their capacity to be adapted and improved upon to achieve greater flood control properties as they will allow future generations to adapt to ever-changing flood risk linked to global climate change. However, a challenge with nature-based solutions to fluvial flooding is the lack of space and technical expertise available, particularly in dense cities in the global south.

Although in the last half century large-scale water infrastructure projects require environmental and social impact assessments to be carried out, there are large gaps in the efficacy of such assessments as they often fail to capture the full extent of impacts. Firstly, small-scale projects, or those deemed to have no environmental impacts, often do not require an EIA. In the Mississippi River basin, unauthorized dike construction was common and clearly did not entail any impact assessments. Even when EIAs have been conducted, studies have found that social and political biases often influence the findings of EIA reports or their use; and impacts are downplayed or omitted. Limitations in funding and/or technical expertise further push assessors to employ non-comprehensive and vague methodologies for assessing impacts. Another major critique is the limited spatial and temporal scope of EIAs as they fail to address long-term catchment-basin level impacts. Finally, as is evident in the Mekong River dike construction case, public engagement and participation at all levels of project planning and EIA processes are rarely done; local knowledge, experiences, and attachments are not appropriately considered. Overall, literature suggests that these gaps could be caused by the lack of appropriate assessment methodologies, inexperience of assessors, shortage of data, social and political biases, and more; even when recommendations are made, sometimes they are not heeded or incorporated owing to various limitations.

In light of these findings, four major tensions have been identified in fluvial flood control planning: (1) poor consideration of transboundary dynamics of rivers and ecosystems, (2) lack of clarity and holistic approach in project planning, (3) insufficient technical expertise and data monitoring, and (4) inadequate public engagement and stakeholder biases.

6.1 Recommendations to overcome flood control planning tensions

The tensions and shortcomings in flood control planning, as described above, are major challenges that need to be addressed. It is of more importance now given the evidence of negative impacts of human activity on the planet. The following section provides some ideas and recommendations for rethinking fluvial flood control management as we know it today.

(1) Poor consideration of transboundary dynamics of rivers and ecosystems

The cases of the Mekong Delta and the Richelieu River-Champlain Lake watershed show that rivers as transboundary entities, need more cooperative and collaborative efforts in flood control and water infrastructure planning and governance. Doing so can ensure that downstream populations are not disproportionately impacted by efforts upstream. It can also help prevent the need for intensive flood control measures downstream of the river. As an added benefit, collaboration of this sort may help foster better geopolitical relations and power between nations that may have otherwise had conflicting interests (Mehta and Warner, 2022)

Project impact assessment processes also need to see significant improvement if we are to change our flood control approaches for the better. In the case of water resource projects, interventions focused on limiting, minimizing or stopping floods should also consider environmental degradation, displacement of local populations, or loss of economic activities and livelihoods in the assessment. Given the transboundary nature of rivers, their hydrological behavior and the ecosystems reliant upon them, it is necessary to look beyond the small radius around a project site and assess impacts at least at the larger catchment scale. Geo-political boundaries often do not correlate to the boundaries of wildlife habitat, and a myopic spatial scope fails to capture the actual impacts of project implementation on different species. Environment and species interactions with projects also vary greatly over time; the extinction of many species have taken decades, if not longer, of threatening impacts and habitat destruction. Studies in recent years have uncovered many impacts of past large-scale projects that conventional non-academic project impact assessments had failed to anticipate or address. In fact, it is these findings that have pushed governments and agencies worldwide to make the slow transition to nature-based solutions for water management and other global challenges. Therefore, we also need to widen the temporal scopes of project impact assessments such that direct and cumulative impacts are fully captured and mitigated.

(2) Lack of clarity and holistic approach in project planning

The findings of this study emphasize the need to recognize rivers as trans-boundary dynamic entities that interact with local and wide-scale ecosystems, hydrological regimes, human lives and livelihoods, and more. Activity upstream can often have magnified effects downstream. Such dynamics indicate the need for flood control practices to take a more holistic approach to flood control going forward that addresses these various interactions at the wider catchment-basin level.

The earth and its numerous ecosystems have the capacity to self-regulate. However, increasingly reckless human activity has tipped the equilibrium to a point where this self-regulation capacity has been impeded; global warming and climate change is a clear example. It is possible for collective action to restore the equilibrium – nations from across the world exerted efforts to stop chlorofluorocarbon (CFC) emissions under the Vienna Convention and Montreal Protocol in a successful bid to heal a hole in the ozone layer (Helfenstein, 2021). Restorative efforts like nature-based flood control measures have been shown to have multi-functional benefits and are inherently less detrimental to the environment. Therefore, the shift towards nature-based solutions can be considered good, especially given the information we have as of now. Nonetheless, engineered solutions are sometimes more fitting in a particular context. In such cases, planners and engineers should incorporate measures to mitigate potential negative impacts, e.g., adding fish steps to enable unimpeded fish migration or like constructing low dikes to attenuate the intensity of floods rather than preventing flooding altogether.

Flood control measures also need to be complemented by better city planning efforts. A critical factor driving the need for intensive flood control is cities and other human settlements are sprawling into floodplains. There is rampant, both planned and unplanned, construction in high flood risk regions. The case of further dike and embankment construction in Vietnam to promote urban development on floodplains is an example discussed in Chapter 3. Another example is along the banks of Bangladesh's Jamuna River where lack of space, growing population and increasing structural interventions are facilitating development along the river. However, continued urban expansion onto flood risk areas with sensitive ecosystems poses increased risks to lives and livelihoods of residents, alters river hydrology, and destroys habitats of native birds and wildlife, among other negative impacts. Therefore, land use regulations and flood risk zoning policies ought to be employed to prevent construction and development in floodplains so that natural seasonal flooding can occur without causing social and economic damages. While this study did not explore such measures, there are many precedents for controlling development on floodplains such as India's Coastal Regulation Zone (Balasubramanian, 2022) and Quebec's Zone d'intervention Spéciale (*Zone d'intervention Spéciale,* n.d.) In addition, the case studies in this report suggest that economic, political, and socio-cultural ties to existing patterns of settlement in floodplains and risk-prone areas serve as barriers to implementing such land-use policies, a tension that needs to be explored through further research and informed policy formulation/design.

<u>(3) Insufficient technical expertise and data monitoring</u>

While many advancements are being made in flood control research, they are often not put into practice as planners and decision makers are not better informed of such new discovery. Even if these actors do have such knowledge, it is typically a result of an individual's own interest and motivation. Dany et al. (2016) attribute this gap to factors like inaccessibility and/or non-usage of research knowledge, lack of participatory approaches and information exchange, disparity in status of researchers and policy makers, and limited interaction between them. If we wish to improve the way we plan for flood control, education of decision-makers is paramount. Regular training sessions and workshops should be conducted for officials to learn about developments in the field, gain awareness of recent literature, transfer knowledge about successes and failures of similar projects in other regions, and be informed of recent discourse around their field. Furthermore, capacity building initiatives can help ensure that officials regularly learn of innovations, so that advancements in areas like flood control planning do not require years of training of actors before being implemented.

Additionally, it is important for assessors to develop a more standardized form of carrying out impact assessments and that they receive adequate time and resources to conduct their study. There needs to be more transparency in the assessment process with no meddling from politicians, funding agencies, and developers, who may prioritize their own interests. Assessors also need to broaden their knowledge by following current global practices and academic literature, and liaise with others in their field, so that their assessments are less constrained by the limits of their knowledge.

(4) Inadequate public engagement and stakeholder biases.

Lastly, but more importantly, the cases from this study illustrate the need for more inclusion of local residents and bottom-up approaches in flood control planning. The case of dike construction in the Mekong Delta's Can Tho city showed how there was growing dissent among residents as planning for flood control occurred via a top-down approach. Local residents' lived experiences and traditional knowledge of living with floods were overlooked; farmers, who made up the majority of the population, were left to deal with poor soil fertility and regular damages to dikes, which forced them to invest heavily in fertilizers and pay out-of-pocket to fix the dikes. In contrast, the case of nature-based flood control in Leuven city and the Dijle basin showed how bottom-up activism and calls from local residents for a sustainable flood control approach resulted in the implementation of a measure that was more widely accepted; higher-up planning authorities were forced to reconsider their planning approaches and residents have benefitted greatly from the resulting ecosystem services. An overhaul in the conventional way of carrying out impact assessments is well overdue, but it can be hoped that with more access to information in this age-of-the-internet, regular citizens would be better informed and have a strong enough voice to resist efforts that would threaten their futures.

Greater inclusion of the public and vulnerable stakeholders brings into perspective socio-cultural ties to the place and alternate ways of coping with floods that otherwise may not have been considered. Singh et al. (2020) found that oftentimes, even when a wide range of stakeholders were consulted, their concerns were not addressed or included in the decision-making process. There also exists biases in how information is shared during consultations where costs are downplayed and benefits are hyperinflated. Political interests and biases are often attributed to for this sort of disparity. Therefore, it is important to proportionately include ALL stakeholders, particularly vulnerable residents who will be most impacted, across all stages of the planning process. The findings of this study suggest that rethinking flood control planning practices as they are today is paramount if they are to better reflect the interests of those most affected by the measure – local residents, communities that live downstream, the environment that they depend on for their lives and livelihoods, and the various ecosystems prevalent in the region.

6.2 Final Remarks

There are numerous approaches to flood control, as highlighted in earlier sections of this report. Owing to the limited scope of this study, only one type each of engineered and nature-based approaches were explored in depth. To achieve the broad objective of a study like this, it would be effective to look at more measures, for example, flood control dams, embankments, and Room for the River programs. Furthermore, while this study attempted to cover cases and examples from different geographic regions, it could be useful to include more countries as many different factors influence flood control planning.

At present, most project impact assessments draw heavily on the dynamics and impacts of similar projects already implemented. Nature-based solutions have only recently been implemented as publicly-funded projects, so there is limited precedent information. This prompts the question of whether or not nature-based solutions are as ecologically beneficial as current studies present it to be. Will we in time find out that there are other negative impacts that we have not considered yet, particularly given the dynamic nature of rivers?

Climate change has made weather and environmental interactions highly unpredictable. Precipitation patterns have drastically altered, rate of snow-melt has sharply increased, tidal patterns have changed, and so has hydrological regimes. In light of this, to what certainty can studies determine future flood water levels, flood risk, and flood control capacity required of interventions? How does such uncertainty influence the reliability of project impact assessments, whether for engineered, nature-based or mixed approaches? While the answers to all these questions may not be readily available, or even accurately predicted, it is necessary for us to rethink fluvial flood control practices as instruments of long-term public good that can exist in harmony with nature and the earth at large.

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