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From a Hard to Soft Approach for Flood Management in the Vietnamese Mekong Delta: Integrating Ecological Engineering for Urban Sustainability in My Tho City

Nguyen Van Long [1,2], Tu Dam Ngoc Le [3], Ho Nguyen [4,5,*], Duong Van Khanh [6], Ngo Thi Minh The [2], Duy Thinh Do [7] and Yuning Cheng [1,*]

[1] School of Architecture, Southeast University, Nanjing 210096, China; lomanscape@outlook.com
[2] Faculty of Environment and Natural Resources, Ho Chi Minh City University of Agriculture and Forestry, Ho Chi Minh City 700000, Vietnam; ngominhthe22@gmail.com
[3] Faculty of Architecture, MienTrung University of Civil Engineering, Tuy Hoa City 620000, Vietnam; ledamngoctu@muce.edu.vn
[4] Institute of Landscape Ecology, University of Münster, 48149 Münster, Germany
[5] Department of Land Management, Dong Thap University, Cao Lanh City 870000, Vietnam
[6] Department of Social Work, Dong Thap University, Cao Lanh City 870000, Vietnam; dvkhanh@dthu.edu.vn
[7] Department of Sociology, University of Chicago, Chicago, IL 60637, USA; doduythinh@gmail.com
* Correspondence: nguyenho@dthu.edu.vn (H.N.); cyn999@126.com (Y.C.)

Abstract: Flooding is one of the leading challenges faced by delta cities in the world. Flood risk management using flood control infrastructure (FCI) is a popular solution to prevent flood damage; however, this is receiving enormous criticism due to its negative impacts on urban ecosystems. Recently, there have been new approaches to flood risk management that gradually shifted the focus away from FCI, such as ecological infrastructure (EI) based approaches. However, the conventional thinking that cities cannot be safe without FCI seems an immutable one, especially in developing countries. This study firstly assessed human–river interaction in direct relation to FCI and outlined the limitations of FCI. Then, an urban ecology research model was used to conduct a case study in the Vietnamese Mekong Delta (VMD), in which the interaction between factors, including riverine urbanization, FCI formation dynamics, the changing hydrological regime, flood risk, and riverine ecosystem degradation were evaluated. Due to the dynamism and complexity of the interactions between humans and rivers at the VMD, this study attempts to demonstrate that building the ability to adapt to flood risks based on EI will have a crucial role in enhancing the sustainability of delta cities. Through a case study in My Tho City (MTC) a flood resilience management scenario for a riverine urban area along the Mekong River was developed to discuss the role of EI in flood risk reduction and the restoration of riverine native ecosystems. The findings from this study suggests that EI should be considered as an effective and indispensable design tool for the conservation of riparian ecological corridors and public open spaces—which is a major challenge for urban areas in the context of increasing climate change impacts in the VMD.

Keywords: urban flood management; flood control infrastructure; Mekong Delta; flood resilience; ecological infrastructure; riverine ecosystem; urban ecology

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1. Introduction

Flood hazards have been the leading challenge for delta cities worldwide [1,2]. Although a large number of flood control infrastructures (FCI) have been built, modern cities are still prone to floods [3,4]. In general, flood management pays little attention to adaptation measures; flood mitigation mainly relies on the flood control model with the perception that floods only bring harm [5]. Large-scale flood disasters in many parts of the world show that FCI-dependent cities can only withstand floods to a certain extent, and they fail to cope with extreme floods when the greater flow exceeds design capacity; sometimes these infrastructures do not work effectively even with a small flow [5,6]. Meanwhile, FCI significantly changes the natural flow regime and river morphology, contributing to the deterioration of riverine ecosystem health and limiting the ecological resilience of urban rivers [7]. FCI-based flood management disconnects humans from nature and fails to address the extreme events expected to increase due to climate change [8]; therefore, flood resistance is not a reliable approach to achieve flood safety in the long term.

Flood control models often assume that floods are catastrophic for cities and that cities are unable to adapt to these disasters [6]. However, the recognition that flooding cannot be completely prevented leads to an "integrated flood risk management" approach that combines different non-structural solutions (e.g., flood insurance, warning systems, riverine land use control) and river basin management [9,10]. In many delta cities, non-structural solutions are rarely selected and only play a complementary role in flood control [10]. River basin management, focusing on maintaining water resources upstream to reduce flood risk downstream, cannot solve the problem of pluvial floods and river floods downstream [8]. Despite many theoretical changes, flood control remains an important task in urban areas [11]. The notion that floods should be prevented in the first place—the so-called "flood control model"—is still very popular [5,8]. Since most delta cities continue to believe in FCI, reconsideration of FCI limitations and flood resilience becomes an essential alternative in urban planning and design.

The concept of interaction between humans and rivers has attracted wide attention in the field of urban flood risk management [5,8]. The well-being of urban habitants depends closely on the health of the rivers flowing through the city [7]. However, misguided flood control efforts have resulted in the deterioration of the ecological health of rivers, affecting biodiversity and culture, and increasing the risk of flooding [5]. As a result, the shift from flood-control to flood-adaptation, or development towards adaptive co-management has led to changes in flood management policies in many places [12–14]. Efforts in forming the concept of "Human–River Encounter Sites" for riverside cities aimed at reconciliation between human and nature in urban river corridors have been initiated [15]. These contributions, combined with available urban ecological infrastructure concepts, may foster further discussions about the sustainable socio-ecological management of riverside urban areas and provide guidelines for implementing ecological restoration and the management of urban rivers in the future [7,16,17].

This present study aims to evaluate the human–river interactions associated with FCI by focusing on feedback mechanisms in the system through a case study at the Vietnamese Mekong Delta (VMD). The difficult problem facing cities in this delta is the heightened risk of flooding despite their great efforts in flood control, while FCIs continue to cause pollution, salinity, and hinder the ecological restoration of rivers. The urban ecology analytical framework is used to evaluate FCI as a coupled human–nature system—in which humans and nature interact through complex feedback mechanisms [5]. After evaluating the human–river interaction associated with FCI in the VMD, the study discusses the complex dynamics arising from this interaction and indicates the limitations of FCI. By reconsidering the issues leading to the formation of FCI, it is concluded that flood resilience, which fosters flood adaptation and protection, is a more reasonable alternative to flood control. Finally, a flood-resilient management scenario will be developed for MTC, Tien Giang province—an urban area along the Mekong River—and the implications of ecological infrastructure (EI) for the mitigation of flood risk as well as the restoration of riverine ecosystems are discussed.

2. Urban Ecology Research Model as the Analytical Framework

2.1. Study Area

The Mekong River is ranked as the 12th longest and 8th largest in water flow in the world. This river begins in the Tibetan plateau, stretches 4800 km through five countries before flowing into the East Sea through nine estuaries. The VMD is a strip of floodplain located on two main distributaries of the Mekong River with a dense network of natural and man-made rivers (Figure 1). A flood is a natural phenomenon that occurs annually in the VMD. The flood season usually starts in July, increases gradually from August to September, peaks in October, and decreases gradually from November to December. During the rainy season, the total average flood flow of the whole VMD is about 38,000 m^3/s, the highest flood flow is 139,000 m^3/s, and the total natural flooded area of the VMD is 12,000–19,000 km^2, with a depth of 0.5–4.0 m [18]. Flood heights in two low-lying areas of the Long Xuyen Quadrangle and Plain of Reeds (known as Dong Thap Muoi), which are bordered by Cambodia, can reach 3–4 m for extended periods. During the flood season, the water level rises by an average of 5–7 cm/day, and the highest level can be 20–30 cm/day [19].

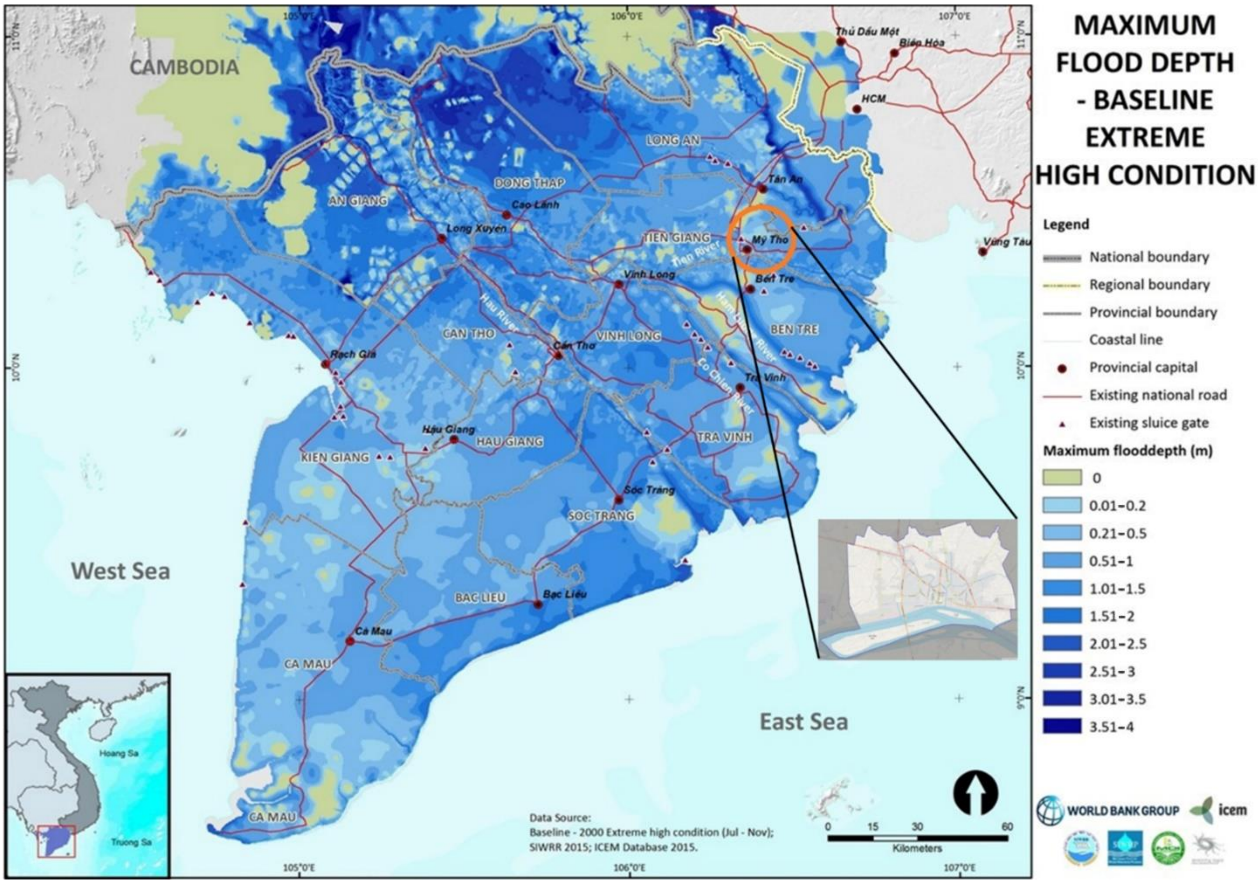


Figure 1. Map of the study area, showing the location of the Vietnamese Mekong Delta (VMD) and My Tho City (highlighted circle) with the maximum flood depth. Sources: Reproduced from ICEM—International Centre for Environmental Management (https://icem.com.au/portfolio-items/delta-tools-a0-and-a3-maps/, accessed on 9 January 2022), and OpenStreetMap (https://www.openstreetmap.org/, accessed on 9 January 2022).

The VMD's landscape can be considered a palimpsest (The term "palimpsest" was first introduced by André Corboz in the essay "The Territory as a Palimpsest" in 1983, where he analyzes how the traces of interventions in history are conserved systematically and how they affect today's landscape. Parts of this historical intervention are kept in the contemporary urban territory and unconsciously direct new urban development) of various logics and knowledge levels in water management systems [20]. Traces of the landscape in the VMD today, including both urban and rural territories, prove the strong pre-colonial and colonial influences through hydraulic engineering and natural approaches to water control. The contemporary (social) landscape is even more expanded—as a self-created landscape that is improved to meet accommodation needs and achieve better control over nature [21]. Although the "artificialization" of the landscape brings many benefits (such as land development, infrastructure expansion, irrigation, public security, and overall policies), the delta is facing the potential hazards induced by climate change and urbanization. Reintroducing the concept of palimpsest, sea-level rise and river floods over time could occur with a greater magnitude that would erase some layers of today's territory.

MTC with a natural area of 81.54 km^2 and a population of 320,740 (Census of population and housing in 2019), is the economic, political, and cultural center of Tien Giang province (Figure 1). The city on the bank of the Tien River has a rich river landscape, a mild climate, and a lot of potential to become a water city. My Tho was originally a center of traditional agriculture and aquaculture, specializing in fruit, fisheries, and ornamental plants. The landscape of the city is characterized by natural waterways, low-lying fields, canals, and regulating aqueducts.

This article uses a case study-based analysis at two different scales, those being regional and city scales. On a regional scale, the study chose the VMD to assess human–river interactions associated with FCI; the urban ecology model was used to consider the complex dynamics arising from this interaction, thereby the limitations of flood control were drawn. A city-scale analysis suggested a change from flood control to flood resilience, in which MTC was selected to evaluate the role of ecological infrastructure in flood risk reduction and the restoration of riverine ecosystems.

2.2. Urban Ecology Research Model as the Analytical Framework at the Regional Scale

The concept of the coupled human–river system could provide insight into the complex dynamics leading to the formation of FCIs. In the VMD, water management policies for different purposes from colonial times to the present have led to complex dynamics in water control [18,20]. To analyze these aspects systematically, an urban ecology research model developed by Alberti [22] was used as the analytical framework for the case study (Figure 2). This analytical framework evaluated FCI as a coupled human–river system, in which humans and rivers interact through complex feedback mechanisms [5,23]. Specifically, the human–river interactions associated with FCI focus mainly on the feedback between riverine urbanization, changes in hydrological regimes, flood risk, construction of FCI, and river ecosystems. In addition, diversion and flood risk perception are also considered key feedback mechanisms in system dynamics [5]. After assessing the human–river interaction associated with FCI in the VMD, the complex dynamics arising from this interaction was analyzed and discussed, thereby the limitations of FCI were drawn.

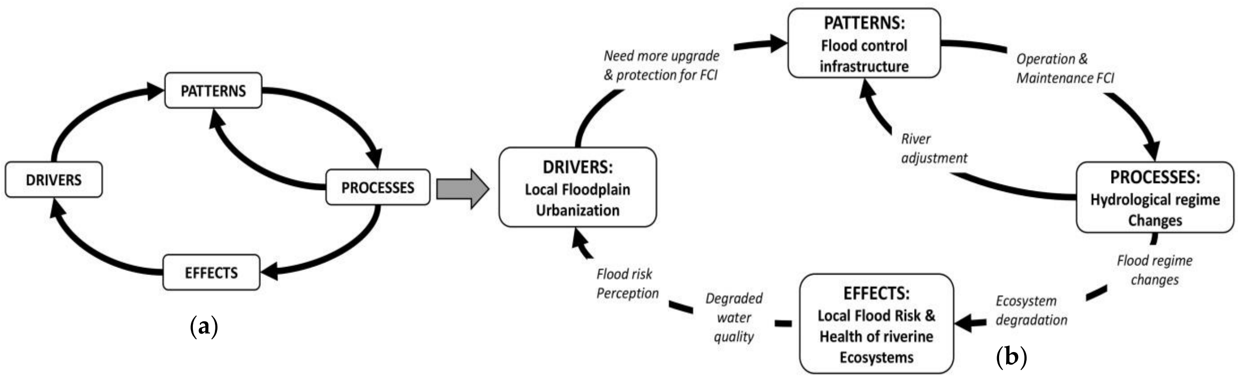


Figure 2. (**a**) Alberti's model of urban ecology [22] is applied to provide insight into the complex dynamics induced by flood control infrastructure (FCI) in the VMD. This model emphasizes the linkage between components and processes, and describes the feedback loop. The structural simplicity of the model allows for easy integration between hierarchies. The analytical framework (**b**) is developed to emphasize the models and processes that link the two components of humans and the ecosystem, describes the feedback mechanism in which human actions affect and are affected by components of the ecosystem, and the degree of interaction at different scales [5,23]. There are many factors involved in human–river interactions associated with FCI, but this study focuses on riverine urbanization, hydrological regime change, flood control, flood risk, and the riverine ecosystem.

Analyzing the interactions in the delta system: Due to the characteristics of space and living habits, the riverine areas of the VMD have become the center, attracting people to settle over the past three centuries [24,25]. Population growth has led to the rapid urbanization of riverine spaces over the past few decades [26]. In addition to the need for increasing agricultural productivity, the riverine lands are rapidly urbanized, and FCI has become an indispensable measure to prevent flooding and saline intrusion [18]. The working principle of FCI is to limit high flood peaks via dikes and to move water downstream quickly through canalization, or to reduce flow upstream via dams [18,27]. Therefore, FCI profoundly changes the hydrological regime and is likely to flood the downstream area during flood discharge [28,29]. The most severe effect of FCI is probably the change in flow and sediment regimes downstream (Figure 3). The changes in flows and sediments lead to hydrogeological and geomorphological homogeneity reducing habitat complexity, which is the key factor in maintaining the ecological integrity of rivers [30]. Riverine urbanization and FCI construction degrade the wetlands and eliminate cyclic floods, thereby creating habitats that are not conducive to native species [31,32]. The riverine ecosystem is also degraded as river ecological functions are affected. As a result, fewer ecosystem services are provided. For example, canalization and leveling of low-lying areas are responsible for the disappearance of some aquatic species, and the degradation of wetland clean-up services [33].

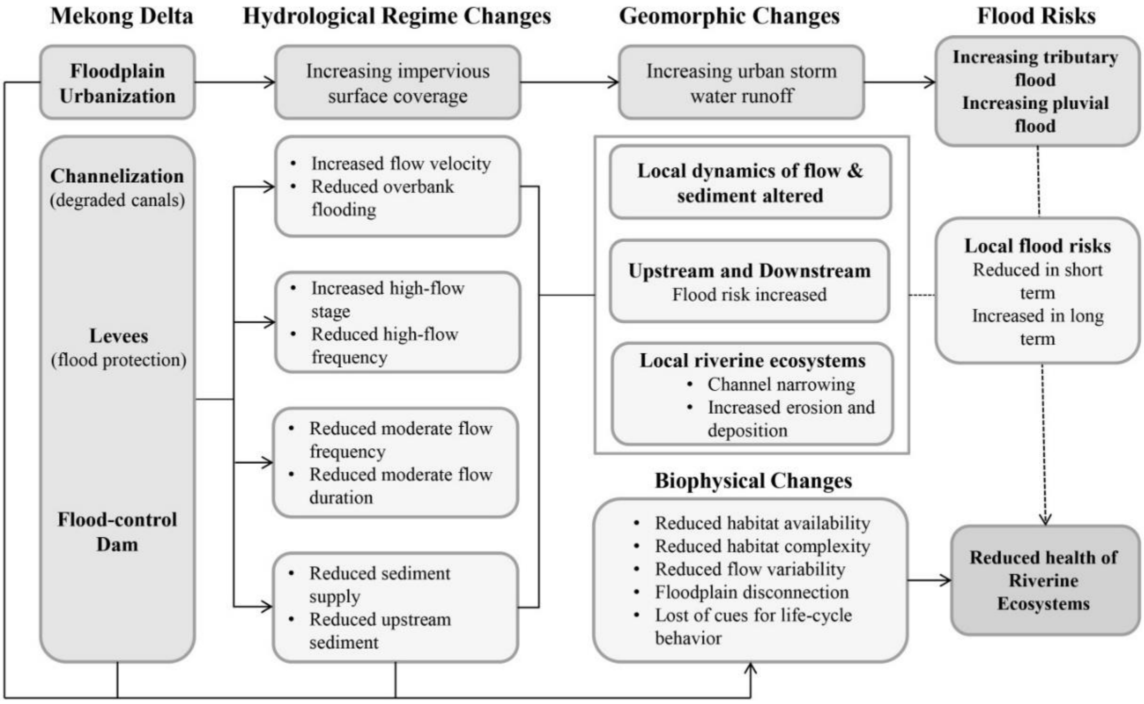


Figure 3. Illustration of the interactions between urbanization, flood control, and flood risk in the urbanized delta at the VMD. Source: Based on [5].

The feedback mechanism of the delta system associated with FCI: Upstream flood control and river diversion for urbanization results in significant changes in flood morphology and the hydrological regime in the Mekong River downstream [28,34]. The increasing number of regulating dams and upstream hydroelectric dams leads to a decrease in cyclical floods, resulting in a decrease in large and extreme floods, and an increase in smaller floods [35,36]. By using diversion, river morphology will be changed, leading to bank erosion, accretion of the riverbed, or the narrowing of canals [37]. In many cities, floods can cause very serious consequences if canal or river sedimentation and heavy rain or flooding occur simultaneously [38,39]. FCI may affect its flood control capacity and disturb the river morphology, thereby increasing the flood risk for the downstream area [5]. In the VMD, FCI allows the riverine urbanization process to take place faster, and the artificialization of canals to be promoted [40]. However, the promotion of urbanization in the low-lying riverine area is responsible for the continuous increase in the number of floods over time [41,42]. Flood risk perception is also one of the important feedback mechanisms in flood control systems—it is a misperception about the security of FCI [43]. Due to the notion that FCI can eliminate most of the flood risk, the dynamics of rivers are therefore neglected, and flood risk perception is lowered [8]. That is why FCI has the potential to reduce flood risk in the short term but increases flood risk and worsens flood risk in the long term [19,44].

2.3. Ecological Infrastructure-Based Flood Resilience Model at Urban-Scale

The problems and risks posed by FCI mainly stem from an underestimation of the complexity and integration of the delta ecosystem. The increasing number of floods forces cities to consider and search for more flexible approaches to adapt to the changing environment [20]. Resilience, or the ability to deal with whatever might happen in the future, is the best strategy to survive in a world of emergence [45]. The concept of resilience is attracting more and more attention in urban flood management, but it is often understood as post-disaster recovery [6]. Flood resilience is the ability to withstand floods, and to avoid (not to prevent) disasters during floods, as well the ability to reorganize quickly if any physical or socio-economic damage occurs [6,43]. In summary, flood resilience requires either "rapid reorganization" or "flood tolerance" [5]. In urban flood management, "flood tolerance" is the ability of a city to preserve, eliminate damage, and still function when flooded; this requires the urban built environment to be adaptive to floods [5,6].

Flood resilience is in contrast with flood control; flood control is an attempt to change the flood regime. Resilience is also understood as an adjustment to match the (actual and expected) flood regime without trying to change the flood regime [43]. Ecosystem resilience, thus, plays an important role in the ability to cope with extreme flood hazards. This is because ecosystem resilience is related to the existence of ecosystem services, and the loss of ecosystem services restricts adaptation possibilities [7]. Due to the significant changes in hydrology, geomorphology, and biodiversity, many urban rivers are in socially and ecologically undesirable regimes and are too degraded to provide ecosystem services. The resilience of urban rivers has an impact on the city's ability to adapt to floods and plays a core role in helping the city to tolerate the severe floods that cause ecological and social disturbances.

In this study, we consider ecological infrastructure (EI) as interventions to protect the integrity of urban and natural ecosystems through the application of ecological engineering to urban planning and design [46,47]. The focus of the EI-based resilience model is to enhance the delivery of natural and urban ecosystem services, while improving existing gray infrastructure to be more friendly to nature's diverse ecological cycles, to help maintain urban sustainability [16,17]. For delta cities, EI is built mainly on a landscape system that intersects between land and water, including riparian ecological corridors, wetlands, rivers and canals. The health of riparian ecosystems will determine the ability of EI to play a role in flood adaptation and the restoration of riparian ecosystems.

Therefore, an ecological design framework (Figure 4) is proposed to build urban resilience to floods. This model emphasizes how the feedback in cross-scale interactions will facilitate the resilience of components in urban and natural ecosystems. In this integrated socio-ecological system, cities depend on ecosystem services from delta ecosystems to maintain their resilience, while delta ecosystems, once exploited to produce goods and services, will depend on urban ecosystems to maintain their resilience capacity.

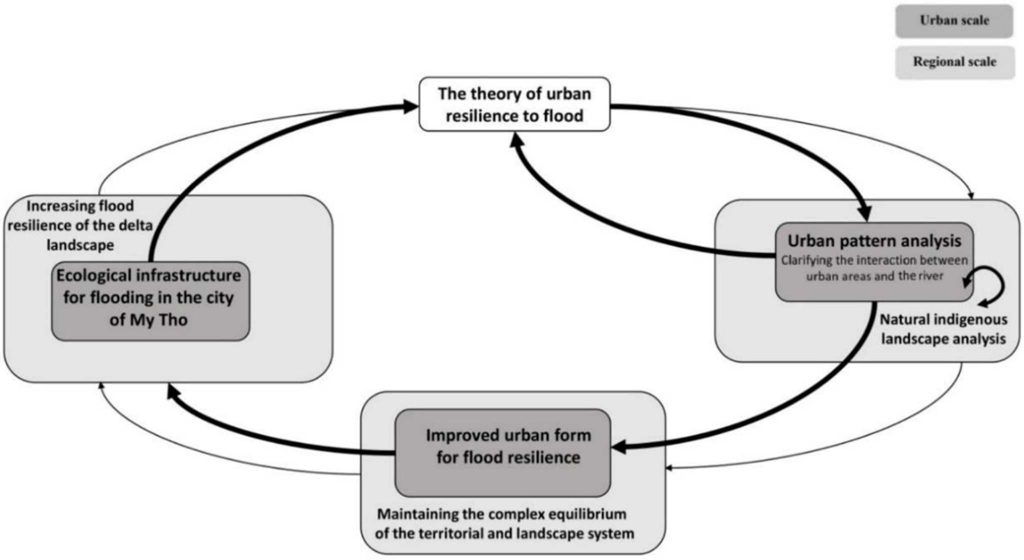


Figure 4. The capacity-based resilience of ecological infrastructure will play a core role in urban flood management. In particular, the cross-scale interactions of the components in the urban ecosystem will contribute to improving urban resilience to floods.

3. Complex Dynamics in Human–River Interactions in the Vietnamese Mekong Delta

3.1. Dilemma of Flood Control in the Vietnamese Mekong Delta

3.1.1. Riverine Urbanization and Flood Control Infrastructure

Historically, the works and projects of nature conquest in the VMD have never been isolated and have even been developed on a larger scale [48]. During the colonial period, the French colonialists expanded their influence and territory by transforming vast wetlands into fertile agricultural areas [49]. The French added an extensive network of canals to the territory for irrigation, aquaculture, and connecting the settlements. Engineering interventions to the rivers and canals drastically altered the natural state of the marsh landscape, transforming the VMD into an orderly arrangement (chessboard water network) that produces economic and spatial benefits [20]. From an uncultivatable swamp, the VMD became a fertile agricultural land specialized in rice export, known as the "rice bowl" of Vietnam. Although the French were interested in waterworks to bring water into the fields, they did not take the influence of these systems into account [18]. New canals, in addition to efficient drainage, brought floodwater to the areas that were previously little or not affected by flooding. Moreover, they also created new streams for saltwater to penetrate further inland from the sea [50].

In the VMD, floods not only bring new sediments and nutrients to the fields but also play a key role in the long-term sustainability of the delta through its ability to counterbalance sea level rise [40]. Flood is also a determinant for the distribution of residential areas and, thus, affects urban development patterns [20,51]. However, the rapid change in the socio-ecological system of the delta has eroded many ancient flood adaptation strategies. Recent rapid urbanization forces most delta cities to cope with poor drainage and localized flooding. Cities are turning their back on the water, while high productivity agricultural policies urge water control systems to be expanded (Figure 5). The construction of modern and centralized FCI was first introduced in the Mekong Delta Development Plan in the 1960s, then realized via large-scale water control systems in the 1990s [18]. The catastrophic flood in 2000 and new economic development policies became the catalysts for the construction of large-scale FCIs. The growing concerns with sea-level rise has recently urged the VMD to find solutions for flood protection and salinity control in which the idea of closing major estuaries by big dams attracts the most attention [40]. The VMD is now dependent on the interaction between new water management approaches and socio-economic changes.

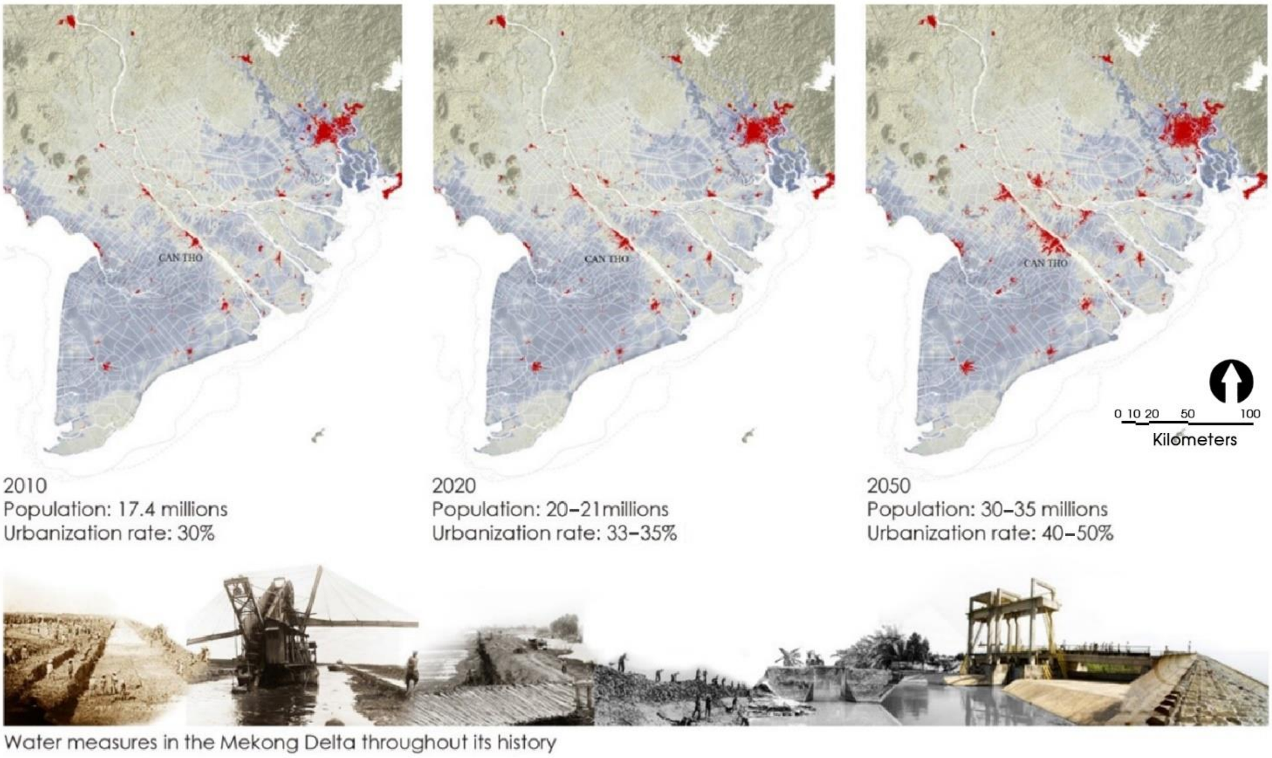


Figure 5. Rapid urbanization of territories and water control policies turn the cities away from water. Given the wet nature of the floodplain, the VMD needs to have a new awareness of a hydraulic city in response to environmental challenges in order to better adapt. Source: Reproduced from source [52].

3.1.2. Hydrological Regime Changes

The development of FCI in the basin exerts a significant impact on the change in the hydrological regime of the Mekong downstream. As of 2015, in the entire basin, there are 42 hydropower dams and irrigation reservoirs in operation or under construction [53]. Some large hydropower reservoirs in China, such as Xiaowan (2010) and Nuozhadu (2012), have come into operation and brought the total reservoir capacity in the basin to more than 40 billion m^3. In the near future, more than 150 hydropower reservoirs will be built on the mainstream or dependent tributaries of the Mekong River basin in the upstream countries, increasing total reservoir capacity to 106 billion m^3 [53]. The operation of these reservoirs, combined with water discharge from upstream reservoirs at the beginning of the flood season, and accumulation of water at the beginning of the dry season, leads to a trend of increasing water level in the first months of the flood season and decreasing water level in the first month of the dry season [54,55]. During the dry seasons of 2015 and 2019, the entire Mekong River basin experienced severe dry seasons, during which VMD was severely impacted by historical drought and salinity intrusion, with water flow into the VMD falling to a historically low level over the past 100 years.

The diversion of the Mekong River flow severely shrinks the irrigated area of the VMD. The floodwater level is low not only in the rainy season but also in the dry season [44,56]. The total reservoir capacity, accounting for about 8–18% of the total flood flow of the Mekong River basin, is considered a factor affecting the flood situation of the VMD and is partly related to a series of continuous small floods and historically low floods in recent years (2003–2010 and 2012 to present) [53]. The total volume of floods entering the VMD, which was previously from 380 to 420 billion m^3 and lasted for 5–6 months, is now only about 330–350 billion m^3 (in 2015, the flood volume was about 220 billion m^3) and lasts for 3–4 months. Additionally, that 50% of the medium flooded areas and 30% of the deeply flooded areas (about 700,000 ha) are under flood control to produce summer-autumn and autumn-winter crops, is the reason why the flood storage capacity of the whole VMD reduces by nearly a half (5–7 billion m^3 to 3–4 billion m^3) [57].

In addition to the quantitative and temporal changes in water levels induced by the development of FCI, it is also important to consider the issues of water quality and hydrogeology. Floods during the rainy season convey rich nutrients along with silt. However, the dams hinder sediment movement downstream. For example, sediment is reduced by 74.1% in the VMD, of which 40.2% is blocked by six main dams on the Lancang Falls [58]. Acid sulfate soil reclaimed in the Plain of Reeds is responsible for the acidification of the water surface. Moreover, the construction of high dams changes the availability of nutrients in protected areas. An attempt to control water led to the increasing use of agrochemicals that could harm ecology and the environment [18]. Additionally, the weak geology of the VMD formed by the alluvium of rivers and estuaries, and the changes in flow are the main causes of riverbank erosion [37]. According to statistics from the Ministry of Natural Resources and Environment (2020) [57], there are 202 landslides with a total length of 218 km on the Tien River, over 90 landslides with a total length of 183 km on the Hau River, and 61 landslides with a total length of 150 km in coastal areas, such as Ca Mau province.

3.1.3. Increased Flood Risk

The central area of the VMD, with many big cities, is the water transition area of the delta where the impact of sea-level rise will be more serious than the impact of the upstream FCIs and other localized FCIs. This is because the central area has a dense system of canals that make it easy to drain water, but also allow seawater to infiltrate the inland fields; when the sea level rises by 38 cm, it will affect 93% of this area [19]. Due to the impact of high tides with high peaks and low water levels on the Mekong River, saline intrusion in the dry season occurs more frequently and intensively [56,59]. As a result, seawater easily infiltrates the inland fields and directly affects coastal cities. Furthermore, groundwater extraction and land subsidence at a rate of 4 cm/year [60] significantly increase the flood depth, directly threatening some areas with high construction density.

Rapid urbanization along rivers and into low-lying areas leads to many long-term risks [24,61]. The leveling of the lowlands (2.0 m higher than common ground) and the increase in the number of impervious surfaces causes stormwater runoff to be faster and groundwater levels to fall [39,62]. At the same time, the promotion of flood control and crop protection in rural areas around cities results in higher levels of river water, which increases flood risk to cities [63]. Additionally, since nearly all cities are located on low geographical ground (1.4–2.0 m above sea level) and located next to high flows, in the event of a sudden flood (e.g., failure of an upstream dam or tsunami), damages will be catastrophic. To solve this problem, dikes are built to ensure structural stability [64]. However, with today's dense network of canals and complex waterway connections between urban and rural areas, the construction of dikes is very expensive and potentially exerts a socio-ecological impact on a large scale.

3.1.4. Degradation of Riverine Ecosystems

Intensified flood control and riverine urbanization both contribute significantly to the decline of the VMD riverine ecosystems [65,66]. Due to habitat narrowing and changes in water flow, some species are on the edge of extinction. In particular, the biodiversity of the VMD is seriously affected, demonstrated by the risk of loss or even extinction of up to 10% of fish species; a reduction in the number of migratory fish species; the loss of Irrawaddy dolphins, a freshwater dolphin of the Mekong River; less distribution and a reduced number of freshwater mollusks; and the limitation of mollusk migration [67,68]. The construction of dams hinders the long-distance migration of some catfish species and disrupts the natural flood cycle that fish have adapted to for thousands of years [69]. When upstream water flow is blocked, small-sized fish are significantly affected as the upstream water flow is an essential mechanism for their migration downstream. Today, the outside-canal habitats have become narrow and inaccessible for small-sized fish as most forests and wetlands have been lost while the remaining lands are affected by FCI [70].

Habitats in the delta system are generally degraded and homogenized. As the floodwaters are blocked by FCIs, a great quantity of water, rich silt, valuable phytoplankton, and fisheries are released into the sea. The floodplains and wetlands—the breeding grounds for many fish species—are eroded, deposited, or gradually disappear. The riverbed is disturbed by the sedimentation process so strongly that it is no longer a suitable habitat for most species of aquatic animals. The greatest localized ecological impact is probably the drainage of wetlands for rice production, typically in Long Xuyen Quadrangle and Plain of Reeds [18]. Certain coastal saline areas become unsuitable for certain species of fish and wildlife. The transition zone between freshwater and saltwater on two main tributaries (Tien and Hau Rivers) is narrow and tends to move upstream. As a result, the growth and survival of some small-sized fish species are significantly affected due to the dramatic reduction in freshwater volume.

3.1.5. The Climate Change Dilemma

As mentioned, the VMD is the most vulnerable part of Vietnam as the future sea-level rise could entail saltwater intrusion into a huge area [71]. More than one-third of the delta, where 18 million people live, and nearly half of the country's rice production will be affected. During major storms, water levels will rise and allow saltwater and pollution to penetrate inland. Moreover, about 85% of the VMD population relies on agriculture, suggesting that a humanitarian disaster is likely to occur due to sea level rise [20]. The geographical location of the VMD could lead to serious consequences in the context of climate change. Therefore, cities tend to focus on stabilizing the structure of flood control systems. By doing that, existing urban areas are expectedly protected by dikes as floodwater could be blocked by FCIs that are well-designed and operated effectively [5]. However, most of the urban areas in the VMD are still flooded due to high tides and heavy rain in the flood season [63]. Some failures of dikes, such as overflow and breaking, also result in uncontrolled flooding. These have significantly eroded faith in the ability of FCI to prevent disasters. Therefore, many efforts are made to call for flood resilience and the restoration of river ecology, as well as saving the landscape and water space for urban areas [72]. However, there is a long way to go before good, advanced, and high-tech water management approaches become a reality.

3.2. Feedback in Complex Systems of the VMD

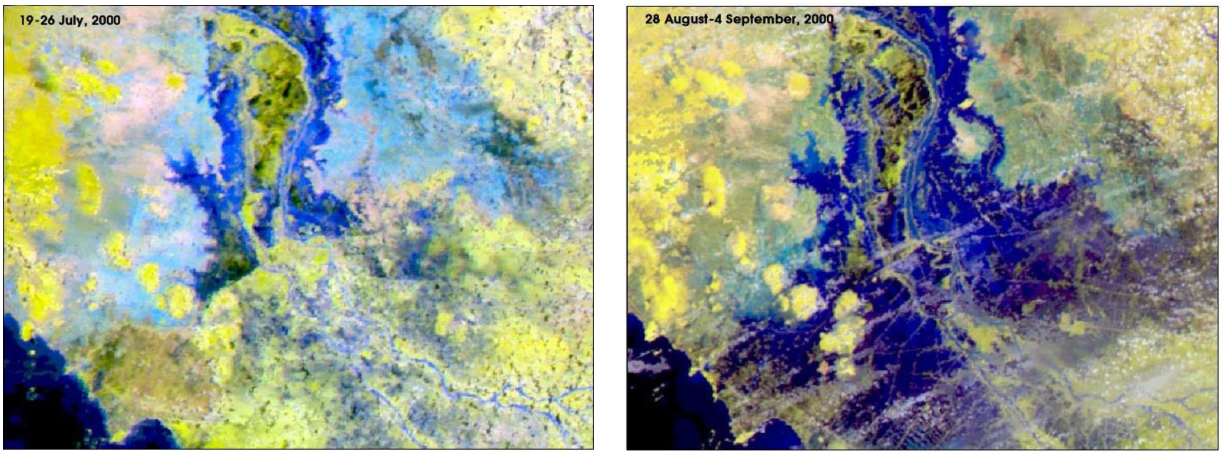
FCI is a popular solution for flood damage prevention, but it receives criticism due to the damage it causes river ecosystems [5]. Today, although non-structural solutions in water management have been adopted more widely and the role of FCI in flood management is less emphasized, many cities in the VMD continuously rely on FCI to prevent flood damage. It is questioned whether these cities should continue to rely on FCI to protect their people and property. To find the answer, in this section, this article discusses the complex dynamics of human–nature interaction associated with FCI.

3.2.1. Cross-Interaction Effects on the Hydrological Regime

The influence of FCI is found not only within the region but also beyond the geographical boundaries it controls [23]. Upstream flood control is one of the prime examples of complex, cross-scale interactions. For example, flood control dams in China and Laos have far-reaching effects on the hydrology of the downstream area by causing abnormal floods [73,74]. The reason is that these FCIs not only interact within the area they control but also affect the flow in the basin and the sedimentation process, thereby affecting the flood risk and sediment transport elsewhere [34,55]. The environmental changes induced by upstream FCIs, such as watershed deforestation, affects the flow regime and flood flow. Consequently, FCIs increase the flood duration upstream, flood some areas unexpectedly [5], and reduce flood flow and sediment into the downstream delta. This amount of sediment would have helped maintain the sustainability of inland and coastal floodplains and protect coastal ecosystems from storm surges. At the city scale, FCI could move flood risk to the suburbs, while storms and floods in rural areas also affect the stability of surrounding FCIs. For example, the unusual frequency and intensity of FCI-induced floods deprive some rivers of major ecosystem services, such as water pollution and loss of natural habitats, due to the disappearance of large wetlands [18]. In the Long Xuyen Quadrangle area, the flood control system introduced a new set of risks. In particular, FCIs increase flow velocities and, thus, worsen bank erosion, heighten the risk of dike failure, and hinder the anticipation of flood impacts.

3.2.2. The Complex Emergence in the Hydrological System

A sudden historic flood in 2000 (the highest in 80 years) is a prime example of system emergence in the VMD (Figure 6). The flood caused nearly 1000 deaths while most of the upstream cities were flooded with water from 1.0 to 3.0 m. The loss of property and crops was estimated at 5000 billion Vietnamese Dong at that time (equivalent to $4 million) [75]. Another example is the historically severe drought and saltwater intrusion in the dry season of 2015–2016 when nine coastal provinces (among the total of thirteen provinces) of the VMD suffered serious damages. These events show that FCI cannot determine its resilience, which depends on external factors, such as extreme weather events or natural disasters. These emergent events are not caused by the natural or human components separately, but by the complex series of interactions in the system components associated with FCI. For example, the flood resistance of FCI depends on its design performance, which is determined by not only the (predictable) design criterion but also the interaction between FCI and geomorphic processes, such as river adjustment, deforestation to make lakes, and the construction of dams on tributaries. As a result, other processes of both human and natural activities that have occurred in the past or elsewhere may have an impact on these events [5,23].



(**a**) (**b**)

Figure 6. Landsat satellite image of the historic flood in 2000 in most parts of the VMD. The flood by mid-end July 2000 (**a**); and the flood in early September 2000 (**b**). Source: Landsat images were free-downloaded from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/, accessed on 9 January 2022).

3.2.3. The Non-Linear Hydrological Relationships

The interaction between FCI and hydrodynamics leads to non-linear interactions with various interaction thresholds. When the catalyst creates an opportunity for threshold-crossing to occur, nonlinearity will occur [23]. In the VMD, extreme high tide and stormy wind are important factors leading to the occurrence of threshold-crossing and non-linearity. For example, high tide and storms occurring simultaneously force the dikes to withstand for a long time before they fail to prevent a high flow exceeding design capacity and causing long-lasting disturbances to the cities. The influence of FCI on changes in river ecosystems is also phased rather than instantaneous or gradual. The time lag, therefore, is also a form of nonlinearity [5]. For example, riverbank erosion in the VMD does not always occur; only when the flow pushes the hydraulic variables to a threshold will they cause severe subsidence over large areas of many rivers. The intrusion of brackish water plants from the main rivers of the VMD into the fields is the result of prolonged saline intrusion, which entails the appearance of coastal plants inland.

3.2.4. Hydrological Surprises: The Consequences of Flood Control

Although FCI could reduce the frequency of flooding, stabilize riverine areas, and facilitate urbanization, its capacity is limited [5]. The ongoing costly urban flood disasters in the VMD show that FCI-dependent cities are not well-prepared for surprises, such as extreme floods. Surprising events occur in the socio-ecological system when cross-interaction, emergence, and non-linearity are unknown or unpredictable [5,23]. In flood management, the surprise is the result of overestimating the design performance of flood control infrastructures. On one hand, the accuracy and long-term trajectory of hydrological dynamics are often random and unpredictable, so any calculation is limited. On the other hand, it is impossible for humans to accurately predict the long-term ecological effects of FCI because the changes in the river ecological system are emergent phenomena and associated with various human–nature interactions, such as low-lying urbanization, water pollution, and climate change [5]. Therefore, a time lag may also entail ecological surprises in the future in flood-controlled areas. Besides, as the failure of FCI to prevent a flood from exceeding its design capacity is considered rare, surprises receive little attention in flood management. However, more and more studies show that surprise is quite normal in the socio-ecological system of the delta [76,77]. If it is proved that the failure of FCI is normal, the flood resilience solution should receive more consideration.

3.2.5. Limitations of FCI in the VMD

The VMD still maintains a huge FCI system, but ecological and environmental problems are becoming more and more serious. The development of the VMD is at a crossroads. To achieve environmental and social sustainability, it is necessary to find new adaptive solutions [18]. Therefore, the VMD should review the limitations of FCI so that it can make wiser decisions, specifically:

First, water control systems have created a new kind of social injustice and risks. The degradation of riverine ecosystems due to FCI has a huge impact on related cities, as these cities often exploit fish and freshwater from nearby water bodies [5]. In addition, the controlled environment affects differently on the local people's livelihoods since their main income depends strongly on aquatic resources and crops, which are exposed to more serious risks associated with extreme flooding [43]. If the water level exceeds the FCI's safe threshold, the damage will be much greater than before because the crops and infrastructure will be destroyed and no longer be adaptive to flooding. Another typical feature of high dikes is that they protect one area and move the problems to other areas that are not protected. Moreover, the water control system also leads to conflicts of interest between provinces. For example, high dikes in Dong Thap province raise water levels and cause flood damage in Long An province [18].

Second, FCI has created complex cross-border conflicts of interest. FCI is built to serve the interests of one country but unintentionally induces problems in another. For example, the operation of the dam system in China affects the flood regime and river ecology of downstream countries. Consequently, the low water level in the Mekong River in the dry season triggers a decrease in agricultural production and fisheries in Laos, Cambodia, and Vietnam in addition to an increasingly alarming situation of saline intrusion in coastal areas [78,79]. During the rainy season, the amount of stormwater is a disaster for downstream countries, especially Vietnam, when it is combined with high tides. Hydropower dams in China and Laos push some freshwater species downstream to the edge of extinction due to their inability to migrate upstream to breed [80,81]. Upstream of the VMD, the late opening of sluice gates to serve crops in Vietnam worsens flooding in Cambodia.

Third, FCI itself can exacerbate the long-term flood risk for the delta cities if structural problems arise. FCI-dependent cities are more resistant to floods if the structure is stable. When FCI fails, flooding becomes a disaster as cities get used to dry and stable conditions rather than flooded conditions. For example, a dam break will release water and sediment into urban areas at such a great speed that these areas will not have enough time to evacuate. Once it happens, intact dikes will hinder drainage work, and prolonged flooding will exacerbate the disaster. In fact, FCI-dependent cities may face one or more of the opposite situations: dryness and stability, or flooding and disaster [6]. Although FCI is a system that enables the combination of various techniques that have their own structural redundancy, these infrastructures have very little diversity and cross redundancy. For example, the attention of an FCI-dependent city on the river rather than the built environment may make it less flexible with regards to making timely adjustments in order to respond to constantly changing conditions. Additionally, climate change is expected to bring intense hurricanes and other unpredictable difficulties that are beyond the control of FCI.

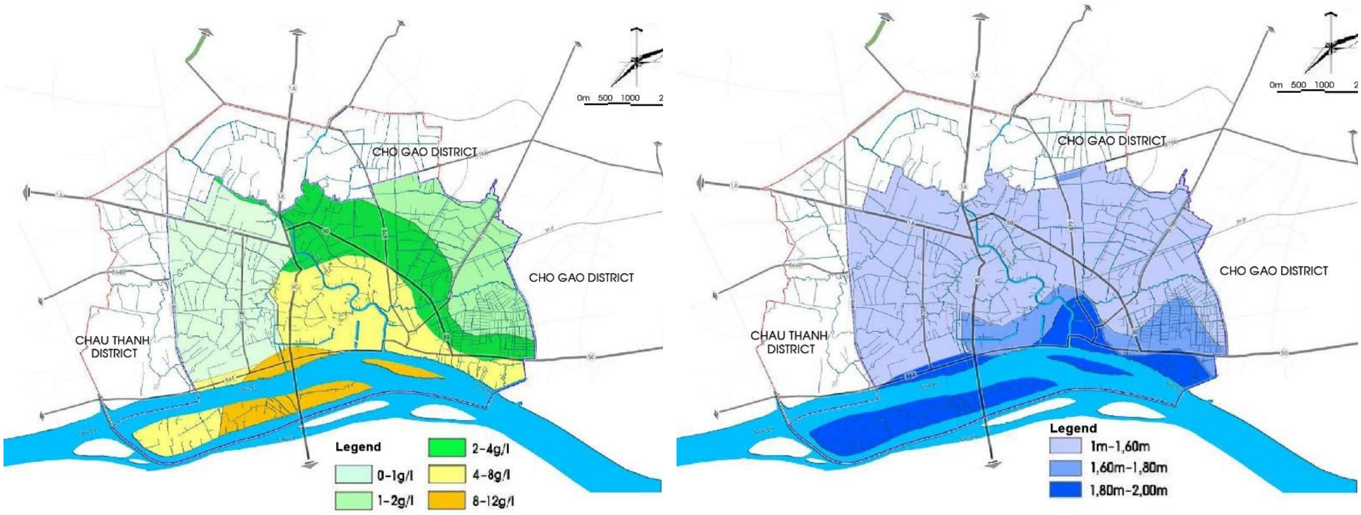
4. Towards a Flood-Resilient City: Ecological Infrastructure for Flood Resilience in My Tho City

The MTC development model proposes building EI as a framework for urban flood management. To thoroughly solve the flood problem, this study proposes ecological infrastructure management and planning at three levels: region, urban area, and sub-area, based on the flood resilient model presented above. The introduction of EI as an essential part of urban development is considered a turning point in preserving public open spaces, retaining the unique characteristics of the local canal landscape, and guiding and limiting urban growth to avoid rampant development.

4.1. My Tho—The City on the Bank of Tien River Facing Challenges from Urbanization and Climate Change

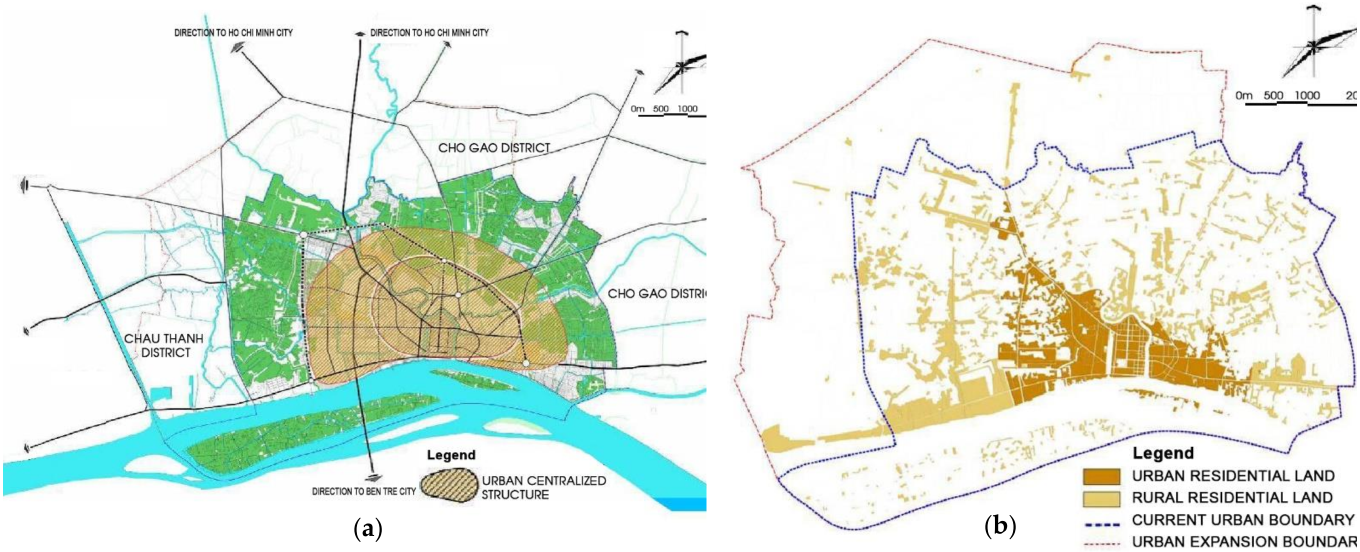
Contemporary rapid urbanization poses serious environmental and ecological challenges to MTC. Urban expansion results in the narrowing of fertile agricultural land and the destruction of indigenous water systems, which entails higher floodwater levels and lower groundwater levels. Furthermore, as the city is not far from the coast, flooding from tides and saline intrusion become urgent problems (Figure 7).

Additionally, the city-building process of MTC also raises many critical questions about sustainability and cultural identity. Specifically, urban planning and development based on unrealistic and infeasible dreams arranged disorderly in urban development priorities are responsible for the loss of typical characteristics of a water city (Figure 8). Furthermore, the transition from water to an urban lifestyle has gradually eroded water cultural identity, which is inherently a valuable asset of local tourism. Therefore, urban planning, landscape architecture, and flood management are facing the great challenge of finding an alternative to reverse the situation. In this context, MTC's development plan and vision based on the EI model have a crucial meaning. As an alternative to uncontrolled urban expansion, the "negative planning approach" for My Tho aims to protect the identity and integrity of the city by identifying essential processes for the conservation of its ecology, landscape, and culture. The EI idea is considered an effective solution for MTC to guide sustainable growth and provide ecosystem services to the city at three levels of scale: large (urban), medium (city), and small (sub-area).



(**a**) (**b**)

Figure 7. Analysis diagram of saline intrusion (**a**) and flooding (**b**) of My Tho City in a 0.5 m sea-level rise scenario in 2022. Source: Adapted from Institute of Southern Construction Planning, Vietnam (SISP).



(**a**) (**b**)

Figure 8. My Tho City today is a densely concentrated urban strip on the Mekong (Tien) River (**a**); the areas that are planned or under construction are eroding the identity of a water city (**b**). Source: Adapted from SISP.

4.2. Urban Morphology and Landscape as the Bases for Ecological Development Strategies

Urban design solutions for MTC are based on a thorough analysis of urban morphology and landscape. The data and analytical map are used to identify the potential of the water network, agricultural landscape, and ecological conditions in a holistic space. This approach identifies an interesting relationship between the existing urban system and the agricultural landscape, thereby shaping the idea of improving flood resilience based on new EI. Figure 9 identifies the overall structural logic of the My Tho urban area through mapping urban morphology, current infrastructure, and agricultural landscape. The results of the overall landscape structure analysis show that the city is identified by three basic factors: (1) the large water surface of the Tien River creating the urban appearance; (2) a rich agricultural area surrounding the existing urban area; and (3) two large islets in the middle of the Tien River. Urban planning for the future essentially takes all of these wonderful landscape elements into account. This analysis reinforces the overview of the urban area as a whole, in which the starting point is the relationship between MTC and water and the existing dense network of canals.

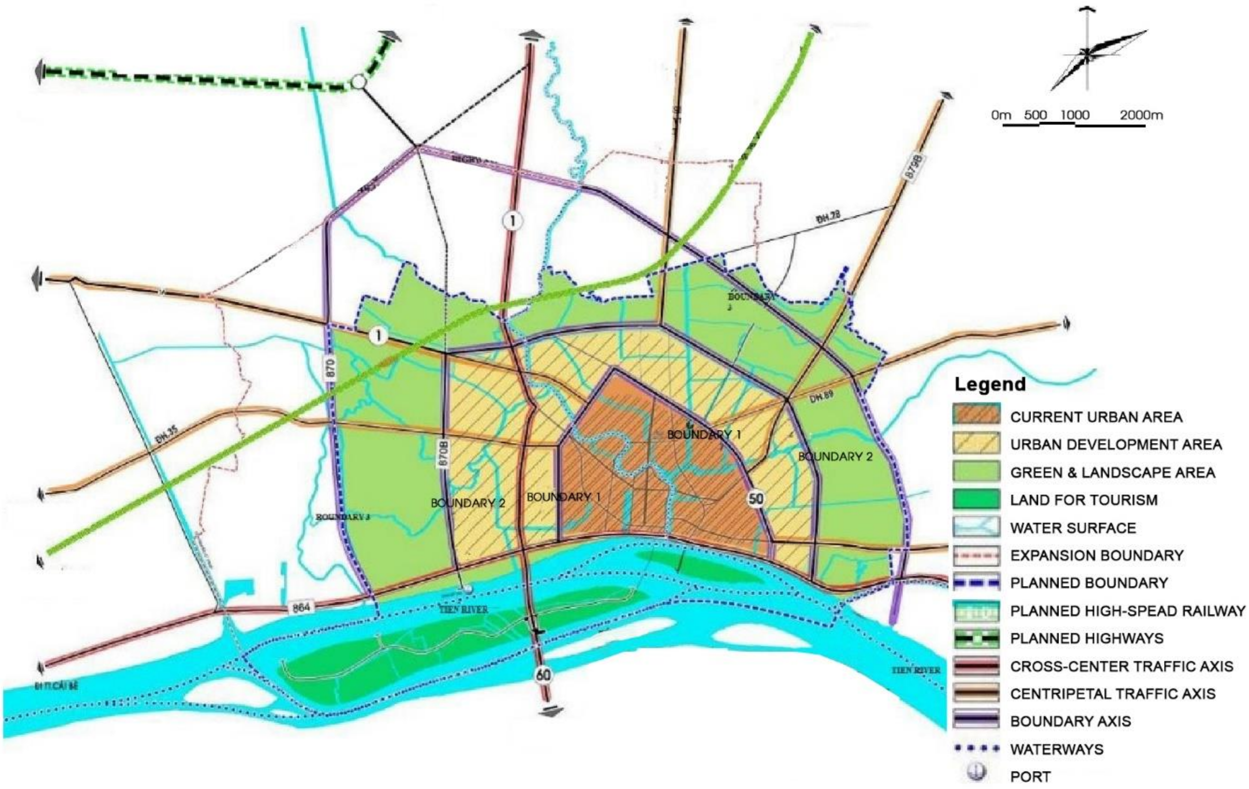


Figure 9. The analysis diagram of MTC's landscape structure including the existing urban area, the urban development area, and the local agricultural landscape. My Tho has an interlaced system of rivers and canals located in the heart of the city, associated with the islet system on Tien River, creating a unique feature for this urban area. Source: Adapted from SISP.

One of the pending problems that existed in previous planning projects is the separation of the local agricultural landscape from long-term development strategies. Abundant agricultural land strips are considered as blank spaces reserved for urban expansion plans. As a result, an agro-ecological mosaic with the water surface, rice fields, fruit trees, ornamental plants, and villages is replaced by new monotonous urban forms where ecological values and tourism potential are overlooked. In rural areas, land use patterns have been formed for a long time and have a close relationship with the water system that forms this area. Therefore, considering these water bodies as the backbone for development is a matter of not only landscape identity but also environmental priorities to protect the fragile ecosystem of the Tien River downstream. Another important value of My Tho is the two natural islets located in the middle of the Tien River, facing the city. These islets have great landscape potential for other ecological purposes in the future rather than being just a place for vegetables, fruits, and aquaculture. In the long term, these islets could be an ecological identity image for the city. They could be planned as an eco-tourism destination, a theme park, or a biodiversity conservation site of the city. Thus, the key challenges and issues identified by territorial logic could form a firm basis for planning direction at the regional scale and strategic projects at the lower scales.

4.3. Ecological Infrastructure as the Framework for Three Levels of Scale

Ecological infrastructure as a regional urban growth structure: To define an EI system for MTC, a variety of strategies are applied, ranging from "self-defense solutions"—protecting endangered structures, such as fruit growing or ornamental garden areas—to "opportunistic interventions"—restoring, completing, and integrating the damaged water systems into urban structures. The analytical basis of the project is created through the data from geographic information systems. By combining different landscape layers and interpreting them spatially, interconnecting the design and geography, a more viable development model is proposed. For developing a regional flood safety model, the analysis of available hydrological conditions is the basis for building a reliable flood risk interpretation map (Figure 10). By doing that, flood-safe landscape structures are proposed to be preserved and upgraded to obtain maximum water storage capacity, such as agricultural land, wetlands, large reservoirs, etc. Flood management and flood control will depend on a dense network of rivers, canals, and ponds, etc., which is a reasonable alternative to concrete dams and river dikes.

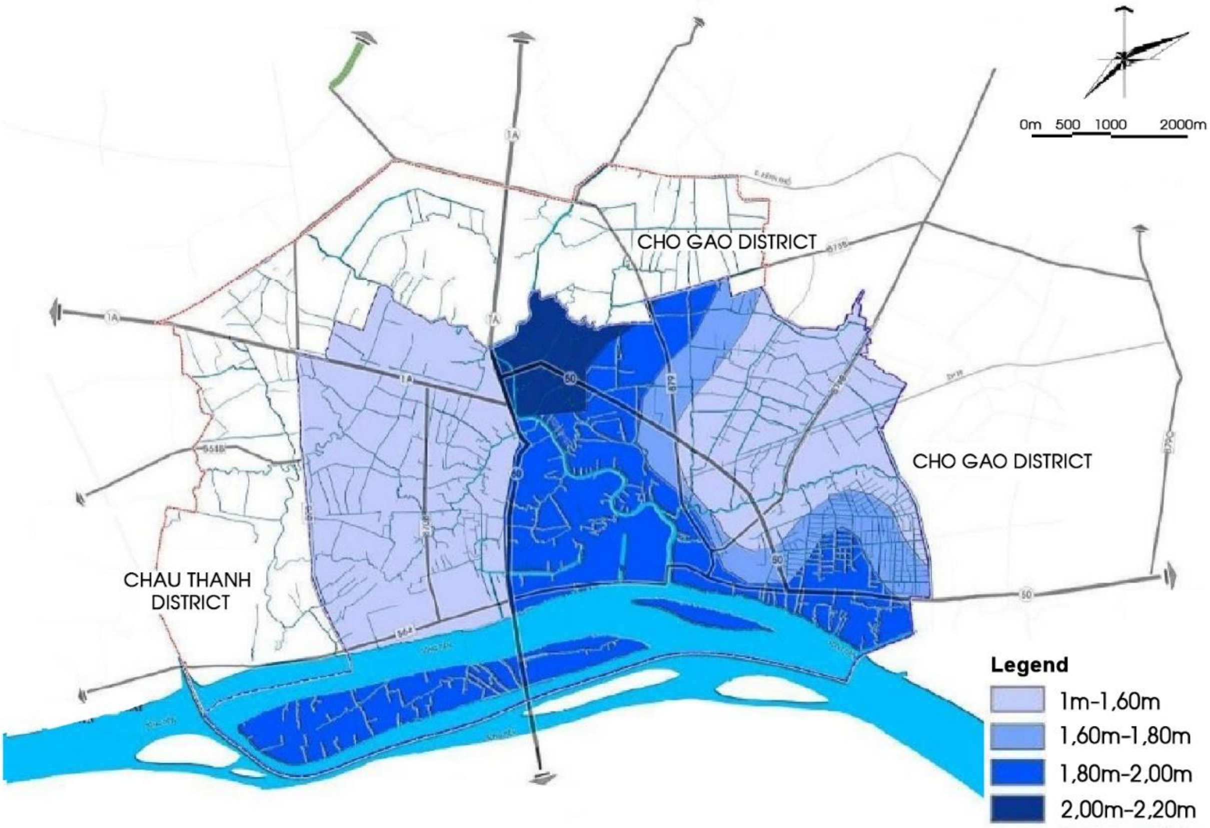


Figure 10. Map of 1 m sea-level rise scenario in 2050 when most of the My Tho City area would be affected. Source: Adapted from SISP.

An ecological network was designed and inspired by the analysis of structures protecting the biodiversity of the area. The analytical maps show an incomplete system of potential ecological corridors that need to be connected by new links (Figure 11). Strategic sites and areas are identified as the centers for design and management (e.g., existing strategic islets, parks). At the intersection between the man-made system and the natural corridor, the design interventions should be to bypass tunnels for some species of organisms and connect water flows and ecological corridors for animals [82,83]. Additionally, biodiversity conservation is based on an analysis of land use and irrigation, which is associated with an analysis of habitability (based on the spatial relationship between people and the principles of landscape ecology). As a result, strategic planning for safety patterns (ecological quality) on a wide scale for both urban and rural areas could be undertaken.

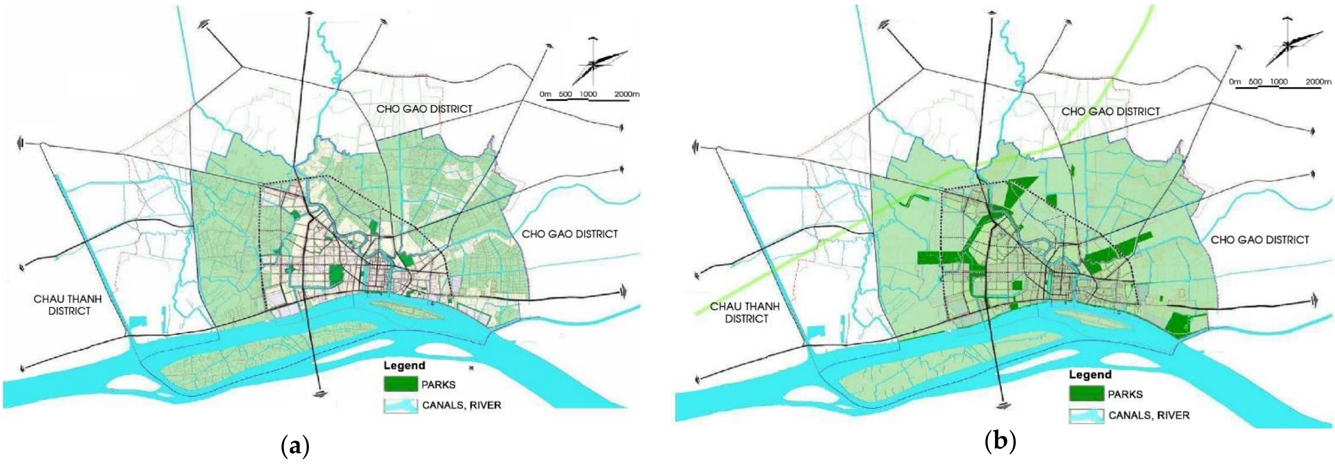


Figure 11. The system of green patches and open spaces is relatively limited in the 2003 Master Plan (**a**); and the addition of green corridors in the form of the EI model (**b**). Source: Adapted from SISP.

Ecological infrastructure as a safety model at a medium scale: At the medium scale (urban scale), the guidelines focus mainly on green corridors, creating the structure of EI planning at the regional scale (Figure 12). These corridors play an important role in all three targeted processes of MTC, including flood management, biodiversity conservation, and tourism. The green corridors are not merely a frame for the EI system but also a venue for programs and activities related to ecological research and education. As a basis for design guidelines, EI is preferentially distributed along river, canal, and wetland corridors. The design guidelines give development direction to the neighboring areas and match different land-use purposes on the sub-area scale. To be specific, the first step is to produce a design and management manual to guide the interventions on a medium scale. This guide should be both basic enough to ensure EI goals, and flexible enough to adapt to possible future construction changes. The outstanding feature of this eco-program is that the new toolkit can be used in many cases and is open to new contexts, rather than providing a rigid master plan. However, to ensure that the manual will meet localized and specific needs, more analysis needs to be supplemented by the opinions of local communities.

Innovative solutions for flood control and surface water management are considered the model for the entire open space and green space of MTC. According to common flood management policy, almost all riverbanks and canals are reinforced by concrete embankments. Thus, one of the fundamental challenges of EI is to persuade local authorities to gradually stop this process as this management policy is both costly and harmful to local ecology and customs. The importance of surface water in the landscape of MTC is obvious, it includes rivers and swamps (factors in the circulatory system that absorb water from heavy rains and high tides), and artificial water bodies (canals, ditches). The alternative, therefore, is to recombine rivers and urban daily life through the restoration of the highly sensitive culture and ecosystems at the intersection of soil and water. Moreover, detailed topographical simulation is an important design tool to guide urbanization and maintain a certain level of balance between excavation and filling (Figure 13). For some canals that have been filled or partly leveled over the past decades, it is proposed to recreate these canals and convert them into attractive open spaces. These new canals could expand the drainage network, provide more space for water storage, and become a center of other urban open space development programs. In addition, some existing parks will be renovated to double their water storage capacity in the rainy season.

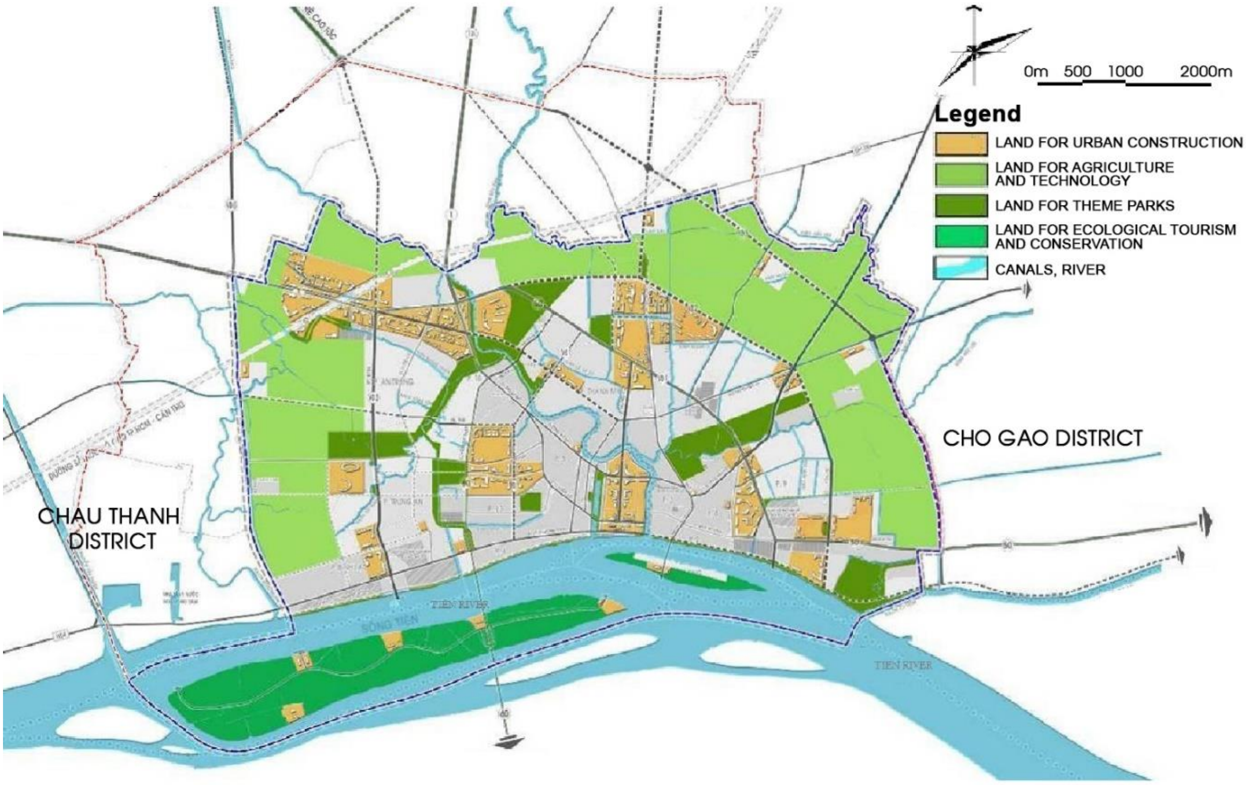


Figure 12. New EI is a combination of urban green patches and agricultural landscape through the network of canals in My Tho City. Source: Adapted from SISP.

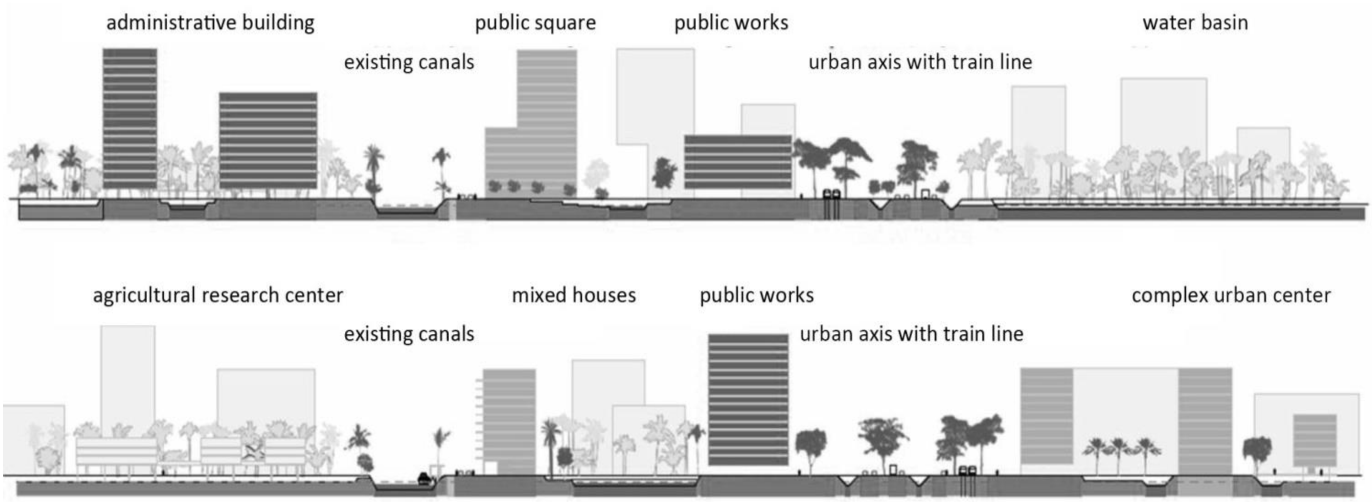


Figure 13. To concretize the design and management manual, the detailed topographic cross-section is an important design tool to guide urbanization and maintain a certain level of balance between excavation and filling. The tiers corresponding to specific activities are proposed, in which green patches are distributed along canals and rivers for flood management and public programs.

Ecological infrastructure as a safety model at the sub-area scale: In MTC, as EI is a research-by-design, the opportunities at the smallest scale are tested in sub-areas along the canal corridor. The challenge at the sub-area level is how to create structures and forms that could be easily connected at higher scales. The purpose of the cross-scale connection is to collect the responses, thereby accurately assessing the role of ecological services at each scale. Moreover, the interconnection between the various scales will maximize the ability to ensure the continuous delivery of ecological services. At this small scale, the idea of EI as a source of service (ecological, cultural, and tourism services) is perceptible. It can be compared with the provision of social and economic services in existing urban infrastructure. Based on the typical characteristics of the local water network, the idea of using water as a design tool is considered an effective solution for EI. As an alternative to concrete canalization and embankment of waterways, it is proposed to avoid flood risks by restoring aquatic ecosystems (Figure 14). The units structured by water lines and the hard surface are interleaved with soft and permeable areas to create an effective morphology that maximizes the water absorption capacity of the green patches instead of promoting the outside drainage system.

(**a**) (**b**)

Figure 14. Restoring ecological services of the canals is the main goal of EI at the sub-area scale. The (partly) filled canals (**a**) will be returned to water space for the construction of riverine flooded parks, the riverine ecosystem will gradually be restored over time (**b**).

Although the hydrological landscape has a close relation with historical origins and urbanization process in the VMD, in reality, water only attracts attention in technical and technological aspects [18]. The spatial, symbolic, and ecological values of the hydrological landscape are often overlooked in urban design. The main orientation of the project is to stick to natural conditions and create a multi-functional landscape system as the backbone for urban development programs. The simultaneous deployment of EI on large—medium—small scales is an important feature of modern urban design. Recent planning initiatives have shown that urban development can be integrated with ecological programs. Moreover, urban development and ecological conservation are not necessarily antagonistic concepts but can be harmonized in the concept of EI [84,85]. In terms of water management, the wisdom of living with floods and taking advantage of natural forces in the VMD could be a perfect tool to develop new flood resilient EI for cities.

5. Conclusions

Based on an understanding of the complex dynamics of human–river interactions arising from FCIs, it is still controversial if we should continue to trust FCI to prevent floods in cities. The socio-ecological system of the VMD is a product of not only contemporary policies but also built infrastructure stemming from colonial times and which still limits and constrains today's development plan. Therefore, the idea that existing cities cannot exist without FCI is unchangeable, while the flood resilient approach—equipping the built environment with a capacity to prevent flood damage—is a reliable but often overlooked option. In fact, the related technologies, management practices, regulatory frameworks, and social perceptions of flood control have assimilated to stabilize each other. Thus, in the short term, a large-scale shift to flood resilience in the VMD is unrealistic. Nevertheless, the intentional changes at a smaller scale are possible via the implementation of several pilot flood resilience projects at the city or regional scale. These pilot projects can be a catalyst for change, and the starting point for a new social learning process in which the hydrogeological, geomorphological, and ecology of rivers can be observed. A better understanding of rivers will promote the awareness that flood is not merely a hazard but also a socio-ecological asset of the delta.

It is not certain if any modern city in the world depends entirely on flood resilience to prevent flood damage, but the design strategies for MTC, as analyzed above, can develop flood resilience at the city scale. The shift from flood control to flood resilience can be done gradually. One intervention that could be used for the shift is the approach to "allow flooding within control limits"—that is, to allow floodwater to be transferred directly to floodable areas. This approach should be implemented at the urban scale and will require time and certain investments, but it is possible. Instead of investing and allocating huge resources to FCIs, it is better to invest in equipping the built environment through planning, design, and construction. Cities with high flood risk and low ground, such as MTC, could benefit from this consideration. Other delta cities also have a similar opportunity, as FCI is currently prone to failure and urban infrastructure is facing a serious crisis of degradation. One topic that has not received sufficient attention is how to make urban infrastructure tolerant to system-level flooding. This leads us to pay more attention to the role of EI in supporting resilience through the provision of ecosystem services to the city. The ecological design and analysis framework above can be modified to integrate the hierarchies to enhance the flood resilience of urban and delta systems spatially and temporally (see Figure 15).

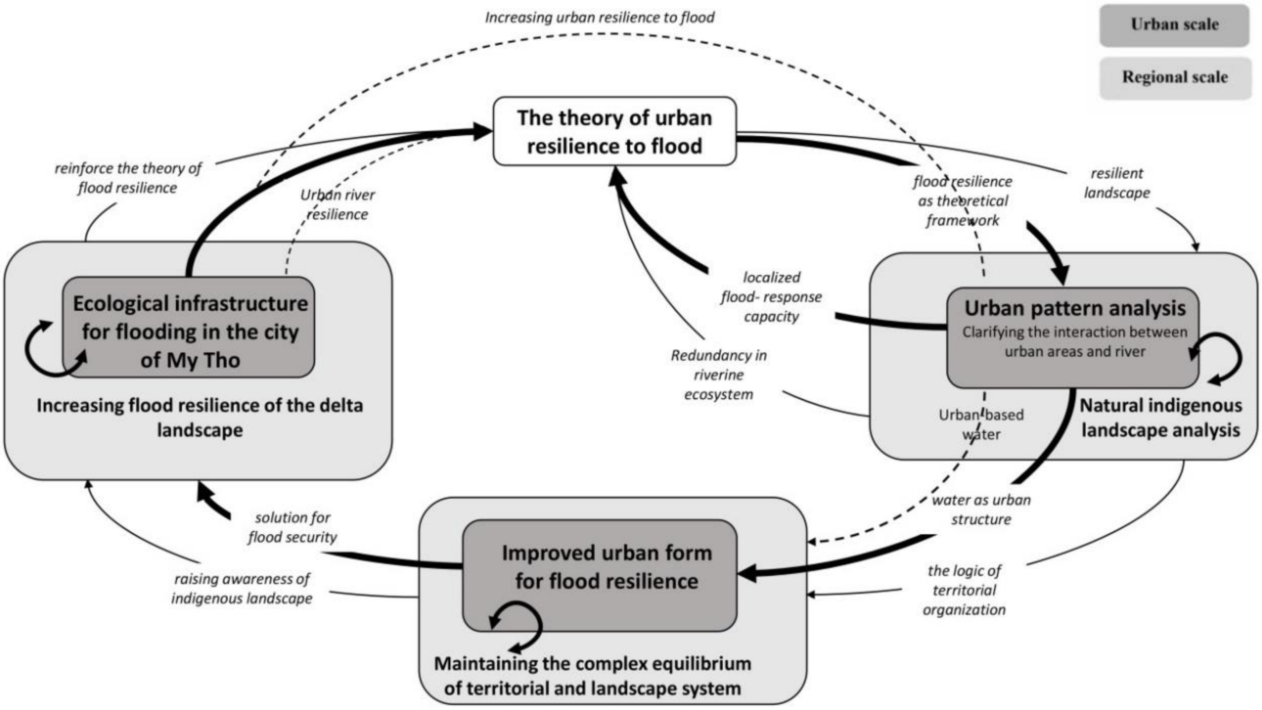


Figure 15. The ecological design framework simulates cross-scale interactions in a sustainable way to enhance the flood resilience of urban and delta ecosystems spatially and temporally.

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