Science of the Total Environment 954 (2024) 176501

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Harnessing a systems approach for sustainable adaptation in vulnerable mega-deltas: A case study of the dyke heightening program in the Vietnamese Mekong Delta's floodplains

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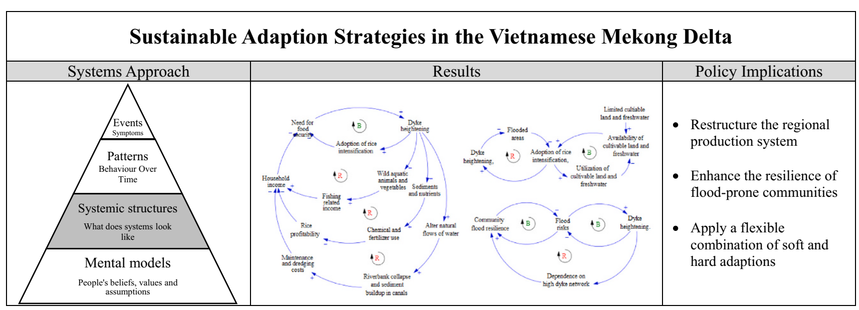
HIGHLIGHTS

- Importance of system thinking for effective management of climate adaptation impacts
- Dyke-heightening program fails to meet its objectives and risks long-term failures.
- Restructuring production system and enhancing flood resilience are key for sustainable delta growth.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Fernando Pacheco

1. Introduction

Coastal river deltas, home to over half a billion people, are of great significance to the environment and society due to their capacity to support agriculture, fisheries, cities, and unique ecosystems (Chapman and Darby, 2016; Loucks, 2019; Tran et al., 2021). They also provide crucial resources such as fertile soil, freshwater, and rich biodiversity (Tessler et al., 2015; Jones and O'Neill, 2016; Edmonds et al., 2020), and offer various ecosystem services, including transportation via waterways, fisheries, tourism, and natural buffering against storm surges (Hagenlocher et al., 2018; Loucks, 2019). Due to these attributes, coastal river deltas often host densely populated areas, and many of them are critical to a nation's economy, serving as substantial food sources (Nicholls et al., 2016; Szabo et al., 2016a, 2016b; Edmonds et al., 2020).

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https://doi.org/10.1016/j.scitotenv.2024.176501
Received 24 May 2024; Received in revised form 15 September 2024; Accepted 23 September 2024
Available online 24 September 2024

Coastal river deltas, due to their low-lying nature, are highly exposed to the impacts of climate change, particularly sea level rise (SLR) (Hinkel et al., 2018; Kirezci et al., 2020; Almar et al., 2021; Nicholls et al., 2021), and natural hazards such as cyclones and storm surges (Jankowski et al., 2017; Pörtner et al., 2019). These impacts potentially lead to permanent or intermittent flooding, disturb coastal ecosystems, cause the salinization of soil and aquifers, and alter natural watercourses (Bongarts Lebbe et al., 2021). These trends are further exacerbated by upstream development activities, such as dam construction, river diversion, and reservoirs (Gracia et al., 2018; Minderhoud et al., 2019; Tran et al., 2021). The consequences of these impacts could significantly affect the provision of services in these deltas, leading to increased poverty (Szabo et al., 2016a, 2016b; Tran and James, 2017), threatened food security (Chapman and Darby, 2016; Arto et al., 2019), displacement of populations (Perry, 2019), and altered marine biodiversity (Bishop et al., 2017). This could potentially impede progress towards the United Nations Sustainable Development Goals (SDGs) (van der Most, 2009; Renaud et al., 2016; Szabo et al., 2016a, 2016b). Therefore, sustainable delta development has been receiving growing interest globally (Day et al., 2016; Hutton et al., 2018; Craig and Ruhl, 2019).

In response to anticipated SLR and the intensification of extreme weather events in coastal river deltas, numerous adaptation initiatives have been implemented in these regions to combat SLR or to adapt to emerging climatic conditions (Lwasa, 2015; Esteban et al., 2019; Berrang-Ford et al., 2021). These adaptation strategies are generally classified into three main approaches: protect, accommodate, and managed retreat (Bongarts Lebbe et al., 2021). In vulnerable mega deltas, a combination of these approaches is recommended to reduce the risk of SLR (Bongarts Lebbe et al., 2021). However, in many deltas, particularly those situated in developing countries, a policy response is often required to address other development-related pressures, including population growth, agricultural intensification, and urbanization (Chapman and Darby, 2016). The impacts resulting from the interaction of these two forces (environmental change and economic development) exhibit a dynamically complex system, which comprises a network of interactions, unintuitive delays, and feedback mechanisms between multiple dimensions of ecological, physical, environmental, and socio-economic aspects (Giosan et al., 2014; Chapman and Darby, 2016; Gain et al., 2020; Bongarts Lebbe et al., 2021), and involves a diverse array of stakeholders (Hutton et al., 2021; Bongarts Lebbe et al., 2021).

Despite the growing recognition of the intricate nature of adaptation strategies' impacts, previous studies, policy responses, and measures designed to mitigate them typically rely on linear or mechanisms that are considered in isolation. These conventional approaches primarily offer quick-fix or short-term solutions that merely address the symptoms of a complex problem (Bosch et al., 2013), and often lead to policy resistance, which refers to the tendency of policy interventions to be delayed, weakened, or obstructed by the system's reaction (Sterman, 2000). That is, an intervention that is made with an intended consequence to 'fix a problem' can inadvertently cause unintended side effects make the problem worse. This study posits that coping with the dynamically complex impacts of adaptation strategies in coastal river deltas requires a systematic framework. Using the iceberg model, this holistic approach views a complex problem in a broader context from four levels of perspective: events, patterns, systemic structures, and mental models (Maani and Cavana, 2007). The iceberg model illustrates how decisions typically focus on immediate and visible issues (events, patterns), but greater leverage from interventions occurs when decisions are based on systemic understanding and transforming mental models (systemic structures and mental models) (Meadows, 2008). This holistic approach aids in developing more effective strategies that address the underlying causes (leverage points) rather than solely treating the symptoms of complex problems (Mai and Smith, 2015; Sahin et al., 2020). It provides a set of necessary analytical skills used to describe the complex interplay between system elements that generate outcomes, forecast their behavior, and develop interventions to achieve desired outcomes while avoiding detrimental results (Kelly et al., 2013; Berry et al., 2018).

The primary aim of this study is to address the following research questions: (i) What variables and feedback loops (which represent the system's structure) are relevant in understanding the efficacy of climate adaptation strategies? and (ii) what are the key leverage points for systems-based intervention towards sustainable delta development?. We deployed a case study approach focusing on a dyke heightening program in the floodplains of the Vietnamese Mekong Delta. The findings from this study are expected to make valuable contributions to reshaping adaptation policies in the Vietnamese Mekong Delta and to facilitate knowledge sharing and learning to help inform policy development around adaptation for other delta systems worldwide.

2. Study area

The Vietnamese Mekong Delta (VMD) is situated in the downstream region of the transboundary Mekong River Basin (Fig. 1). Spanning approximately 45,000 km^2 (12 % of Vietnam's natural landmass), it is home to nearly 20 million inhabitants, accounting for 20 % of the Vietnamese population (Triet et al., 2017; Xuan et al., 2022). Administratively, the delta is divided into 13 provinces and the city of Can Tho, which is regarded as the delta's center (Vo, 2021). The VMD is a critical region for the country's economy and is commonly known as the 'rice bowl' of the country, accounting for 18 % of its GDP, primarily from fishery and agricultural production (Tran et al., 2019).

The VMD, despite its economic importance, is facing significant challenges. In addition to rising sea levels (Minderhoud et al., 2019), the region is experiencing substantial land subsidence due to excessive groundwater extraction (Minderhoud et al., 2020). This has made the VMD, the world's third-largest delta, one of the most vulnerable regions to the impacts of climate change (Chapman and Darby, 2016), with significantly increased risks of flooding during the rainy season and saltwater intrusion during the dry season (Tran et al., 2021; Xuan et al., 2022).

The delta is divided into two parts: the upstream floodplains and the downstream delta (Fig. 1). The upstream area, also known as the high-flood zone, experiences seasonal flooding up to 3 m deep from July to December (Triet et al., 2017), while the downstream area encompasses the central and coastal zones, which are heavily affected by saline intrusions (Nguyen et al., 2017). These transboundary environmental phenomena have impacted the lives of millions and pose a significant threat to the delta's agricultural sector. In response, the Government of Vietnam has implemented an array of development programs in the VMD over the last three decades, enforced by large-scale water control infrastructures and an intensified agricultural production strategy (Smajgl et al., 2015; Pham et al., 2020).

Large-scale water-control systems were constructed in the early 1990s, followed by the development of extensive dyke networks in two stages: low-dyke and high dyke (Nguyen et al., 2017). Low dyke systems, constructed based on the flood peak in 1978, range in height from 2 to 4 m, typically 3 m (Triet et al., 2017). These low dyke systems enable control of the early floods (mid-August), thus allowing for the cultivation of two rice crops annually (Thanh et al., 2020). The high dyke systems were built based on the peak of the catastrophic flood in 2000 by heightening the low dykes (Tran et al., 2018). This high dyke system completely blocks floodwaters, thus allowing three rice crops per year.

The dyke heightening program in the VMD was considered a crucial infrastructure initiative aimed at mitigating flood risks while enhancing agricultural productivity to improve national food security (Chapman and Darby, 2016). This study focuses on the VMD's upstream region or high flood zone, which lies in the Long Xuyen Quadrangle (LXQ) and the Plain of Reeds (POR). These floodplains serve as natural retention areas, absorbing surplus water during the flood season and discharging it back into the primary watercourses during the dry season (Tran et al., 2019). The construction of high dykes has noticeably increased in the

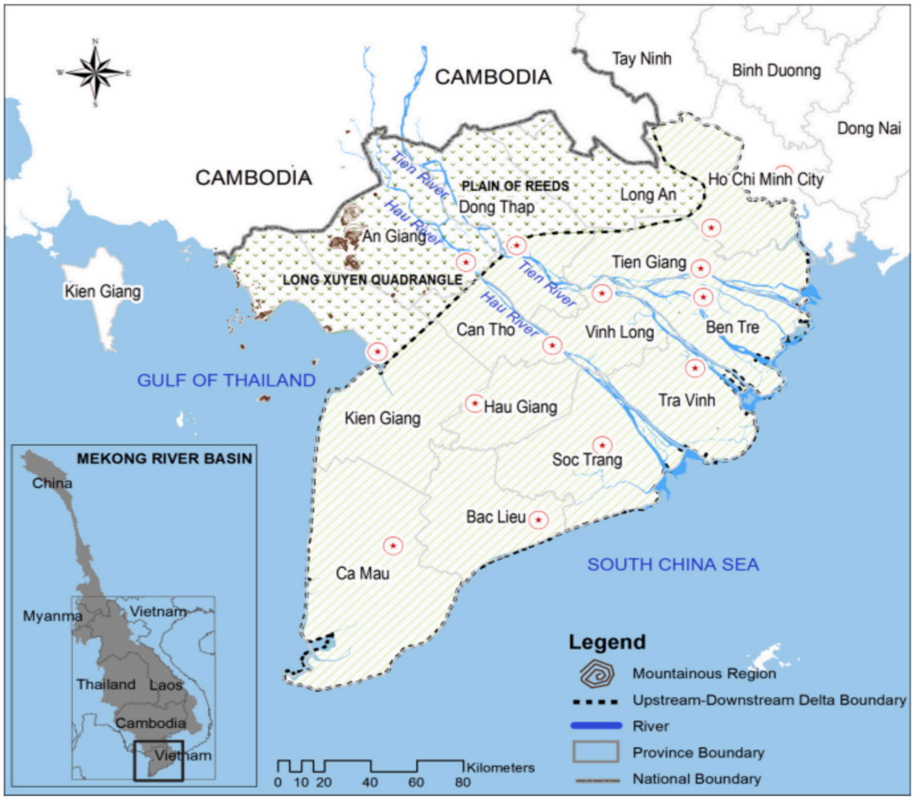

Fig. 1. The Vietnamese Mekong Delta with marked upstream-downstream boundary (Source: Tran et al., 2019).

floodplains over the last three decades as a means to facilitate agricultural intensification in the VMD's upstream region (Thanh et al., 2020). However, the impacts of high dykes on the delta are complex and require a holistic assessment to identify appropriate interventions to mitigate adverse effects.

3. Research approach

Our research approach is anchored in systems thinking, which fosters a comprehensive understanding of how system elements connect and how these connections produce observable behavior over time (Arnold and Wade, 2015; Berry et al., 2018; Sterman, 2000). By providing a bundle of 'synergistic analytic skills', this holistic approach can facilitate the identification of leverage points where systemic interventions can be implemented to redesign the system for positive and sustainable success (Meadows, 2008). Overall, the implementation of a systems thinking approach comprises five main successive phases: (i) problem articulation, (ii) formulation of dynamic hypotheses, (iii) development of a simulation model, (iv) model testing, and (v) policy design and evaluation (Sterman, 2000).

The first two phases of our approach predominantly involve qualitative modeling, aiming to develop a conceptual model that illustrates the underlying dynamics of interactions among the system's components. Conversely, the last three phases emphasize quantitative modeling, with the ultimate objective of creating a computer-based simulation model that simulates the dynamic relationships among the system components. In this study, the first two phases were employed to determine the underlying system structure aimed at explaining the dynamic impacts of the dyke heightening program in the VMD's floodplains. Phases 3, 4, and 5 were excluded as they extended beyond this study's scope.

3.1. Problem articulation (Phase 1)

Problem articulation is the most critical step in applying a systems thinking approach, as it sets the foundation for the subsequent phases, including the formulation of dynamic hypotheses. The primary purpose of this phase is to address the questions 'what is the problem' and 'why it is a problem' by engaging and consulting with stakeholders (Mai and Smith, 2015). Once the problem is identified, information and datasets are collected to gain a deeper understanding of the nature and context of the problem.

An Giang and Dong Thap provinces were purposively chosen as representative regions for this study, because they have some of the most extensive and advanced dyke systems including both high dyke and low dyke systems, which has led to various social, economic, and environmental impacts. Additionally, these regions are prominent rice-growing areas, where dyke heightening program significantly impacts agricultural productivity, cropping patterns, and local livelihoods.

Stakeholders involved in this study were identified through mutual discussions with key staff from the School of Economics at Can Tho University in Vietnam. During these meetings, we identified 11 key stakeholder groups. The stakeholder groups, along with the methods used to collect data and information on the issues associated with the dyke heightening program, are outlined in Table 1.

In-depth interviews were semi- structured with a set of predefined questions (Table 2) and additional questions arising during the interactions. The purpose of these interviews was to capture issues associated with the dyke heightening program in the VMD from a wide range of perspectives, but not to elicit any information about the system structure.

Household interviews and field observations were also conducted among rice-producing farmers in two district in An Giang province, namely Thoai Son (110 households) and Chau Thanh district (99 households). In Thoai Son, farmers cultivate three rice crops per year under high dykes. In contrast, in Chau Thanh district, farmers cultivate

Table 1
Key stakeholders and data collection methods.

Stakeholder	Stakeholder group	Data collection methods
Provincial Department of Plant Protection Stations of An Giang and Dong Thap province Provincial Department of Agriculture and Rural Development of An Giang and Dong Thap provinces Provincial Department of Environment and Natural Resources of An Giang and Dong Thap provinces Provincial Department of Irrigation of An Giang and Dong Thap provinces	Government officials	In-depth Interview
School of Economics, Can Tho University DRAGON-Mekong Institute, Can Tho University Mekong Delta Development Research Institute College of Environment and Natural Resources, Can Tho University College of Aquaculture and Fisheries, Can Tho University College of Agriculture, Can Tho University	Academia	In-depth Interview
Famers in Thoai Son and Chau Thanh district, An Giang province	Program beneficiaries	Household survey, Field Observations

two rice crops annually under low dykes. These two districts are situated in close proximity to each other, separated only by a single canal that serves as the boundary between them. These locations formerly possessed comparable social and natural conditions, including soil fertility.

3.2. Formulation of dynamic hypotheses (Phase 2)

During this phase, dynamic hypotheses, which in the system dynamics discipline represents are candidate conceptual models that help explain the dynamics of the problem (identified in Phase 1), are developed using causal loop diagrams (CLDs). A CLD is a visual representation of key system components, referred to as variables, and their cause-effect relationships. From a systems thinking perspective, the presence of feedback loops and delays between variables is of key interest in these CLDs, because they help to explain the time-varying nature of the problem e.g. patterns of exponential growth can be linked to the presence of a reinforcing feedback loop.

A CLD is made up of two primary elements: variables of the system and arrows that depict the causal relationships between pairs of variables. Each arrow is assigned a positive '+' or negative '-' polarity, with the former indicating that the cause and effect move in the same direction (analogous to being positively correlated) and the latter indicating that they move in opposite directions (analogous to being negatively correlated). Feedback loops occur when a connected path of variables leads back to the initial variable (circular causality). There are two types of feedback loops: reinforcing loops (R), which represent an amplifying effect leading to exponential growth, and balancing loops (B), which counteract changes leading to a stabilized system (Sterman, 2000). The type of feedback loop (R or B) is determined by the number of negative polarities in the loop, a zero or an even number of negative polarities indicates an R loop, otherwise, it is a B loop, as described in system dynamics literature (Maani and Cavana, 2007).

The development of a CLD for the dyke-heightening program involved three main stages. Initially, a preliminary CLD was constructed based on our prior knowledge of the dyke-heightening program. In the second stage, we incorporated the key issues identified by stakeholders (as listed in Table 3) into the preliminary CLD to produce the working CLD. This working CLD was subsequently reviewed and validated through consultations with key staff from the School of Economics at Can Tho University in the Vietnamese Mekong Delta, and experts who possessed knowledge of the program and were familiar with the study region. The insights gathered from these experts were used to create the final CLD.

Based on the final CLD, system archetypes (SAs) were identified, which were subsequently used to suggest improvements to the current dyke heightening policy. SAs represent commonly observed structures (particular combinations of reinforcing and/or balancing feedback loops) that explain the temporal behavior exhibited by variables within the focus system (Braun, 2002). Their utility lies in their ability to distill key dynamics from complex systems, such as the CLDs, in a way that provides additional insight for decision-makers (McLean et al., 2019). Examples of common SAs used in systems thinking include 'fixes that fail' (where a management intervention used to achieve an intended consequence causes an unintended consequence), 'limits to growth' (where the growth rate for an entity [e.g. economic growth of a firm] is inhibited by inherent limitations that restrict this growth [e.g. availability of capital]), and 'shifting the burden' (where an applied management solution fails to fix a problem properly and simultaneously increases the difficulty in implementing a proper solution) (Maani and Cavana, 2007). The identification of SAs always suggests deep leverage points (Senge, 1990), where a small shift can produce significant impacts (Meadows, 1999).

4. Results

4.1. Problem identification

The issues associated with the dyke-heightening program, as articulated by the stakeholders, are presented in Table 3. These issues are categorized into four major themes: ecology, economy, environment, and social aspects. Economic and environmental themes are the most frequently identified issues among stakeholders. Each stakeholder group was observed to focus on specific aspects of the program's impacts. Specifically, government officials prioritized enhanced flood protection as a major benefit, aiming to safeguard homes, agricultural land, and livelihoods. Conversely, stakeholders from academia expressed broader concerns about hydrological and economic interactions at the deltaic scale. For example, academics have highlighted the impacts of high dykes on flow velocities, salinity intrusion, and the division of river branches. They also noted the recent disturbances in the flow regime, such as low floods and delayed floods due to reservoir filling upstream in the Mekong River. Furthermore, they expressed concerns about the potential impacts on the delicate ecosystem balance, fearing disruptions of habitats for wild fish and vegetation. On the other hand, local residents shared a range of concerns related to their livelihoods and well-being, such as high farm input costs, low prices for improved rice varieties, and limited off-farm employment opportunities. Additionally, they voiced apprehensions about the inability to flush out toxins within high dykes, fearing this could lead to water and air pollution that adversely

Table 2
Set of questions used during stakeholder interviews and group discussions.

1. What are the negative impacts you see from the dyke heightening program on the VMD?
2. What are the positive impacts you see from the dyke heightening program on the VMD?
3. In your view, what are sustainable solutions for the VMD?
4. What are the opportunities and challenges for your suggested sustainable solutions?

Table 3
Issues associated with the dyke heightening articulated by the stakeholders.

Theme	Issues	Description
Ecology	Declined wild aquatic animals and vegetables	These species whose populations have significantly decreased in their natural habitats
	Reduced biological pest control	Refers to a decline in the effectiveness of natural mechanisms that help regulate pest populations in an ecosystem
	Increased pests and diseases	Refers to a situation where the population of pests and the incidence of diseases have risen beyond normal levels
Economy	Economic pressure	Stress or strain on the economic system, potentially due to increased costs or limited resources
	Increased food expenditure	A situation where households are spending more money on food compared to a previous period
	Risk of severe flooding	Refer to the impacts caused by severe flooding
	Costs of flood-related losses	Expenses incurred due to damages or losses caused by flooding
	Increased costs of illness	A situation where households experience higher expenses associated with healthcare and medical treatment
	Increased chemicals and fertilizers use	A situation where there is a rise in the application and utilization of chemicals and fertilizers in agricultural practices
	Increased in adoption of improved rice varieties	The growing utilization of rice varieties that have high level of resistance to disease and insects
	Increased maintenance and dredging costs	The rising expenditures related to upkeeping of high dyke
	Damages or losses of crops	Losses incurred due to damages to agricultural crops
	Damages properties or losses of people's lives	Impact of flooding on homes and human lives in flood-affected areas
Environment	Increased in duration and depth of inundation in the extreme flood events	The prolonged periods and greater depths of water covering land areas during exceptionally severe flooding incidents
	Increased in duration and depth of flood displaced in downstream areas	The prolonged periods and greater depths of water inundating regions situated downstream
	Increased in duration and extent of saline intrusion in the lower delta in dry season	The prolonged period and expanded area over which saltwater infiltrates into freshwater systems in low-lying deltaic regions during the dry months
	Decrease in water retention capacity and groundwater recharge	A reduction in the ability of the land and subsurface to store and replenish water resources
	Reduced flushing out of toxins inside high dykes	A situation where the natural process of removing toxins within areas protected by high dykes is diminished
	Reduced deposition of sediment	A situation where there is a decrease in the accumulation of sediment
	Increased flow velocity of water in river	A situation where the speed at which water moves within the river channel experiences a noticeable rise
	Collapse of the coastal banks	Failure or erosion of coastal banks due to flooding or other factors
Social	Risk of high dykes being breached	Probability of high dykes being breached or broken during flooding events
	Risk of low dykes being overtopped	Probability of low dykes being submerged or flooded over during high water levels
	Increased community's health-related issues	A situation where there is a noticeable rise in various health problems within the community
	Immigration	Influx of people move rural areas moving to cities

affects their health.

4.2. Dynamic hypotheses of the dyke heightening program

4.2.1. Preliminary CLD

We began the dynamic hypotheses or conceptual model of the dyke heightening program with a simple CLD (Fig. 2), based on our prior knowledge of the program. This CLD includes two feedback loops, B1 and R1, which depict the dual objectives of the program: (i) adapting to increasingly intense flooding (represented by B1) and (ii) promoting agricultural development in the Vietnamese Mekong Delta's floodplains (Chapman and Darby, 2016). Feedback loop B1 illustrates the mutual dependency between 'dyke heightening' and 'flood damage'. Advocates for increasing dyke height point to its role in reducing flood damage, shown by the negative polarity between dyke heightening and flood damage. This reduction in damage encourages the government to further support the construction of high dykes, as depicted by the positive polarity between flood damage and dyke heightening actions. Feedback loop R1 indicates that dyke heightening influences agricultural development by reducing flooded areas, which leads to an increased adoption of rice-based intensive cropping (adoption of rice intensification). This increase in agricultural productivity, in turn, leads to further dyke heightening.

4.2.2. Final CLD

The initial CLD served as the foundation for developing a more detailed and complex CLD, outlining the potential benefits and drawbacks of the dyke heightening program on the region. This advancement was achieved by integrating variables associated with the stakeholder-identified issues presented in Table 3. From this integration, we produced the working CLD, which was subsequently validated and confirmed through expert consultations. These insights were used to create the final CLD (Fig. 3). This final CLD visualizes the system's feedback mechanisms and time lags between system components, thereby providing a holistic picture of the causal relationships between the impacts of the program. For example, it illustrates how high dykes

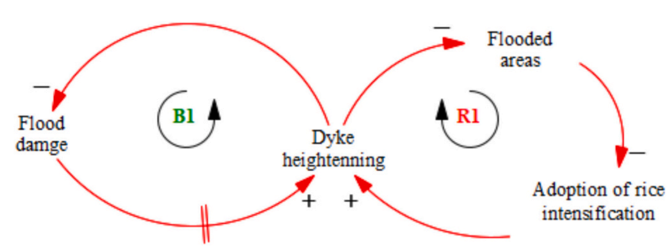

Fig. 2. A preliminary CLD of the dyke heightening program in the VMD's floodplains. A positive sign (+) indicates that the two variables move in the same direction, while a negative sign (−) means they change in opposite directions. Loop identifiers R and B indicate reinforcing and balancing loops, respectively, where reinforcing loops are positive feedback that amplify changes, and balancing loops are negative feedback that present stability. A double bar (||) implies a time lag between a pair of variables.

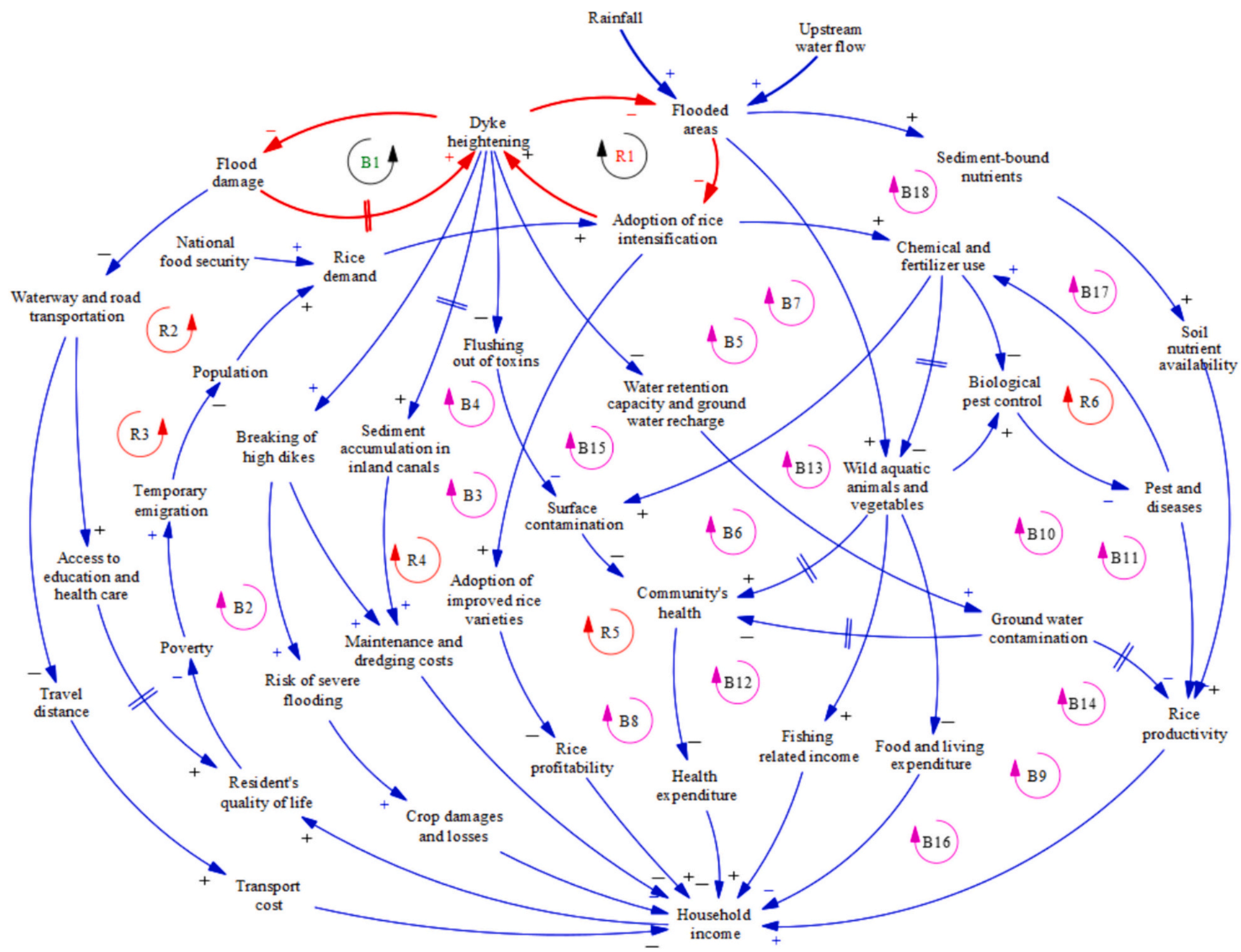

Fig. 3. Final CLD of dyke heightening program in the VMD's floodplains.

influence flow velocities, erosion, salinity intrusion, the division of river branches, as well as the recent disturbances in the flow regime due to low and delayed floods caused by upstream dam filling. The final CLD comprises four reinforcing loops (R1 to R4) and eighteen balancing loops (B1 to B18). The details of the variables involved and the core insights delivered by each loop are presented in Appendix A.

4.3. *System archetype*

4.3.1. *Fixes that fail*

The first archetype identified in the final CLD is 'fixes that fail'. This archetype describes instances where a managerial solution to a problem initially acts as a strategic remedy. While this solution can be effective in the short term, it is often associated with unforeseen and potentially harmful consequences that may exacerbate the initial problem over time. Consequently, the system may revert to its original state or even deteriorate further after a period of time (Senge, 1990). In the case of the dyke-heightening program, the 'fixes that fail' archetype is associated with national food security issues in the early 1990s. The quick fix implemented by the government involved the extensive development of high dykes, which was initially perceived as a robust, long-term investment to control flooding and salinity intrusion, thereby enhancing agricultural productivity (Tran et al., 2021), which in turn improving the national food supply, as represented by balancing loop B in Fig. 4.

It's important to note that at the time of the dyke heightening program's implementation, this intervention was not always recognized as hasty or short-sighted. Initially, the policy helped increase rice production and address food security concerns. However, evolving circumstances have since revealed its limitations, as the program later encountered sustainability challenges due to emerging factors such as sea level rise and land subsidence. Consultations with key stakeholders in An Giang and Dong Thap provinces highlighted that the construction of high dyke networks had altered the natural water flow, leading to downstream effects that compromised the ecological benefits that floodwaters provide for delta ecosystems. This has led to both internal and external consequences for farming. Internally, the effects include substantial requirements for investment and increased farming expenses. Externally, the effects include increased flood damage resulting from breaches in high dykes, which primarily affects the third crop, decreased sediment flows, exacerbated saltwater intrusion, and accelerated riverbank erosion. Consequently, this negatively impacts household income and thereby food security, as illustrated by the reinforcing loops in Fig. 4. The quick fix of dyke heightening addresses food shortages in the short term; however, the consequences act to increase internal and external costs over time, resulting in reduced household income and, therefore, food security (Fig. 4(b)).

4.3.2. *Limits to growth*

The second archetype identified within the final CLD is 'limits to growth'. This archetype represents situations where constraints or limitations eventually hinder the continued improvement or expansion of a system's performance or growth (Senge, 1990). In the context of the dyke heightening program, the development of agriculture in the VMD's floodplains is driven by the construction of high dykes. The benefits derived from high dykes have incentivized the Vietnamese government's investment in expanding high dyke networks in the region. This

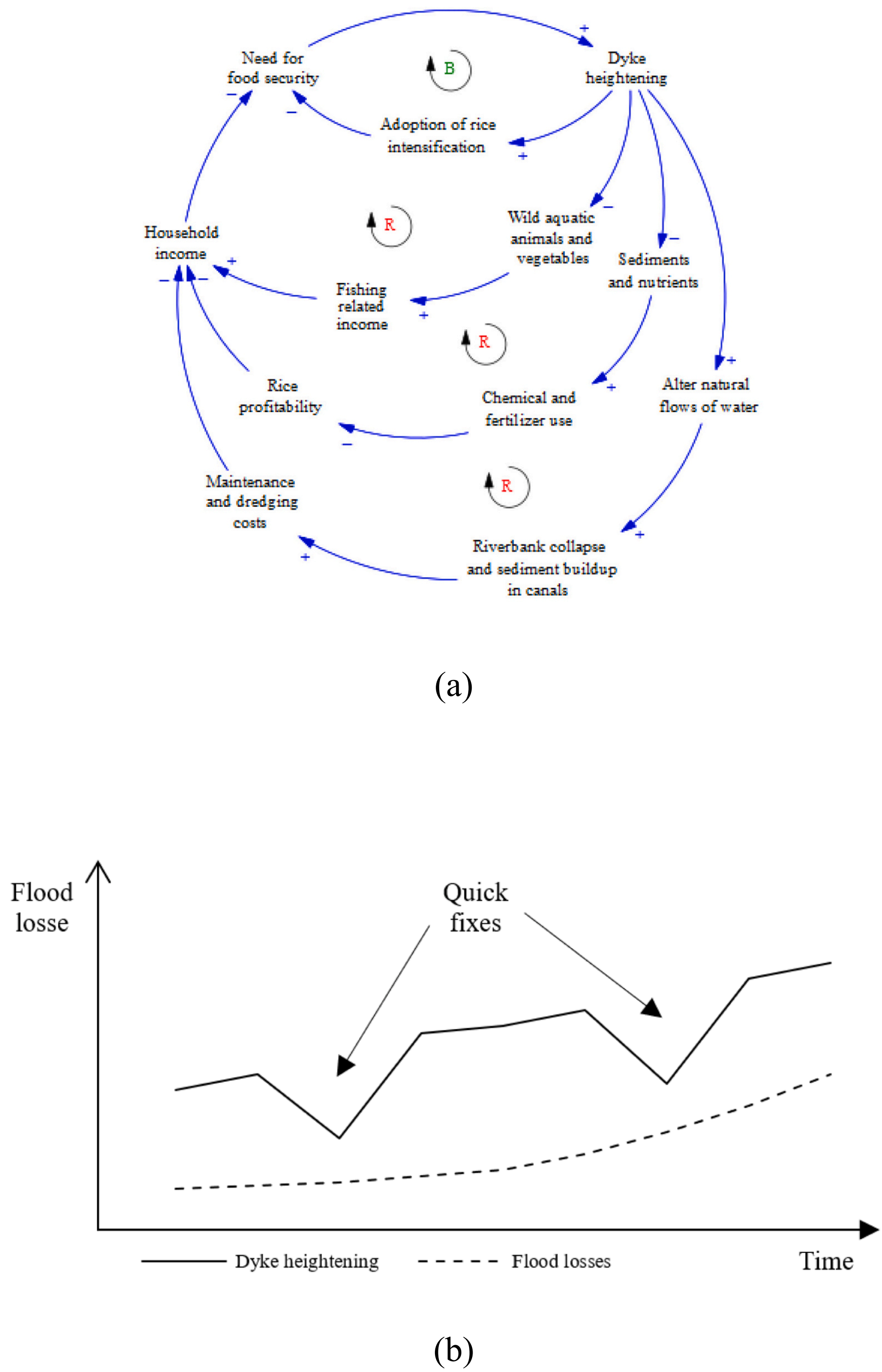

Fig. 4. (a) system structure and (b) behavior of the fixes that fail archetypes for the dyke heightening program in the VMD.

virtuous cycle is represented by reinforcing loop R in Fig. 5. Nonetheless, this reinforcing action will eventually be constrained by the depletion of natural resources in the region, such as cultivable land and freshwater, along with other factors like farm input costs and high dyke maintenance costs. This is represented by balancing loop B(i) in Fig. 5, which will eventually brake, potentially causing a halt or collapse in agricultural growth if carrying capacities are exceeded. Therefore, the system structure and its behavior of the 'limits to growth' archetype can be illustrated in Figure (a) and (b).

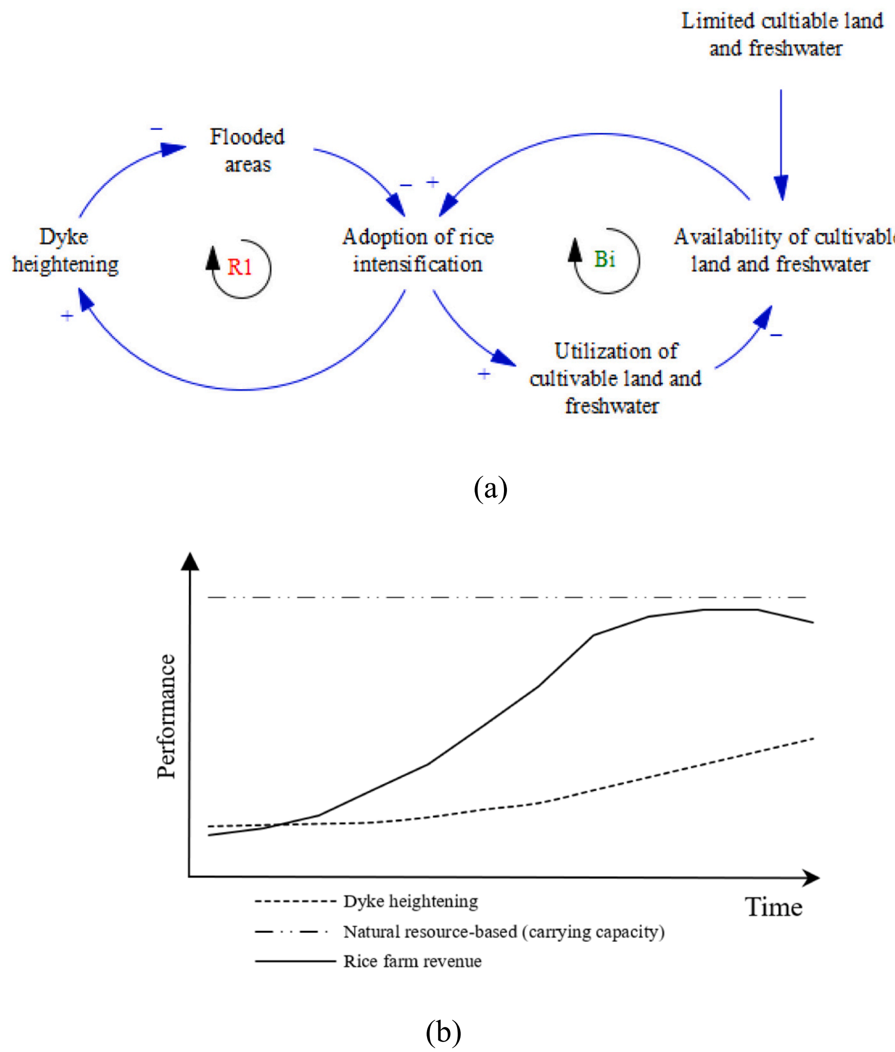

Fig. 5. (a) system structure and (b) behavior of the limits to growth archetype for the dyke heightening program in the VMD.

4.3.3. *Shifting the burden*

The third system archetype identified within the final CLD is 'shifting the burden'. This archetype represents a common human tendency to address immediate, visible, and urgent problems rather than tackling the underlying, deeper, and more complex issues that may require long-term solutions (Senge, 1990). In the context of the dyke heightening program in the VMD, the 'shifting the burden' archetype is clearly evident. Its generic system structure and behavior are depicted in Fig. 6 (a) and (b) respectively.

Similar to the 'fixes that fail' system archetype, the construction of higher dykes serves as a quick fix to mitigate significant flood-related losses for communities, particularly in high flood years. Despite substantial investments in the dyke heightening program, flood-related damages and losses persist during extreme flood events. This is partly because high dykes can create a false sense of security, leading local communities to rely solely on these structures to protect their properties and crops. Consequently, it becomes challenging to implement long-term solutions, which would involve building local capacities for flood resilience or adopting strategies for living with floods. The bottom balancing loop (B) in Fig. 6 represents the need for a fundamental response to the problem, emphasizing the empowerment and equipping of local communities with the knowledge, skills, and resources required to adapt to and cope with flood risks sustainably.

5. Discussion

Coastal river deltas play a vital role in achieving global sustainable development. However, their future is uncertain due to climate change and ineffective governance (Sutton-Grier et al., 2015; Nicholls et al., 2020; Loucks, 2019; Edmonds et al., 2020). Despite global climate adaptation efforts, long-lasting outcomes have rarely been achieved in delta's worldwide (Berrang-Ford et al., 2021; Bongarts Lebbe et al., 2021). Key barriers include an inadequate understanding of the multi-faceted impacts of climate adaptation (Perry, 2015; Termeer et al., 2016), and the absence of a shared vision among stakeholders (Hutton et al., 2018). This results in fragmented decisions and uncoordinated efforts, which can lead to poorly informed long-term policies and planning in responses to climate change (Jeuken et al., 2015; Perry, 2015).

Another significant factor contributing to poor outcomes is that many adaptation interventions employ reactive approaches, which only treat the symptoms of a problem and fail to address the complex consequences of adaptation initiatives (Perry, 2015). This linear or reactive thinking is not only incapable of delivering sustainable solutions, but it also potentially leads to unintended consequences and policy resistance that ultimately impede the effectiveness of adaptation interventions. This was evident in the case of the dyke-heightening program in the VMD's floodplains, underscoring the need for decision-makers, delta

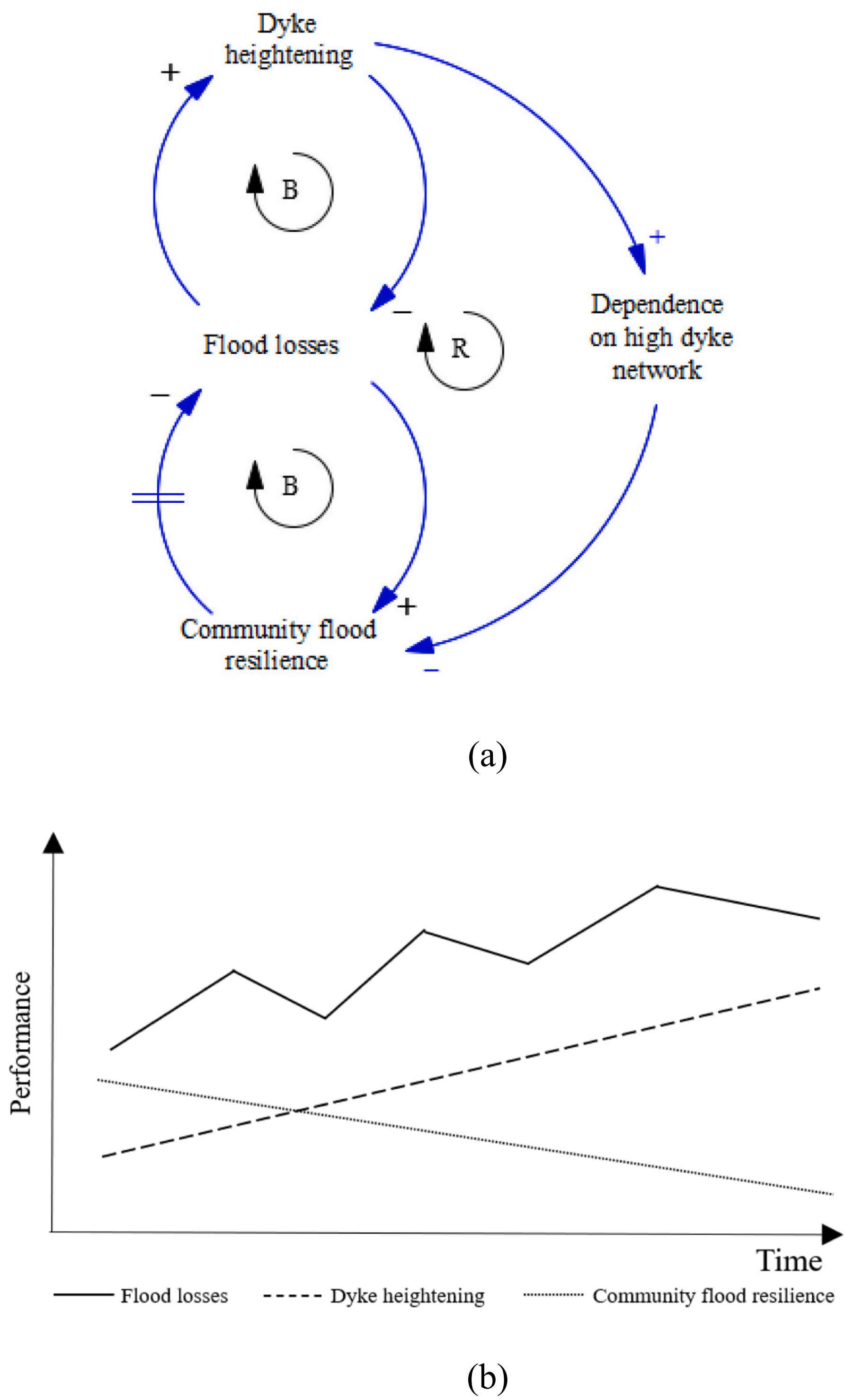

Fig. 6. (a) system structure and (b) behavior of shifting the burden archetype for the dyke heightening program in the VMD.

managers, and other relevant stakeholders, who share responsibilities for sustaining the delta, to develop a deeper understanding of the interconnectedness between the program's impacts and how these connections collectively influence the delta's resilience and sustainability.

Our conceptual model, represented by a causal loop diagram (CLD), elucidates the dynamically complex impacts of the dyke heightening program and visualizes the feedback mechanisms. It articulates the inherent interconnectedness within the system, aiding in understanding the socio-economic dynamics, natural environmental changes, and infrastructure development that collectively shape the delta's overall resilience. This has significantly assisted stakeholders in gaining a more comprehensive understanding of the factors contributing to the complexity and dynamism, which pose challenges in adapting to emerging climatic conditions. Developed through a participatory approach (Ross et al., 2015; Rich et al., 2018), our conceptual model serves as a platform that facilitates the development of a shared understanding and enhances stakeholder engagement, collaboration, and decision-making (Mai et al., 2020; Laimon et al., 2022). This is critically important for vulnerable mega deltas like the VMD, where collective vision and collaboration among stakeholders have been identified as tipping points for ensuring long-term management and planning (Hutton et al., 2021).

The conceptual model serves a robust foundation for identifying system archetypes (SAs) relevant to this study, including 'limits to growth', 'fixes that fail', and 'shifting the burden'. These archetypes assist policymakers and delta managers anticipate the unintended consequences and systemic pitfalls associated with the dyke heightening program, which could undermine sustainable delta development. Importantly, these archetypes can reveal potential tipping points that guide the formulation of system-based interventions aimed at addressing underlying systemic issues, rather than merely treating 'problem symptoms' or resorting to 'quick fixes', which may seem easier, but do not provide lasting solutions (Bosch et al., 2013). In essence, system archetype can be used as diagnostic tools to formulate policies that better align with enhancing the delta's resilience and sustainability.

A primary lesson for sustainable delta development policy, drawing from the 'fixes that fail' archetype, is the importance of prioritizing long-term management while using quick fixes only to buy the necessary time to implement enduring solutions (Senge, 1990). Specifically, the Vietnamese government should carefully consider the long-term impacts of dyke heights, including both internal and external factors, and take proactive measures to mitigate them. Recommended measures may include non-structural solutions such as sustainable land-use planning and nature-based interventions like wetland preservation and mangrove restoration, in addition to engineering interventions. Employing this combination of soft and hard adaptations is highly advised to ensure the long-term effectiveness and sustainability of the delta (Chapman and Darby, 2016; Bongarts Lebbe et al., 2021).

The 'limits to growth' archetype highlights a critical early warning sign: the more effort you put in, the less progress you seem to make, or you may even find yourself regressing (Senge, 1990). This observation leads to a second lesson for sustainable delta development policy: failing to account for limits is essentially planning to fail (Senge, 1990). Recent comprehensive cost-benefit analysis (CBA) of high dykes conducted by Tong and Clarke (2020) indicates that the net farm benefits gained from dyke heightening are not economically viable, and are likely to adversely impact the economic resilience of poorer groups due to increasing future farm input costs. These findings are corroborated by Chapman and Darby (2016) and Tran et al. (2019). This suggests that continued investment in the construction of high dykes will eventually result in declining returns over time, due to the depletion of natural resources, leading to a decline in agricultural growth due to the erosion of the carrying capacity of the region's natural resource base, including arable land and freshwater, as depicted in Fig. 5(b).

Recognizing the need for higher income-generating opportunities in the VMD's agricultural sector, the Vietnamese government has implemented various policies since 2013 to transition from rice monoculture to higher value-added practices (Royal HaskoningDHV, 2013). Among these initiatives is the Mekong Delta Master Plan for 2021–2030, followed by the Mekong Delta Integrated Regional Plan to 2030 with a vision to 2050, which was formally approved by the government in 2022 (Hutton et al., 2021). These plans mark a significant shift in focus from rice intensification to the cultivation of higher-value crops that are better suited to the region's land, water, and climate conditions. The policy of prioritizing rice intensification has been de-emphasized, reflecting a broader perspective on food security. This perspective now encompasses not only the availability of sufficient food but also the generation of cash income, which is essential for the region's economic resilience (Seo and Park, 2021).

For the 'shifting the burden' archetype, management principles suggest a dual approach: weakening the symptomatic response and strengthening the fundamental solution (Senge, 1990). This leads to the third lesson for sustainable delta policies, which advocates that symptomatic responses may be employed when necessary, but only as temporary measures while also addressing underlying or long-term solutions. Notably, the VMD has a master plan that encompasses floodplains, outlining both short-term measures to mitigate flood risk and long-term solutions aimed at enhancing the resilience of local communities to adapt to flood events (Royal HaskoningDHV, 2013). However, the implementation of this plan has predominantly focused on short-term adaptation through the extensive construction of high dykes. The 'shifting the burden' archetype warns that an excessive reliance on such constructions could subtly undermine the long-term ability of local communities to withstand extreme flood events. Therefore, future policy initiatives should prioritize fundamental solutions by developing adaptation strategies that strengthen the overall resilience of communities vulnerable to floods (Kuenzer and Renaud, 2012; Schelfaut et al., 2011; Mai et al., 2020). While the effects of these solutions may not be immediately apparent, they are essential for achieving long-term success (Mai et al., 2020).

In this study, we have employed a systems thinking approach to analyze the multi-dimensional impacts of the dyke heightening program. The resulting conceptual model illustrates the complex interconnections among socio-economic dynamics, environmental changes, and flood levee developments. These elements collectively influence the VMD's resilience. By recognizing system archetypes within the extensive dyke heightening framework, policymakers and delta managers can better manage unintended consequences and avoid systemic pitfalls associated with such intervention strategies. These insights are crucial for formulating effective and sustainable interventions that not only enhance the delta's resilience but also mitigate any unintended consequences that may exacerbate its vulnerabilities. This approach offers an alternative to conventional linear methods, which typically only address the symptoms of a problem, providing a more holistic solution to delta management and planning (Maani and Cavana, 2007). With the launching of Delta Networks (Delta Alliance - Home (delta-alliance.org), the lesson learned from this research can be shared to improve the resilience of the world's river deltas.

By embracing holistic and integrated strategies that address the root causes of the delta's vulnerabilities, we can promote enduring resilience. This approach is especially critical for vulnerable deltas such as the VMD, where sustainability is influenced not only by internal factors but also by significant external forces, including upstream development activities like dam construction, reservoirs, and deforestation. Neglecting any of these factors may lead to policy resistance, a phenomenon where policymakers either overestimate or underestimate the effectiveness of their decisions and policies (Sterman, 2000). To prevent policy resistance, it is imperative to broaden the scope of our model to include the feedback mechanisms that influence the future behavior of the system. In other words, the VMD's long-term sustainable development plans must account for all potential external drivers. A pressing concern is Cambodia's Funan Techo Canal Project, approved in August 2023, with construction scheduled from 2024 to 2027. Experts predict that this large-scale project could lead to a 50 % decrease in the VMD's water supply. This significant reduction could result in increased water shortages and greater salinization, potentially harming local livelihoods, production activities, and natural ecosystems in the region (VnExpress International, 2024). By incorporating these broader considerations, our strategic development plans become more robust, ensuring their effectiveness in the face of evolving regional dynamics.

Despite its numerous advantages, a systems thinking approach has its drawbacks. In this study, we implemented the first two phases of the systems thinking framework to develop the conceptual models and underlying system structures for the dyke heightening program. The system archetypes and feedback loops identified in this study are hypotheses that do not distinguish between stocks and flows, and therefore cannot be used to quantitatively model systems. The development of quantitative system dynamic models for the VMD is the focus of our ongoing research, involving the implementation of the remaining three phases of the systems thinking framework. This computer-based simulation model will enable us to gain a much deeper understanding of the complex impacts of the dyke heightening program by simulating shifts in feedback loop dominance and the effects of delays on the overall system behavior over time. Consequently, a system dynamic model can help to anticipate the system's reactions and design higher leverage impacts that can lead to sustainable success.

6. Conclusion

The impacts of climate change adaptation in coastal deltas are highly complex and cannot be effectively addressed through 'quick fix' solutions. To navigate these dynamics, it is essential for policymakers and delta managers to make informed decisions that consider the broader system dynamics. By using a systems thinking approach, this study has demonstrated the role of systems thinking and how the conceptual model and its associated system archetypes can provide valuable insights into the long-term consequences of management decisions, supporting more holistic and strategic decision-making processes. The conceptual model, represented by a causal loop diagram, make the systems' components and their internal relationships explicit, which is crucial for understanding of the system' responses and the long-term implications of management decisions. It serves as the common language that enhances communication and collaboration among stakeholders. The study also identifies system archetypes and leverage points that assist policymakers in designing effective and sustainable adaptation measures, thereby enhancing the delta's resilience to climate change impacts. Moreover, the research emphasizes the importance of avoiding short-term fixes and prioritizing fundamental, long-term solutions.

The present dyke heightening program in the VMD, characterized by extensive construction of high dykes, is short-sighted and threatens long-term sustainability due to 'fixes that fail' and 'limits to growth' archetypes. To ensure enduring viability, future delta development strategies must consider the interdependent relationship between delta development, the increasing intensity of climate change, the region's natural resource limitations, and upstream development activities. Achieving this objective requires restructuring the regional production system and enhancing the supply chain to emphasize environmentally friendly farming practices, increased product value, and improved business and production efficiency. Moreover, it is imperative that future plans focus on enhancing the adaptive capacity of local communities to flooding, rather than simply increasing the height of dykes.

CRediT authorship contribution statement

Thanh Mai: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Shahbaz Mushtaq:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Yen Dan Tong:** Investigation, Data curation, Conceptualization. **Thong Nguyen-Huy:** Writing – review & editing, Visualization, Validation. **Russell Richards:** Writing – review & editing. **Torben Marcussen:** Visualization, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the Federal Ministry for Economic Affairs and Climate Action (BMWK) in close cooperation with the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety, and Consumer Protection (BMUV), and the Federal Foreign Office (AA) through the International Climate Initiative (IKI).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.176501.

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