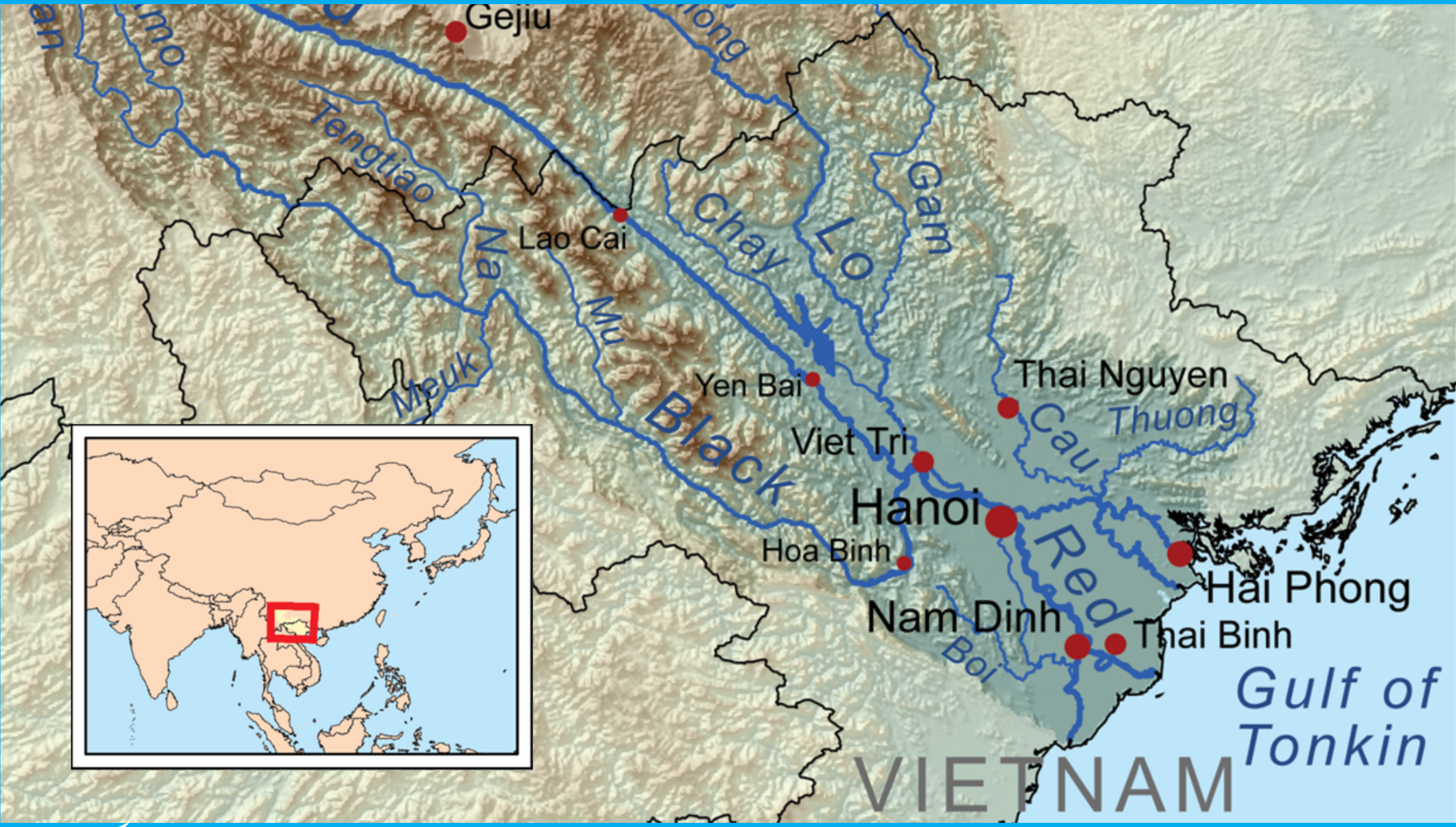
Red River Basin: The WEFE Nexus Dynamics

Interactions Between Water, Energy, Food and Environment: A Case Study of Thac Ba and Bac Hung Hai

MDP MP403



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Interactions Between Water, Energy, Food and Environment: A Case Study of Thac Ba and Bac Hung Hai

by

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Abstract

The Red River-Thai Binh basin in northern Vietnam is situated within a rapidly developing area, in which water, energy, food, and environmental (WEFE) sectors are strongly connected. Increasing pressures from climate change, population growth, and economic development intensify competition over water resources, resulting in complex trade-offs between these sectors. This study explores these interactions through a WEFE nexus perspective, with the aim of identifying suitable methods and indicators for an integrated system assessment.

The first part of this report consists of a literature review of the entire Red River–Thai Binh basin, analysing the key developments and challenges within each of the WEFE sectors. This provides a broad system understanding and identifies the main drivers and interactions characterising the basin.

The second part of the report presents two case studies that reflect different parts of the basin and highlight specific WEFE interactions. The first case study focuses on the Thac Ba dam reservoir system in the upstream area, where hydropower generation, flood control, and the livelihoods of communities surrounding the dam must be balanced. The second case study examines the Bac Hung Hai irrigation system in the downstream area, where water is primarily used for agriculture and where water quality has become a critical concern due to pollution.

The study combines literature research, field visits, social surveys, actor- and stakeholder analyses, water balance modelling, and system dynamics modelling. Based on these analyses, a set of potential indicators is proposed to assess system performance within a WEFE nexus framework.

The results show strong links between water quantity and quality, energy production, agricultural demand, and climate change. Upstream, key trade-offs are observed between hydropower generation and downstream flood risk, and between water availability and agricultural vulnerability under both extreme wet and dry conditions. In the downstream system, pollution from upstream areas and limited wastewater treatment capacity significantly affect water quality. In addition, the results indicate increasing system vulnerability to both water scarcity and flooding, driven by climate change and ongoing human interventions. Governance challenges and fragmented stakeholder responsibilities further complicate effective system management.

This study demonstrates the value of combining qualitative and quantitative methods and provides a foundation for selecting indicators that capture WEFE dynamics. The findings contribute to a better understanding of water resource management challenges in the Red River-Thai Binh basin and support the development of a WEFE Nexus tool to assess the whole Red River-Thai Binh basin.

Introduction

In September 2024, Typhoon Yagi struck Vietnam as the strongest storm in 70 years. It killed more than 300 people, injured nearly 2 000, damaged or destroyed over 280 000 homes, and flooded roughly 184 000 hectares of rice and other crops across the northern region. The accompanying storms and floods caused 803 dike breaches across 15 provinces and cities, while 2 283 irrigation works and 1 318 drinking water facilities were damaged. Total losses were estimated at US$3.47 billion (81 700 billion VND), equivalent to 0.62% of Vietnam's 2023 GDP (Tuoi Tre Online, 2024). Typhoon Yagi was neither the first nor the last event of its kind, and as climate change intensifies, such disasters are expected to become more frequent and severe.

Events like these show that water security, food security, energy security, and environmental impact in Vietnam can no longer be managed as separate issues, but must be approached as a single interconnected system.

The Red River–Thai Binh basin illustrates this challenge clearly. As Vietnam's second most productive rice region and the country's political and economic core, it depends on a river system that originates largely upstream in China and is regulated by a dense network of dams and dikes along its course. The rivers face simultaneous demands from hydropower, irrigation, urban water supply, industry, and aquaculture. Climate change is amplifying every one of these pressures at once: heavier wet-season rainfall, longer dry seasons, rising sea levels, and more intense tropical cyclones.

In response, the Vietnamese government has launched a three-year research programme on the basin aimed at understanding the system as an interconnected whole, through the lens of the Water–Energy–Food–Environment (WEFE) Nexus.

This report is the contribution of multidisciplinary project (MDP) group 403 to that programme. Vietnam's tropical climate, its two-season hydrology, the scale of the basin (roughly four times the size of the Netherlands), and the political and institutional setting all differ fundamentally from the European context the team is trained in. Therefore, before a meaningful problem could be defined, it first had to build a working understanding of the basin itself: its history, its hydrology, its actors, and the way the four WEFE sectors are entangled within it. For that reason a substantial portion of this report is dedicated to a structured literature review. In addition the aim of the literature review is to provide future MDP groups and other newcomers to the project with a reference document on which to build from.

Part 1 gives a literary basis for future understanding of the system. Chapter 1 sets the historical, political, socio-economic and climate context of Vietnam. Chapter 2 introduces the WEFE Nexus framework and reviews the methods, indicators and tools used in existing Nexus assessments. Chapter 3 describes the physical characteristics of the Red River–Thai Binh basin. Chapters 4 through 7 then take each Nexus sector in turn Water, Energy, Food, and Environment describing the key processes within each sector and the most important interactions between them. Chapter 8 closes the foundation with an actor scan that maps the governance structure and the institutional players shaping the overall resource management in the basin. Readers who are new to North Vietnam or to the WEFE Nexus are advised to read this part to get a good overview of the systems problems. Chapter 9 states the concluding remarks of the literature research.

Part 2 zooms in on two very different subsystems within the basin where WEFE trade-offs are particularly visible. This part aims to answer the research question: *What methods and indicators can be used to assess the WEFE Nexus in the Thac Ba reservoir–dam system and the Bac Hung Hai irrigation system?*, with the broader objective of contributing to the development of generalizable methods and indicators for the Red River–Thai Binh basin. Chapter 10 examines the Thac Ba reservoir, the country's oldest hydropower project, where energy generation, flood protection, downstream water supply and ecotourism increasingly compete under growing climate variability. Chapter 11 examines the Bac Hung Hai irrigation system, a large-scale agricultural network in the red river delta where water quality, food production and pollution intersect. Both chapter 10 and 11 are structured as follows: first, the system characteristics and problem statement are introduced, followed by the methodology, results, and discussion.

In Chapter 11, the conclusion, the research question is answers. Finally, Chapter 12 states future recommendations.

1

Contextualisation

1.1. Introduction

The Red River–Thai Binh River system serves as a crucial water supply for the Northern Delta, which ranks as Vietnam's second most productive rice-growing region (Figure 1.1). This area functions as the nation's core hub for politics, history, culture, and society, while also hosting several key economic centers (Yuen et al., 2021).

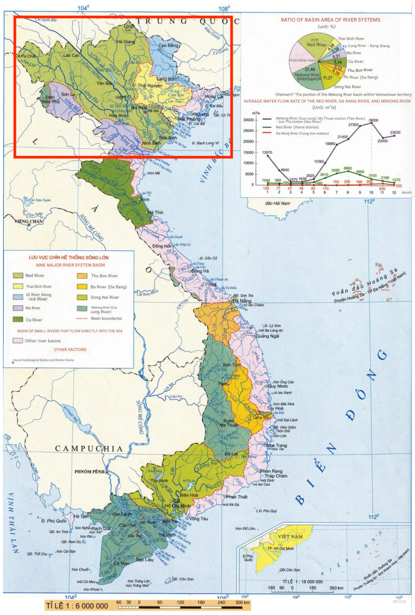

Figure 1.1: Overview of Vietnam and its river systems

Due to the significance of the Red River–Thai Binh river system, a wide range of hydraulic infrastructure has been constructed, including reservoir dams upstream, large-scale dike networks throughout the delta, and pumping stations downstream. Throughout the decades, this infrastructure has been instrumental in ensuring adequate water availability for farming, household use, and various economic activities. Furthermore, the reservoir systems play a role in power generation and assist in managing flood levels across the basin (Shannon, 2021).

At present, the effects of climate change and increasingly severe weather events have led to a reduction in water availability during the dry season and a worsening of saltwater intrusion in downstream areas, posing significant challenges in meeting the water demands of downstream regions (Luong, Hiep, & Bui, 2021a; Van Pham & Lee, 2015).

Rapid socio-economic development, urbanisation and industrialisation are increasing water demand in the Red River Basin, placing growing pressure on water quantity and quality. At the same time, reservoir operations must balance competing demands for hydropower generation and downstream irrigation, particularly during the dry season. This illustrates the complexity of coordinating water allocation between energy production and downstream water users within the basin. (Prime Minister of Vietnam, 2019a; Shannon, 2021).

This report examines key challenges in the Red River Basin from a Water–Energy–Food–Environment (WEFE) Nexus perspective, highlighting the interdependencies between water resources, energy production, food systems, and environmental conditions.

The report first contextualises the basin by outlining its historical, political, socio-economic, and climate-related background. It then reviews the WEFE-Nexus framework, including previous research, commonly used indicators, and possible analytical approaches. Building on this foundation, the physical and socio-environmental characteristics of the basin are analysed, followed by individual chapters on the four WEFE sectors: water, energy, food, and environment. Each chapter discusses key processes and highlights the most important interactions between sectors. Finally, an actor analysis identifies the governance structure and key institutional actors influencing resource management in the Red River Basin. Together, these components provide the basis for understanding the interconnected challenges within the basin and for analyzing them through a WEFE-Nexus perspective.

1.2. Historic Context

1.2.1. Post-World War Two

Vietnam gained independence in 1945 following the August Revolution, which took place after Japan surrendered at the end of the Second World War. France then attempted to restore the colonial rule it had previously lost to Japan, which resulted in nine years of armed resistance from the Vietnamese. This conflict ended with the French defeat at Dien Bien Phu, after which France officially recognised Vietnamese independence in 1954. Under the Geneva Accord, the country was divided along the 17th parallel into two separate states: the Democratic Republic of Vietnam (DRV) in the north, led by the Communist Party, and the Republic of Vietnam in the south, which was backed by the United States. The conflict that followed, generally known as the Vietnam War, was fought over reunification and national independence, and lasted until the fall of the Saigon government in 1975 (Van Thuy, 2020).

1.2.2. Vietnam War

The Vietnam War served as a proxy conflict between the Soviet Union and the United States, with North Vietnam backed by the Soviets and China while South Vietnam was supported by the Americans, turning the country into a devastating battlefield. The bombing campaigns wreaked enormous destruction on the land, obliterating the dams and canals that peasants had built to irrigate their farms, and when combined with widespread chemical spraying, wiped out nearly half of South Vietnam's crops, a staggering blow for a country that had once been among the world's largest rice exporters. In the North, bombing was concentrated more on urban areas, meaning only an estimated 5.6 percent of farmland suffered severe damage, though the war created its own agricultural challenges there as well; with so many peasant men conscripted into the North Vietnamese Army, women took over the rice paddies and developed new cooperative farming and irrigation systems capable of sustaining production with a reduced workforce (Vietnam War Reference Library, n.d.).

1.2.3. Post Vietnam War

After the Vietnam War, the Communist Party of Vietnam (CPV) resumed its long-term plan of socialist economic reformation, which had been interrupted when the war escalated in 1964. The Five-Year Plans of 1976 and 1981 were implemented, with both plans pursuing socialist industrialisation with a major focus on heavy industry and rapid agricultural growth. By 1980, the second Five-Year Plan had only achieved 50 percent of its targets, with no significant progress made. The government budget deficit increased and inflation rose to 774%. A decade after reunification, Vietnam was on the verge of economic collapse (Van Thuy, 2020).

1.2.4. Doi Moi

Realising the shortcomings of excluding the incentives of market mechanisms, at its Sixth National Congress the Communist Party of Vietnam introduced a new policy that combined elements of market mechanisms with socialism.

Introduced in 1986, Doi Moi ("Renovation") represented a fundamental shift in Vietnam's economic policy, moving away from the rigid centrally planned model that had left the country mired in hyperinflation, widespread food shortages, and chronic stagnation. Faced with an economy on the verge of collapse, the Vietnamese Communist Party made the pragmatic decision to liberalise key sectors of the economy, decollectivising agriculture, encouraging private enterprise, and opening Vietnam up to foreign investment.

The impact of these reforms was significant, and farm output increased considerably, Vietnam went from struggling to feed its own population to becoming one of the largest rice exporters in the world, which was a remarkable turnaround given the devastation the country had suffered in the preceding decades. Poverty levels dropped and living standards gradually improved as Vietnam began integrating into the broader global economy. It is widely regarded as a very important moment in Vietnam's modern development and a compelling case study in state-managed economic transition. (Van Thuy, 2020).

1.2.5. Vietnam in 21st Century

With Vietnam opening up to the world, the country has experienced pretty significant changes, particularly in terms of economic development. Joining the World Trade Organization (WTO) in 2007 was a major turning point, opening the country up to global trade and drawing in large amounts of foreign investment, which helped transform it into one of the region's leading manufacturing hubs. Poverty levels decreased considerably and a new middle class began to emerge, especially in major urban centres. On the international stage, Vietnam has had to carefully balance its complicated relationship with China over disputes over the South China Sea, while also warming relations with the US and other Western countries (B. H. Tran, Nguyen Anh, & Đinh Tran, 2024).

Today, the results of this transformation are hard to ignore, with Vietnam's GDP growing by around 400% over the past 15 years, bringing it closer to the economic output of wealthier regional neighbours like Thailand.

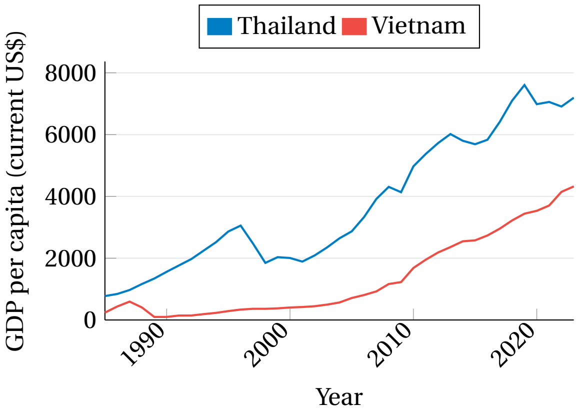

Figure 1.2: GDP per capita comparison between Thailand and Vietnam (1985–2023) (World Bank Group, n.d.)

Perhaps more impressively, Vietnam's GDP per capita growth rate has outpaced Thailand, one of the richer countries in South East Asia, and the GDP per capita gap is steadily closing with Thailand as well.

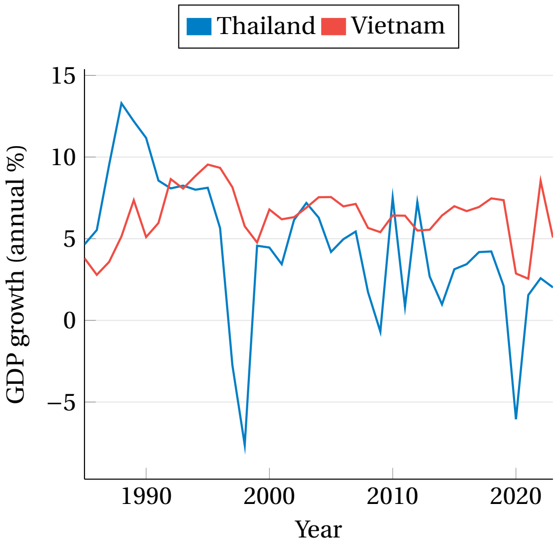

Figure 1.3: Annual GDP growth comparison (1985–2023) (World Bank Group, n.d.)

1.3. Political and Institutional Context

Vietnam's decision-making operates through a dual structure where the Vietnamese Communist Party sets overall policy direction while elected government bodies implement these decisions.

At the national level, the party's Politburo and Central Committee establish broad strategic priorities, which the National Assembly, president, and cabinet then translate into specific legislation and programs. The cabinet, led by the prime minister, coordinates various ministries that handle sectoral policies. For critical issues like water, energy, and food security, specialized ministries develop plans aligned with party directives, often coordinating through inter-ministerial committees for complex projects (Vietnam Government Portal, n.d.). This system is visually shown in Figure A.1 in the Appendix.

1.3.1. Current Developments

Vietnam has been undergoing organisational consolidations to decrease the amount of bureaucracy in the country and increase organisational efficiency.

Ministry Merger

In early 2025, Vietnam implemented a major government restructuring, merging the Ministry of Agriculture and Rural Development (MARD) with the Ministry of Natural Resources and Environment (MONRE) to form the Ministry of Agriculture and Environment (MAE). The consolidation aims to streamline operations and enhance the government's capacity to manage agricultural and environmental policy (OECD, 2025).

Provence Merger

On 1 July 2025, Vietnam consolidated its 63 provincial-level administrative units into 34 new entities, comprising 28 provinces and 6 centrally administered municipalities (Vietnam Government Portal, 2025). This restructuring introduces a two-tier governance system designed to reduce bureaucratic overhead while simultaneously granting provinces greater autonomy in policy implementation and legal enforcement. The overarching objectives are to streamline administrative processes, improve operational efficiency, and foster sustainable economic growth (Hanh, 2025).

This transition may present short-term challenges since newly merged provinces will need time to establish effective inter institutional coordination, and adjustments to communication structures and administrative workflows could take several months. At the same time, the reorganisation creates an opening for institutional renewal. As established processes are reevaluated and bureaucratic rigidities may decrease, there might be more room for innovation and adaptive governance than before.

1.4. Socio-Economic Context

According to World Bank Group (n.d.) Vietnam is a remarkable development success story. Economic reforms since the launch of Doi Moi in 1986, coupled with favorable global trends, helped transform Vietnam from one of the world's poorest countries to a dynamic middle-income economy in a single generation. The transformation over the past four decades has brought tangible improvements in people's lives, lifting millions out of poverty, expanding access to health care and education, and connecting nearly all households to essential infrastructure. Health outcomes and living standards have improved significantly. Infant mortality fell from 32.6 per 1,000 live births in 1993 to 12.1 in 2023, and life expectancy rose from 70.5 years in 1990 to 74.5 years in 2023 (World Bank Group, n.d.). Access to health care has expanded substantially, with a large majority of the population now covered by the national health insurance system. Vietnam also achieved universal primary education in the early 2000s, and school enrollment rates remain high at both lower- and upper-secondary levels. Educational outcomes are strong compared to many countries at similar income levels, reflected in high learning-adjusted years of schooling and a human capital index that ranks among the highest for lower-middle-income countries (World Bank Group, n.d.). Infrastructure development has also improved living standards significantly. By 2019, almost all households had access to electricity, compared to only a small share in the early 1990s. Access to clean water in rural areas has also increased markedly over the same period (World Bank Group, n.d.). At the same time, Vietnam continues to invest in sanitation, transport infrastructure, and digital connectivity to support future growth. Looking ahead, the country aims to become a high-income economy by 2045 while pursuing inclusive and environmentally sustainable development. In line with these ambitions, Vietnam made several international climate commitments at COP27 in 2022, including reducing methane emissions, stopping deforestation by 2030, and achieving net-zero carbon emissions by 2050 (World Bank Group, n.d.).

Dependency on Agriculture and Aquaculture

Regarding the economic structure in 2024, Table 1.1 gives an overview of the distribution between different sectors National Statistics Office (2024).

Table 1.1: GDP distribution of Vietnam, 2024

Sector	**Share (%)**
Agriculture, Forestry & Fishery	11.86
Industry & Construction	37.64
Services	42.36
Product Taxes minus Subsidies	8.14
Total	**100.00**

Looking at the numbers, it is clear that Agriculture, Forest & Fishery is still a significant part of the Vietnamese economy. Comparatively, the Netherlands, which is considered a large exporter of agricultural goods, has a GDP contribution of 1.72% (Statista, 2025).

Dependency on outside water sources

Even though Vietnam relies much on its agriculture it has less control on the source of its water supply. This is because the Red River (Hong River) and some of its tributaries originate from China (Figure 1.4). There are more than 60 dams with their reservoirs located in China's section of the Red River basin, according to L. Pham (2021).

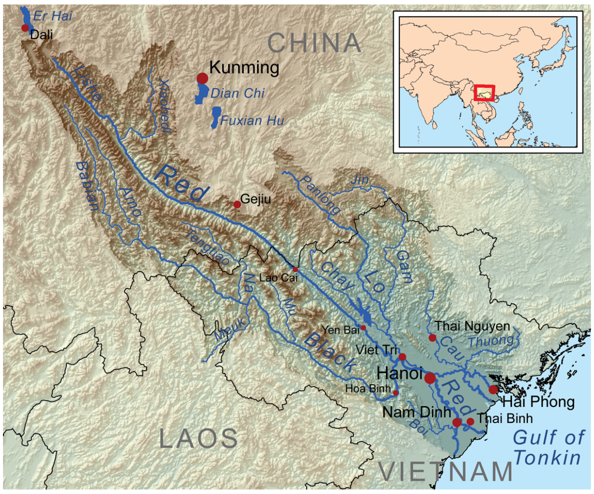

Figure 1.4: Red River basin area in Vietnam and China (Kmusser, 2011)

By trapping sediment behind their reservoir dams, the upstream hydropower plants have changed the river's ecology. The river sometimes runs clear at Lao Cai in the dry season, as the red silt that gives it it's name is no longer arriving. Less silt means the water flows faster, leading to more riverbed erosion and meagre soil deposits for Vietnamese farmers (L. Pham, 2021).

Studies show significant impact of Chinese dams on the Mekong and Red River. Therefore, Vietnam and China have tried to negotiate better ways to cooperate over both river's risks and resources. In 2009, the two countries signed a memorandum of understanding to share flood season data. China shared flow data from five hydro-meteorological stations along the Da and Thao rivers. In return, Vietnam shared data from three stations at Bang Giang, Lang Son and Van Mich. But that agreement has since been lapsed and information sharing has been limited since (L. Pham, 2021).

Population

The population of Vietnam has been steadily growing over the past few decades making it the 16 largest country in the world by population. The population is mostly grouped around two main urban centres. In the north Hanoi and in the south Ho Chi Minh City (World Trade Reference, n.d.). Across the coast the population density is higher than inland (Figure 1.5). Making the country more susceptible to sea level rise, natural disasters such as typhoons or cyclones and salt water intrusion.

Figure 1.5: Population density map of Vietnam (World Trade Reference, n.d.)

1.4.1. Migrational Patterns

Internal migration

Patterns of internal migration in Vietnam have evolved considerably between 2009 and 2024. After a period of strong growth, particularly between 2014 and 2019, migration levels have begun to stabilise and redistribute geographically. Although overall migration has declined, movements over shorter distances, especially within districts, have become more common. These trends are largely driven by persistent regional disparities. The Southeast Region continues to attract a large share of migrants due to stronger economic opportunities, whereas less developed regions such as the Mekong River Delta and mountainous areas experience outmigration because of fewer employment prospects and lower living standards (Internal Migration in Vietnam report, 2025).

The composition of migrants is also becoming more diverse. While individuals aged 20–34 still represent the largest share of migrants, other groups—including middle-aged adults, children, elderly people, and ethnic minorities are increasingly part of migration flows. Migrants generally earn higher incomes than non-migrants, yet many remain in vulnerable situations. They often work under unstable conditions, have limited access to social protection, and face higher risks of unemployment. These vulnerabilities are particularly pronounced among women and ethnic minority groups, who frequently encounter additional structural disadvantages in the labour market (Internal Migration in Vietnam report, 2025).

Education also plays a role in mobility patterns within and beyond Vietnam. Literacy rates are high nationwide, and the education system places strong emphasis on science, technology, and—since the introduction of market reforms—economics and business studies. Each year, thousands of Vietnamese students pursue education abroad. In the past, most studied in the Soviet Union and Eastern Europe, but today increasing numbers attend universities in Western countries, the United States, or Japan. This shift became more visible after Vietnam joined the WTO in 2007 (Hickey et al., 2026).

Insights from the 2019 Population and Housing Census (General Statistics Office & United Nations Population Fund, 2019) further highlight the dynamics of internal mobility. Migration flows are dominated by young adults aged 20–39 who move primarily toward larger urban centers. Only 12 of Vietnam's 63 provinces record positive net migration rates, reflecting a strong concentration of population growth in a limited number of urban areas. The main motivations for migration include employment opportunities, housing changes, and marriage. As a result, major cities such as Ha Noi and Ho Chi Minh City face substantial migration pressure, with around 200 in-migrants per 1,000 residents—approximately 2.7 times the national average.

External migration

External migration from Vietnam is primarily driven by labor mobility. Data from Ministry of Foreign Affairs of Viet Nam and International Organization for Migration (2024) indicate that between 2017 and 2023 nearly 860,000 Vietnamese workers went abroad under labor contracts, averaging more than 100,000 departures annually. The main destinations for these workers include Japan, Taiwan (Province of China), and the Republic of Korea. At the same time, Vietnam also receives a diverse group of foreign nationals. Labor migration constitutes the largest share of this inflow, with more than 475,000 foreign workers receiving work permits in Vietnam between 2017 and 2022(Ministry of Foreign Affairs of Viet Nam & International Organization for Migration, 2024).

Compared with internal migration, however, external migration patterns are less clearly documented. This may indicate that cross-border mobility plays a relatively smaller role in Vietnam's overall migration system or that it has received less scholarly and statistical attention in existing research.

Overall the migration statistics for external migration are less clear cut than internal migration, Compared with internal migration, external migration patterns appear less extensively documented in existing literature.

1.5. Climate Change Impacts

The paper D. L. T. Anh, Anh, and Chandio (2023) concludes that Vietnam is one of the nations most vulnerable to climate change due to its high dependency on agriculture and its extensive coastline. To mitigate these risks, the paper provides policy recommendations aimed at; assisting the government in limiting the negative economic effects of climate change. Promoting sustainable development and poverty alleviation. Protecting the agricultural sector, which remains a "pillar of the economy" and a source of employment for nearly half of the country's labor force.

Another study by D. L. T. Anh et al. (2023) examines the macroeconomic effects of climate change in Vietnam and finds that global warming has significant negative impacts on the country's agricultural sector in both the short and long term. In this context, changes in rainfall patterns and labor-related factors adversely affect agricultural output and overall economic performance. The study further estimates that climate-related disasters could cause Vietnam's GDP to decline by between 0.7% and 2.4% by 2050 (D. L. T. Anh et al., 2023).

1.6. Implications

Vietnam's rapid economic growth and industrialisation are putting increasing pressure on water, energy, and food resources at the same time. While agriculture still plays an important role in the economy and employment, growing industrial and urban demand is changing how resources are allocated across the nexus.

Vietnam's young and well-educated population is an important asset here. Combined with a strong central government capable of directing long-term investment, there is real capacity to build and manage more integrated resource systems. Decisions made in the coming decades will largely determine how well the system handles the increasing demand.

Climate change adds significant uncertainty to all this, threatening aspects like agricultural output, water availability, and coastal areas simultaneously as will be discussed in this report. However, because much of Vietnam's infrastructure and industries are still upcoming, there is an opportunity to leapfrog older and less efficient technologies into more sustainable solutions from the start.

2

WEFE Nexus Literature

This chapter reviews the existing literature on the Water–Energy–Food–Environment (WEFE) Nexus. It begins with an introduction to the WEFE Nexus approach, followed by three core components of the WEFE Nexus: methods used (Section 2.2), indicators applied (Section 2.3), and the tools developed (Section 2.4) in existing studies. The chapter concludes with the main takeaways (Section 2.5).

2.1. Introduction to the WEFE Nexus

Before the WEFE Nexus approach emerged, water, energy, food, and environmental sectors were typically analysed and managed in isolation. Policies were designed to optimise each sector individually, without accounting for how decisions in one sector affect the others. This compartmentalised approach can lead to inefficient outcomes and missed opportunities such that interventions that appear effective locally may create unintended pressures elsewhere in the system.

The Nexus framework was first presented at the Bonn 2011 conference about the WEF Nexus by Hoff (2011). Since approximately 2015, the traditional WEF Nexus framework began to evolve into the WEFE Nexus (Wang et al., 2016). It offers a way to understand both the synergies and the trade-offs between water, energy, food, and environment systems, making it easier to find solutions that work across all for sectors rather than just one (Figure 2.1).

Addressing these interdependencies has become increasingly urgent under growing pressure from population growth, economic development, climate change and resource degradation (Hoff, 2011). Furthermore, the WEFE Nexus framework contributes to mapping and understanding linkages with the Sustainable Development Goals (SDGs). Beyond water, energy, food and the environment, aspects such as poverty, land use, equity, gender, and health are closely interconnected and equally important (Albrecht, Crootof, & Scott, 2018; Simpson & Jewitt, 2023).

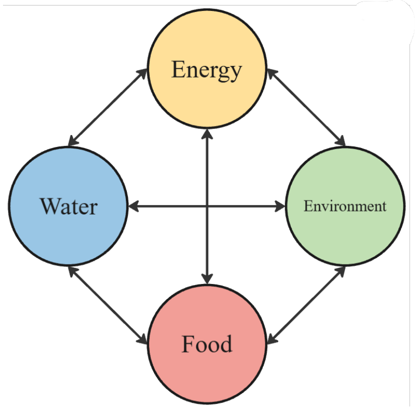

Figure 2.1: Visualisation of the WEFE Nexus

The WEFE Nexus concept has grown rapidly in both academic literature and policy discussions. To understand how it is applied in research, this chapter reviews existing literature to identify a solid literature base to start from.

The literature shows that the WEFE Nexus can be approached in many different ways. Despite this diversity, WEFE Nexus approaches share three core components: a method, a set of indicators, and a tool used to operationalise the analysis. Which method, indicators, and tool is chosen is highly context- and spatially specific and differs for every WEFE Nexus assessment. This chapter reviews these three components individually to demonstrate the various possibilities within these components. It is important to note that these components are not always clearly separated in practice. The order in which methods, indicators, and tools are applied may vary or occur iteratively. Nevertheless, this review distinguishes between these three components as analytical categories, as they represent distinct elements of WEFE Nexus approaches. They can be developed or selected independently, while still influencing one another. Therefore, this review is structured in these three components.

2.2. Methods

The WEFE Nexus system is first defined by identifying the key sectors and their interconnections within the study area. A conceptual framework is then developed to map system boundaries, feedbacks, and cross-sector interactions. Based on this system understanding, appropriate analytical and modelling approaches are selected to capture relevant physical, socio-economic, and governance dynamics. These steps provide the basis for identifying indicators that can quantify system performance, trade-offs, and synergies within the Nexus.

However, there is currently no standardized methodology for conducting a WEFE Nexus assessment. Albrecht et al. (2018) conducted a systematic review in which 73 articles were identified as applying a methodological approach to assess the WEF Nexus. Their analysis showed that a wide range of analytical methods is used in the literature, reflecting the interdisciplinary nature of Nexus research (Table **??**). The review also revealed a strong preference for quantitative approaches: approximately 70% of the analysed studies relied mainly on quantitative methods, 19% combined quantitative and qualitative approaches, and only 10% used qualitative methods alone.

Similarly, a systematic review by Vrachioli et al. (2025) found that WEFE Nexus assessments rely on a diverse set of analytical approaches. The authors grouped these approaches into six methodological frameworks. These frameworks differ in criteria such as the level of integration, spatial and temporal scale, stakeholder involvement, model complexity, data requirements, and policy relevance (Table 2.1).

System dynamics modelling and stakeholder and policy integration both score high on integration of different WEFE sectors, but they differ in focus. System dynamics modelling underlines complex simulations of system interactions, while stakeholder and policy integration approaches focus on participatory processes and co-design. Biophysical and engineering models provide detailed simulations of physical processes but typically involve limited stakeholder engagement and policy integration. Decision-support models offer a more balanced approach, combining moderate complexity with policy relevance. Socio-economic models provide insights into economic trade-offs at broader scales but often have lower cross-sector integration. Indicator-based approaches require relatively limited data and technical effort, while offering strong policy applicability.

Both systematic reviews show that a wide variety of analytical methods are used to assess WEF and WEFE Nexus systems. However, Albrecht et al. (2018) notes that many existing Nexus methods struggle to adequately address several key objectives of Nexus research. In particular, methods often fail to fully capture the complex interactions between sectors, incorporate the dynamic and context-specific nature of local systems, or produce results that are directly relevant for policy and resource management. To address these limitations, the authors propose four key features that Nexus methodologies should incorporate: innovative analytical approaches, stronger consideration of local context, collaborative and participatory processes with stakeholders, and practical applicability for policy and planning.

2.3. Indicators

A core part of WEFE Nexus research is identifying indicators that describe the state of the system. These

Table 2.1: Summary of key criteria for WEFE Nexus analysis for modelling and monitoring (Vrachioli et al., 2025).

Framework component	Integration level (WEFE sectors)	Spatial/ temporal scale	Stakeholder involvement	Model complexity	Data requirements	Policy relevance
1. System dynamics modelling	High (dynamic feedback across sectors)	Medium–large (basin/national; yearly to decadal)	Medium	Medium–high	Medium–high	Medium–high
2. Biophysical & engineering models	Medium–High (focus on WEF)	Fine–large (field to watershed; daily to yearly)	Low	High	High	Medium
3. Decision-support models	Medium (resource flow focus)	Multi-scale (local to regional)	Low–medium	Medium	Medium	High
4. Socio-economic modelling	Low–Medium (mainly economic trade)	Global to regional	Low	Medium	Medium	High
5. Indicators & quantification tools	Medium (cross-sector metrics)	Variable (context-dependent)	Medium–high	Low	Low–medium	High
6. Stakeholder & policy integration	High (all WEFE sectors)	Local to regional	High	Low–medium	Medium	Very high

indicators can be sector-specific or they can span multiple sectors at once. Indicators are essential because they reveal how a system performs, what trade-offs exist between its components, and where synergies occur. Choosing the wrong indicators can lead to an incomplete or misleading understanding of the system.

In this section, the different indicators used in past research are discussed. The goal is to identify important or overlapping indicators that are relevant across WEFE Nexus contexts, and to provide a basis for indicator selection for the Red River Basin.

A case study of the Upper White Nile (UWN) conducted by Schlemm et al. (2024) basin compares indicators derived from modelling with those identified through stakeholder engagement. The study found a mismatch between the priorities suggested by modelling and those considered important by stakeholders on the ground. Specifically, water quality, aquatic biodiversity, fisheries, and eutrophication were almost entirely absent from current modelling tools, despite being among the most pressing concerns for local communities. As a result, the authors developed a revised set of indicators that better reflected both analytical results and local stakeholder perspectives (Schlemm et al., 2024). This shows the importance of choosing a suitable method to find valuable indicators.

The case study is similar in context to North Vietnam in that the population relies on agriculture and fisheries for their livelihood while at the same time facing challenges such as land degradation, soil and water pollution, biodiversity loss, and overall climate change. The novel proposed WEFE Nexus indicators for the UWN basin (shown in Table A.2) therefore offer a relevant reference point for the Red River Basin.

Song et al. (2023) constructs a context-specific WEFE Nexus assessment for Uzbekistan using 52 indicators, tracking their performance over time and identifying synergies and trade-offs across the system. Their methodology combines the Coupling Coordination Degree (CCD) model with Spearman's rank correlation coefficient. The CCD model measures not only how strongly Nexus subsystems interact, but whether those interactions are harmonious or imbalanced distinguishing between a system where water and food sectors develop in sync versus one where growth in one sector comes at the cost of another. Tracking the CCD annually from 2000 to 2018 revealed three phases of development: rapid growth, slowdown, and decline.

The most important finding was that the environmental sector's CCD was declining while the others were still improving. Because the overall CCD requires all four sectors to perform well simultaneously, this single deteriorating subsystem was enough to drag the whole system's score down.

Water indicators seen in table A.3 focus on water stress, efficiency across industry and agriculture, and freshwater access. This is fitting given that water functions as the medium of the WEFE Nexus through which pressures and trade-offs across energy, food, and ecosystems are most directly transmitted.

Energy seen in Table A.4 indicators seem to consistently reflect the balance between production and consumption.

Food indicators (Table A.5) predominantly capture the production side of the Nexus, with crop yields, agricultural output, and land use reflecting the central role of agriculture.

Environmental indicators (Table A.6) are the most context-specific: many of Song et al. (2023)'s indicators reflect Uzbekistan's landlocked geography and have limited direct applicability to North Vietnam. However, several could transfer somewhat well across contexts: ecological deficit, CO_2 emissions per unit of GDP, population carrying capacity, and salinisation remain relevant given Vietnam's growing environmental pressures from agricultural intensification and climate change.

Putra, Pradhan, and Kropp (2020) go further by not only selecting indicators but also quantifying their interactions. This provides insight into how indicators function within the system and how they influence one another. Their analysis identifies the indicators with the strongest positive influence on the system, namely access to electricity, electricity consumption, and renewable energy consumption. In contrast, the indicators with the strongest negative influence are fossil fuel consumption, emissions from the energy sector, and declining arable land per capita.

The clear policy message from these outcomes is that transitioning away from fossil fuels and towards clean energy has the single largest positive ripple effect across the entire WEF system, a finding that is likely relevant to Vietnam given its similar WEFE Nexus challenges. For more indicators, see figure A.2 and figure A.3.

Main Takeaways from the Indicators

The literature consistently highlights that WEFE Nexus indicator development must be grounded in participatory processes involving diverse stakeholders, particularly local actors, who tend to have a clearer grasp of pressing contextual issues. Since indicators are highly context-specific, they must be tailored to capture cross-sectoral feedback and relationships rather than applied universally. Water, energy, and food indicators transfer reasonably well across contexts, capturing production, consumption, and efficiency dynamics relevant to North Vietnam.

Environmental indicators, however, are strongly tied to the specific geographic and environmental conditions of the study area.

2.4. Tools

Beyond methodological approaches and indicator selection, the WEFE Nexus literature has produced a range of tools aimed at operationalising Nexus analysis. This section reviews these existing tools, their capabilities, and their limitations.

Taguta, Senzanje, Kiala, Malota, and Mabhaudhi (2022) conducted a review of WEF Nexus tools, screening 2 325 records down to 183 eligible studies and ultimately identifying 46 distinct, operational WEF Nexus tools. A key finding is that the tools described in the literature are often not clearly explained or defined, making them impossible to reuse or review. The paper gives an overview of the 46 tools and explains their function. The WEF Nexus Discovery Map, for example, is a map-based pool/database of catalogued and classified WEF Nexus information from diverse independent and academic communities worldwide. See Table A.7 for a compact selection of the most used tools.

After reviewing the tools, several important gaps were identified. Only 30% of the tools are applicable to local scales. Since, localities cannot use a tool that aggregates all parts of a country into a homogeneous system. This is a significant limitation since local-scale implementation is often where WEF Nexus interventions actually matter the most.

Additionally, only 30% of the tools have GIS capabilities, meaning most cannot map or visualise how WEF resources vary across space. This is a big limitation since the WEF Nexus is inherently spatial, and different regions in a country have different WEF Nexus stress points.

Taguta et al. (2022) calls for several improvements to WEF tools:

1) Improve usability and move away from code-only solutions, so that a broader public, such as policymakers, can use the tools.

2) Design for transferability and scalability rather than building bespoke tools repeatedly, so that new researchers are able to adapt them for their own contexts.

3) Integrate GIS capabilities to map hotspots and visualise results in a more intuitive way.

Daher and Mohtar (2015) developed an online WEF Nexus Tool 2.0 that lets scientists and policymakers build and compare resource allocation scenarios by adjusting variables such as food self-sufficiency levels, agricultural practices, water sources, energy sources and import countries. For each scenario, the tool calculates total requirements across water, land, energy, emissions, and financial costs. Next to that it ranks scenarios using a sustainability index that combines scientific limits with policy-defined importance weights.

The authors acknowledge several limitations: the tool assumes linear relationships, covers only agricultural crops, captures environmental impact only through carbon emissions, and represents a static snapshot rather than a dynamic prediction. Furthermore, condensing all information into a single sustainability index reduces the complexity of the Nexus and gives a false sense of understanding of the system and risks oversimplifying problems that policymakers may then use as the basis for real decisions.

Schlemm et al. (2024) found that the majority of existing WEFE Nexus tools tend to be developed without consideration of practitioners at the local level, constraining their practical application in real-world contexts. Present Nexus modelling tools are extensive in the geographic ranges and environmental issues they represent, but lacking in their ability to holistically represent WEFE Nexus challenges and trade-offs in specific basins. This suggests that for a truly holistic approach, both Nexus modelling and broad stakeholder involvement are needed.

Main Takeaways from the Tools

Taken together, the WEF Nexus field is productive at generating tools but poor at ensuring those tools actually reach the people who need them. The tools available for WEFE Nexus analysis are numerous but fragmented. Most are designed for large scales or lack GIS functionality. Usability and transferability remain persistent weaknesses. For this study, these gaps reinforce the case for developing a context-specific, locally grounded approach for the Red River Basin rather than applying an existing tool directly.

2.5. Conclusions

In conclusion, there is no single, universally accepted approach to conducting WEFE Nexus research. The diversity of methods used to identify indicators, combined with differences in indicators and methodological implementation, means that Nexus studies are inherently context-specific.

What remains consistent, however, is the importance of a holistic approach. Effective Nexus research must integrate both the technical characteristics of the system and the perspectives of on-the-ground stakeholders. Only by combining these dimensions can researchers develop a comprehensive and grounded understanding of the Nexus indicators relevant to their specific context.

Equally important is the need to resist over-aggregating the system. While aggregation may offer analytical convenience, it risks stripping away the local detail that makes Nexus research actionable. It is precisely at the local level, where communities, resources, and trade-offs intersect in practice, that WEFE Nexus insights matter most. A framework that is too broad or abstract loses its practical relevance for the very actors it is meant to serve.

While the WEFE Nexus has certain universal elements, it is also highly context- and spatially specific, especially the environment. This suggests that rather than treating water, energy, food, and environment as four separate sectors that interact with one another, the Nexus should be understood as energy, food, and water as deeply embedded within the environmental context in which they operate (Figure 2.2).

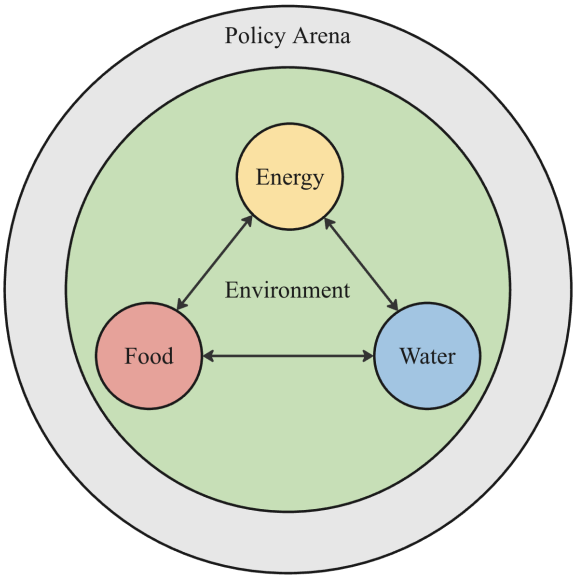

Figure 2.2: WEFE Nexus re-conceptualisation

Lastly, the Nexus does not exist in a vacuum: it is situated within a broader governance context, including a country's institutional structures, cultural norms, and prevailing policies, all of which play a role in how resources are managed and distributed. This means any meaningful analysis of the WEFE Nexus should not be limited to quantification alone but demands a holistic understanding of the system, one that recognises the perspectives of a diverse range of stakeholders, from national policymakers to local communities. Only by integrating these multiple perspectives can a true and functional understanding of the Nexus be constructed.

3

System characteristics

This chapter provides an overview of the system characteristics. It begins with the geographical characteristics, then examines the meteorological conditions, next it elaborates on the projected climate change, and finally discusses the main human interactions shaping the system.

3.1. Geographical characteristics

The Red River - Thai Binh Basin is located in the North of Vietnam, China and Laos. The river basin area is approximately 169 000 ^{2}, of which 51.3% is located in Vietnam, 86 680 km^2 (H. T. Tran, 2010). Figure 3.1 gives an overview map of the river basin with its sub-basins.

The total length of the Red River is about 1,150 km, of which about 500 km is in Vietnam (G.J. Klaassen, 2005). The basin consists of three important rivers that together form the Red River: the Da, Lo, and Tho rivers (Quang, Viet, Thang, & Hieu, 2024). The main tributary is the Da River with a catchment area of about 53,000 km^2 (G.J. Klaassen, 2005). In Hanoi, the Duong branches off from the Red River, which together with the Cua, Thuang, and Luc Nam merges into the Thai Binh River. The Red River and the Thai Binh River eventually drain into the Gulf of Tonkin.

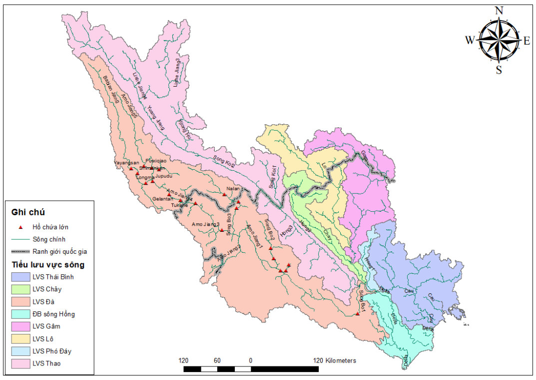

Figure 3.1: Spatial overview of the area, including sub-basins, the main rivers, and borders.

The Red River system consists of two types of landscapes: high altitude terrain (mountains and hills) and a delta region (low altitude). With most of the area consisting of high altitude mountainous terrain, 70% is over 500m (G.J. Klaassen, 2005).

3.1.1. Mountainous and midland region

The Northern part of the basin in Vietnam consists of an altitude higher than 500 meters. Figure 3.2 shows the elevation of this region; the map consists of the whole Northern part of Vietnam. Within this area, there are a lot of places with steep slopes and V-shaped valleys. Next to that, the region has a dense network of rivers and streams, resulting in fragmentation. These two characteristics of the land make the area vulnerable to landslides and flashfloods. In the ground, there are abundant mineral resources available (H. G. Pham & Kieu, 2025). The soil consists of a mixture of sand, clay, and loam (Hiep et al., 2018)

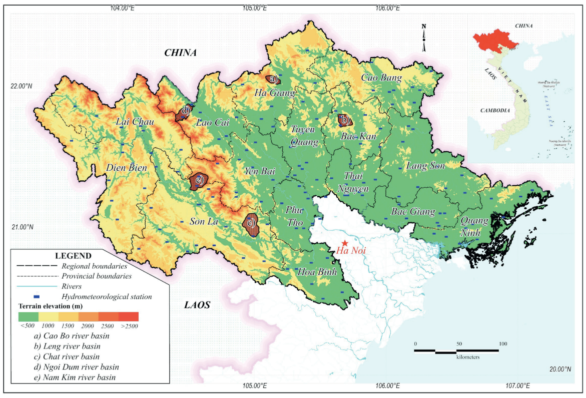

Figure 3.2: Elevation map of the Northern mountain area of Vietnam (Hiep et al., 2018)

3.1.2. Delta region

The delta is low-lying, with elevations ranging from 0.7 to 1.2 m above sea level (Van Binh, Kantoush, & Sumi, 2020). It is composed of relatively young, fine-grained Holocene sediments, which overlie coarser Pleistocene fluvial deposits. Beneath these layers lies a thick sequence of even older Neogene sedimentary rocks, including sandstone, clay, and siltstone (Mathers & Zalasiewicz, 1999).

Within the Red River delta, different sections are dominated by various forces. The northern coastal section is protected by the island of Hainan from strong wave forces. Therefore, the river mouth is shaped by the primary forces, river and tidal forces. Resulting in funnel-shaped river mouths. In contrast, in the southern part, wave forces dominate, and the river mouths are predominantly convex in shape. The central section is influenced by mixed forcing, resulting in a mixed tide- and wave-dominated coast (Vinh, Ouillon, Thanh, & Chu, 2014a).

The Red River system drains into the Gulf of Tonkin. Therefore, the estuaries are influenced by the tide. In the Gulf of Tonkin, the tide is predominantly diurnal, with one ebb–flood cycle occurring each day (Minh et al., 2014). The regime is mesotidal, the mean and maximum tidal ranges are 1.9-2.6 and 3.2-4 m, respectively (Mathers & Zalasiewicz, 1999). The mean and maximum wave heights at the river mouth are 0.73 and 5.6 m, respectively (Hori et al., 2004). The tidal influence on water level and discharge extends up to 120 km upstream. However, salinity intrusion occurs up to 40 km inland from the Cam River mouth within the delta, 38 km from the Lach Tray mouth, 28 km from the Thai Binh mouth, and 20 km from the Ba Lat mouth (Fig. 3.3) (Vinh et al., 2014a).

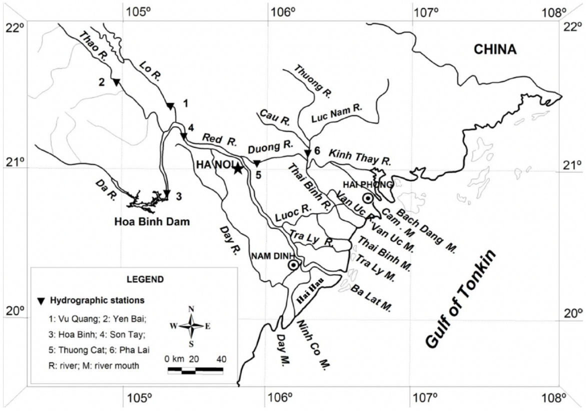

Figure 3.3: Red River coastal area (Vinh et al., 2014a).

3.2. Meteorological conditions

The climate of the Red River Delta is tropical monsoon, with three seasons. The hot and wet season (May-Sep) is characterised by high temperatures and heavy rainfall, whereas the cool and dry season (Oct-Jan) is typically known for low temperatures and low rainfall. The cool and humid season (Feb-Apr) has low to moderate temperatures and low rainfall (Huong, Everaarts, Neeteson, & Struik, 2013).

The mean annual rainfall varies between 800 mm/yr to 3000 mm/yr. It is important to note that 70–90% of the annual rainfall occurs during the wet season, which runs from May to September or October. In contrast, the three driest months, December, January, and February, account for only 1.8-7.5 % of the yearly rainfall (Quang et al., 2024).

The mean air temperature varies from below 14 °C in the high mountains to 20–24 °C in the hilly regions Quang et al. (2024). In the delta, the mean temperatures range from 14.4 °C in winter to 33 °C in the summer (Li et al., 2006). Figure 3.4 shows the monthly temperature and rainfall at the Son Tay hydrological gauging station in Northern Vietnam between 1958-2021 (Hao Quang, Huu Loc, & Park, 2023).

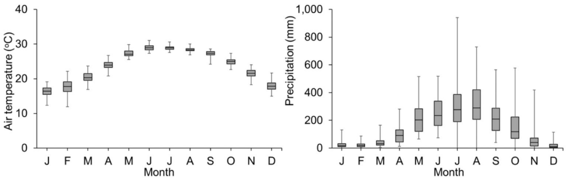

Figure 3.4: Monthly air temperature (1958–2021) and precipitation (1960–2021), observed at the Son Tay station (Hao Quang et al., 2023).

3.3. Climate change

As described in Section 1.5, Vietnam is ranked as one of the nations most vulnerable to climate change. In the Red River-Thai Binh basin, climate change is expected to manifest primarily through rising temperatures, sea-level rise, a change in rainfall patterns and tropical cyclones. These changes are elaborated below.

3.3.1. Temperature rise

At a global scale, surface temperatures have increased significantly over the past century. The last decade (2011–2020) was approximately 1.09 °C warmer than the period between 1850–1900, reflecting a global warming trend driven by human-induced greenhouse gas emissions (Zhou, 2021).

This global warming trend is also seen in the Red River basin. N. T. P. Hang, Long, and Hung (2024) analysed data from 23 meteorological stations over the period 1961–2020 and reported an increase in mean annual temperature ranging from 0.013 to 0.034 °C per year.

Future projections indicate a continued temperature increase. According to the 2020 Climate Change Scenarios by the Ministry of Natural Resources and Environment, mean temperatures in northern Vietnam are projected to rise by 1.9–2.4 °C under RCP4.5 and by 3.5–4.2 °C under RCP8.5 by the end of the 21st century (N. T. P. Hang et al., 2024).

3.3.2. Sea-level rise

Rising global temperatures, as discussed above, directly contribute to the reported sea-level rise. This process is mainly driven by the melting of glaciers and polar ice sheets and the thermal expansion of seawater. In 2016, global sea-level was 82 mm above the 1993 average, and global sea level continues to rise at a rate of 3.4 mm per year (Lindsey, 2021).

Within the Red River - Thai Binh basin, this observed sea-level rise is also present. H. M. Nguyen, Ouillon, and Vu (2022) analysed sea surface height data from the Hon Dau tidal gauge station in Hai Phong, which indicates a mean sea-level rise of 202.8 mm between 1961 and 2020, corresponding to an average rate of 3.08 mm per year. The rate of increase accelerated between 2001 and 2020, reaching a sea-level rise of 7.16 mm per year.

By the end of the 21st century, sea levels along the coast, from Mong Cai to Hon Dau, are projected to rise by approximately 44–72 cm (N. T. P. Hang et al., 2024).

3.3.3. Rainfall variability

As discussed before in Section 3.2, the Red River climate is tropical monsoon, with a dry and rainy season. Tam and Nga (2018) observed the annual rainfall in Hanoi, between 1991 and 2015. The annual rainfall is seen to have increased slightly in this period, with 4.4% per year. The total rainfall in the dry season decreased by 17%, while the total rainfall in the rainy season increased by 12.8% per year (Table 3.1).

Year	Annual rainfall (mm)	Dry season rainfall (mm)	Rainy season rainfall (mm)
1991	1536.50	304.5	1232
1992	1371.30	328.6	1102.3
1993	1442.40	259.5	1226.9
1994	2536.00	217.0	2249.9
1995	1220.30	208.6	1040.9
1996	1596.80	317.1	1040.0
1997	2037.51	700.5	1581.81
1998	1590.60	330.9	1076.9
1999	1556.60	355.9	1266.5
2000	1278.10	398.1	1054.5
2001	2264.70	272.9	1930.6
2002	1264.80	86.0	1130.8
2003	1582.50	260.6	1427.2
2004	970.70	245.1	679.4
2005	1771.80	159.2	1535.6
2006	1240.90	203.8	1049.0
2007	1659.70	272.7	1479.0
2008	2267.10	207.7	1814.7
2009	1612.10	406.4	1471.0
2010	1239.20	155.2	1076.6
2011	1795.20	186.8	1537.3
2012	1920.40	238.1	1700.8
2013	2676.40	228.0	2336.4
2014	1662.00	432.8	1357.0
2015	1395.00	95.0	1263.0

Table 3.1: Annual, dry-season and rainy-season rainfall (1991–2015) (Tam & Nga, 2018).

This trend is consistent with the latest climate change scenarios for Vietnam. According to Tam and Nga (2018), mean annual rainfall has slightly increased over the past three decades. Climate projections indicate that by 2030 rainfall during the dry season may decrease by approximately 10.3%, while rainfall during the wet season is expected to increase by about 20.9% compared to the baseline period 1981–2000.

These projections suggest that rainfall in the Red River region will become increasingly seasonal, with wetter wet seasons and drier dry seasons. Both extremes happened in 2018, when a long period of heat was followed by heavy rainfall and tropical storm Son-Tinh (Phan et al., 2019).

3.3.4. Tropical cyclones

Vietnam is regularly affected by tropical cyclones originating from the Western North Pacific and the South China Sea. These tropical cyclones range from tropical storms to more intense typhoons and storm surges, and represent one of the most important natural hazards affecting the country. Climate change is expected to increase the intensity and impact of these storms. Tropical cyclones form above warm ocean waters when moist air rises from the sea surface, creating low pressure and rotating winds. As global temperatures rise, higher sea surface temperatures provide more energy for tropical cyclones, potentially leading to stronger winds. At the same time, a warmer atmosphere can hold more moisture, which may result in heavier rainfall during these storms. In addition, rising sea levels increase baseline coastal water levels, amplifying the height of storm surges generated during tropical cyclones (Poynting, 2017).

Between 1961 and 2014, more than 295 major storms (levels 6-12) made landfall in Vietnam. As shown in Figure 3.5, the annual number of storms affecting the country has increased over time. During the 1960s to the 1990s, an average of five major storms occurred each year. In contrast, during the 2000s this number increased to more than seven storms annually (Luu et al., 2017).

More intense tropical cyclones, known as typhoons, mostly affect the northern part of Vietnam, with peak activity typically occurring in August. Between 1995 and 2018, 29 typhoons made landfall in the Red River Delta (Yuen et al., 2021). Recent events illustrate the potential severity of these storms, in 2024, Typhoon Yagi produced extremely high rainfall intensities, with 356 mm recorded within 55 hours in northern Vietnam (Tien et al., 2025).

Typhoons frequently generate storm surges along the coast. In the Red River delta, storm surges typically reach heights of approximately 1–1.5 m above mean sea level, although higher surges can occur during more intense typhoons (Yuen et al., 2021). Neumann, Emanuel, Revela, Ludwig, and Verly (2015) estimates that by 2050, sea-level rise could reduce the recurrence interval of a present-day 100-year storm surge with a height of 5 m to approximately once every 49 years.

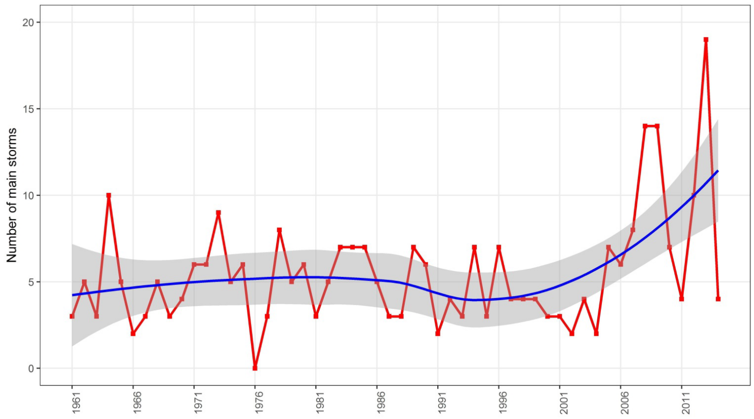

Figure 3.5: Number of major storms (levels from 6 to 12) making landfall in Vietnam between 1961 and 2014. The storm level is determined by the average wind speed (Luu, Von Meding, & Kanjanabootra, 2017).

3.4. Primary human interactions

3.4.1. Dam-reservoir system

Dam-reservoir systems play an important role in Vietnam. There are over 7,000 irrigation and hydropower dams (World Bank, 2014). A hydropower dam captures energy from the height difference of stored water by releasing it through turbines to generate electricity. The main functions of most dams in Vietnam are flood control, agricultural irrigation, and electricity production (A. Q. Nguyen & Le, 2024). Large hydropower plants have a significant impact on the energy system, while smaller non-power dams generally have lower impacts and more local effects. Therefore, this research focuses on the hydropower plants.

The ambition to develop hydropower was strongly influenced by postwar reconstruction goals. It was driven by a combination of commitment to social and economic transformation and the country's natural conditions: the mountainous terrain and high rainfall. This created a focus on large-scale dam construction, partly inspired by Soviet development models. Hydropower became a strategy to achieve energy independence. Earlier experiences of energy insecurity, including oil shortages and electricity supply disruptions during and after the war, reinforced the importance of domestic energy production. As a result, Vietnam remained largely energy self-sufficient until the 2000s, before coal and gas power expanded more significantly (Sasges & Ziegler, 2023b).

When the hydropower plants are categorised by installed capacity (IC), Table 3.2 is created. Although mega-dams dominate individually, the cumulative installed capacity is distributed across many medium and small facilities. The cumulative impact may therefore be more significant than single large dams alone.

Category	IC Range (MW)	No. HPFs	Frac. HPFs	IC Total (MW)
Mega	≥1000	3	0.01	5520
Very Large	300–999	9	0.02	3602
Large	100–299	29	0.05	4914
Medium	30–99	79	0.15	4109
Small (Large)	8–29	219	0.41	3435
Small (Small)	<8	193	0.36	802

Table 3.2: Installed capacity classification of operational hydropower facilities in Vietnam (late 2022)(Sasges & Ziegler, 2023b)

Figure 3.6 shows the spatial distribution of these hydropower plants.

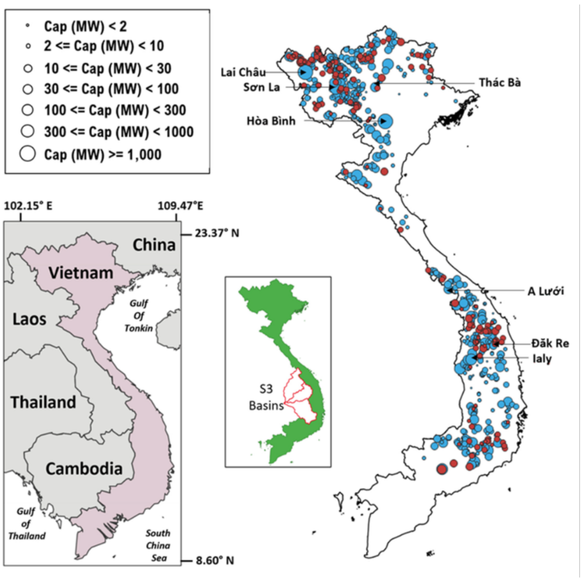

Figure 3.6: Spatial distribution of hydropower plants in Vietnam Sasges and Ziegler (2023b)

The 9 major dam-reservoir systems (capacity >0.1 km^3) in Vietnam and China are described in Table 3.3 (Hao Quang et al., 2023). While the national hydropower landscape is numerically dominated by small and medium facilities, Table 3.3 shows that storage volume and generation capacity are highly concentrated in a limited number of large reservoirs.

Dam with reservoir	Constructed period	Watershed area (km^2)	Volume capacity (km^3)	Power capacity (MW)
Thac Ba (TBa-Lo River)	8/1964–12/1971	6,170	2.49	120
Hoa Binh (HB-Da River)	11/1979–12/1988	57,285	9.45	1,920
Tuyen Quang (TQ-Lo River)	12/2002–12/2008	1,360	2.24	342
Nansha (NS-China-Red River)	2/2006–12/2008	263	0.26	150
Madushan (MS-China-Red River)	1/2008–12/2010	–	0.55	300
Son La (SL-Da River)	12/2005–12/2010	43,760	9.26	2,400
Ban Chat (BC-Da River)	1/2006–2/2013	2,017	2.13	220
Huoi Quang (HQ-Da River)	1/2006–12/2015	2,930	0.18	520
Lai Chau (LC-Da River)	1/2011–12/2016	26,000	1.21	1,200

Table 3.3: Major dams with reservoirs within the Red River basin in both Vietnam and China.(Hao Quang et al., 2023; T.-V. Nguyen, 2017; Vietnam Electricity (EVN), 2016; Vinaconex Joint Stock Corporation, 2021)

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3.4.2. Sand mining

The world's top three most utilised resources are: air, water, and sand. Sand is needed for construction; this demand is rising worldwide due to urban growth and population increase (Runeckles et al., 2023).

As explained in Section 1.4. Vietnam undergoes rapid economic growth. To sustain this growth, a significant amount of construction-grade sand is needed in the Red River - Thai Binh Basin. This sand can be found in the rivers (Rentier & Cammeraat, 2022). It is often extracted without full consideration (Runeckles et al., 2023) even though the consequences can be immense (Rentier & Cammeraat, 2022).

River sand mining affects the environment in all cases. The extent to which this happens depends on the rate, the method applied, and the manner of execution. Problems arise when the extraction rate exceeds the rate of natural replenishment (Rentier & Cammeraat, 2022). Sand mining commonly begins within the active channel and expands to the surrounding floodplain and terraces. Five principal types of river sand mining can be distinguished. Per method, the magnitude of the impact differs (Rentier & Cammeraat, 2022).

1. Channel-wide instream mining
2. Wet pit excavation
3. Dry pit excavation
4. Bar skimming
5. Bar excavation

Channel-wide instream mining is considered the most destructive method. It removes sand from the entire active channel during the dry season. Both wet-pit and dry-pit excavation extract the sand from the riverbed, resulting in the formation of pits. Bar skimming is the most controlled technique. Sand is removed from exposing sand bars, therefore it is possible to leave the active water channel largely unaffected. Lastly, bar excavation removes sand downstream of a sand bar (Rentier & Cammeraat, 2022).

Between 2009 and 2012, an average of approximately 16.2 million m3 of sand per year was extracted from the riverbed in the Red River between Viet Tri and Hung Yen (Trinh et al., 2025). It is important to note that these are one of the few numbers available on sand mining. Due to the illegality of sand mining, it makes it difficult to regulate the sand mining sector (Chinh, 2018).

3.4.3. Land use change

The Red River - Thai Binh basin has experienced substantial changes in land use over the past century. As described in Section 1.4, socio-economic development and population growth have increased the demand for food production, which stimulated the expansion of agricultural land.

Between 1930 and 1965, many sea dikes along the Red River delta coast were relocated seaward. These relocations were associated with large-scale land reclamation for agricultural purposes during the periods 1957–1962 and 1968–1971. In the past two decades, smaller seaward relocations have primarily been associated with the development of aquaculture ponds (Fan, Nguyen, Su, Bui, & Tran, 2019).

At the same time, agricultural expansion contributed to widespread deforestation between 1930 and 1990. However, around 1990, this trend began to change. Following a period of severe deforestation, the Vietnamese government introduced reforestation policies. Reforestation mainly took place on mountain slopes while valley bottoms were increasingly converted to permanent agriculture (Meyfroidt & Lambin, 2008).

More recently, land use patterns in the Red River delta have shifted again due to rapid urbanisation and economic development. Remote sensing analysis by Thien, Phuong, and Huong (2023) shows substantial land use transitions in Thai Binh province between 2000 and 2020 (Figure 3.7). During this period, agricultural land decreased from 1255.01 km^2 in 2000 to 740.49 km^2 in 2020, while settlement areas expanded significantly from 207.00 km^2 to 727.07 km^2. In contrast, water bodies, forests, aquaculture areas, and bare soil or rock surfaces showed relatively minor changes.

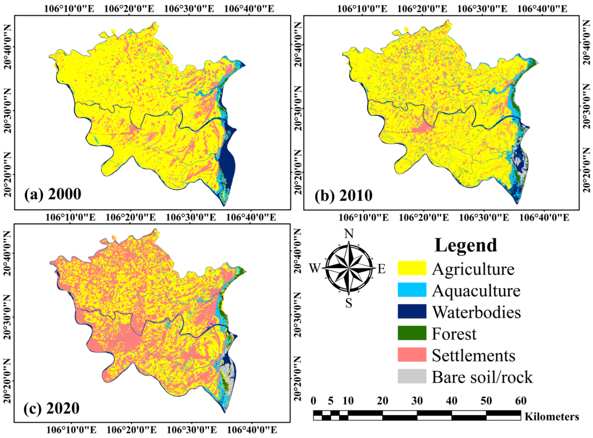


Figure 3.7: Classification maps of land use/land cover in Thai Binh province in a 2000, b 2010, and c 2020 (Thien et al., 2023).

These trends illustrate a clear transition in land use within the Red River delta, from agricultural expansion and deforestation towards recent urban growth.

3.4.4. Groundwater extraction

In this section, human intervention in groundwater is discussed. The following subsections will discuss the reasons for people to extract groundwater in the area, followed by what extraction is. Concluding on where the fresh groundwater is extracted from and how much.

Drivers of Groundwater Extraction

In Section 1.4, it is stated that Vietnam is experiencing rapid growth in terms of population and economy. This growth increases the demand for water supply:

- Drinking water demand (population and livestock)
- Irrigation water demand (crop production and agricultural area), particularly during dry periods when precipitation is limited
- Industrial water demand (manufacturing industries such as beverage production)

Increasing water demand, combined with greater uncertainty in precipitation patterns due to climate change (see Section 3.3), may lead to a growing reliance on groundwater extraction to compensate for surface water shortages (Luong, Hiep, & Bui, 2021b).

The increase in demand calls for an increase in water supply. Looking at surface waters, this is for most people not a valid option. Since the surface water is heavily polluted, as further explained in Section 4.4. Closer to the coast the saltwater intrusion process plays a role in water availability and quality (explained in Chapter 4). The saline water is not suitable for the irrigation of crops, aquaculture and livestock. These causes of surface water pollution, intensification of agriculture, and saline water intrusion combined lead farmers, industries, and households to turn to extracting clean fresh water from groundwater aquifers.

Domestic, irrigation and industrial water supply in the Red River Basin and also Hanoi is mainly from groundwater. Groundwater pumping has started in Hanoi since 1909 with an initial pumping rate of some 20,000 m^3/day. The groundwater abstraction has rapidly increased to over 500,000 m^3/day in 2010 (T. T. Nguyen et al., 2012). Showing the rapid increase in pumping and possible overexploitation.

Processes and mechanisms of groundwater extraction

Groundwater can be defined as any water in natural voids in the subsurface (Beckie, 2013). The water flows horizontally through aquifers towards lower water levels. Eventually also flows to lakes, rivers or oceans. The groundwater can be seen as a large reservoir underground. Groundwater recharge is the process by which surface water enters the subsurface. Water from precipitation events is partitioned at the ground surface into recharge, evaporation or, if the rate of precipitation is higher than the infiltration capacity or the near-surface is saturated, into runoff Beckie (2013). Recharge is also possible close to water bodies above the surface, such as lakes and rivers. The water pressure is lower in the voids in the soil, so water flows from the water bodies into the soil. In the subsurface, groundwater flow is driven by both gravity and pressure gradients. The ease of flow in the subsurface is characterised by the permeability. These processes are much slower than the water flow above the surface. The water is pumped from saturated aquifers through wells. An aquifer is a permeable underground layer of rock, sand, or gravel where groundwater flows slowly through tiny pores and fractures, usually moving from higher recharge areas to lower discharge areas. An aquifer system includes one or more aquifers together with less permeable layers (like clay or rock) that confine or separate them, controlling where the water can flow and which specific saturated layer can be tapped for groundwater extraction.

When pumping starts, the water comes entirely from the storage. Groundwater levels drop in a circular movement, called the depression cone. The groundwater table is lowered and the voids are now filled with air where the water is withdrawn. The schematization of groundwater extraction is visible in figure 3.8.

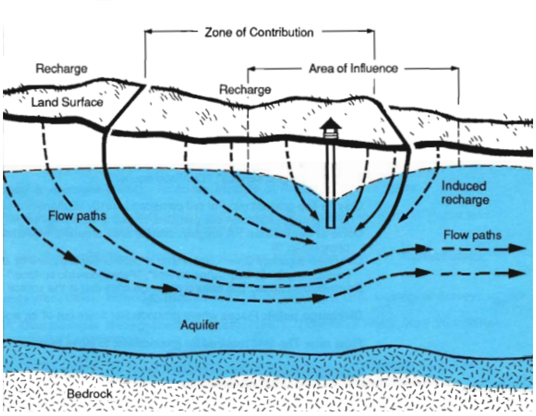


Figure 3.8: Schematization of a pumping well with it's effect on the groundwater table and flow in the area. Raymond (1988)

Groundwater extraction is considered sustainable if there is no net reduction in groundwater stored in the system over a water year (Bredehoeft, 2002). As the situation is now, people construct their own wells and extract water as needed. The wells are not monitored or controlled. Which results in a lack of knowledge about actual pumping discharges and possible overexploitation of groundwater, which effects are discussed in section 4.4) (fresh water availability) and 7.3 (land subsidence).

Spatial distribution of groundwater extraction

Uncontrolled groundwater pumping mainly occurs in downstream areas that are both dry and heavily polluted. In these relatively flat regions, irrigation by gravitational flow is often not feasible, which increases the reliance on groundwater resources. Groundwater is therefore primarily used in agricultural areas for irrigation and drinking water supply. In the Hanoi region, groundwater is mainly extracted from two Pleistocene aquifers, which are shown in Figure 3.9. The first is the Upper Pleistocene aquifer (qp_2), composed of medium-sized sands, pebbles, and cobbles. The second is the Lower Pleistocene aquifer (qp_1), which consists predominantly of gravels (M. Nguyen et al., 2022). Together, these two aquifers account for approximately 98.7% of the total groundwater extraction, with about 97% originating from qp_1 alone, indicating that this aquifer is the dominant source of groundwater in the region. Although groundwater abstraction from qp_2 is relatively limited, the aquifer remains an important component of the regional groundwater system. Above qp_2 lies the unconfined Holocene aquifer (q_h), which has an average thickness of approximately 13 meters. Beneath qp_1 is the Neogene aquifer (n), which begins at roughly 80 meters below the surface. The combined average thickness of qp_1 and qp_2 is about 60 meters, although the thickness of both aquifers varies along the cross-sections shown in Figure 3.9.

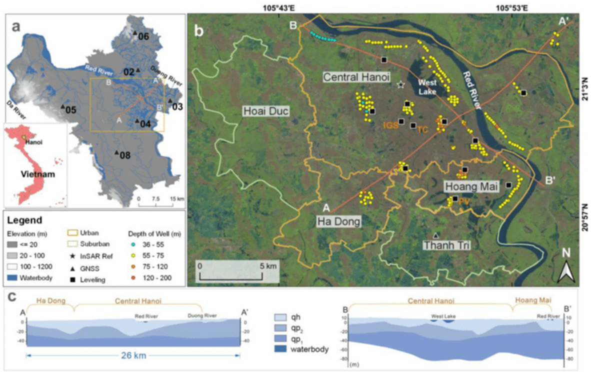


Figure 3.9: Visualization of the aquifers (qp1, qp2) along a cross section through the Hanoi area. M. Nguyen et al. (2022)

Magnitude of groundwater extraction

So looking at the Red River Basin, most people get their water supply from wells. Combining the normal wells and dug wells we achieve a percentage of 53.49% which is more than half. An overview of the distribution in water supply in percentages according to L. V. Anh (2018) is shown in the figure below. The term "other" consists of people using water sources such as local ponds, lakes, rivers and springs. A little more in-depth view on the numbers of extraction of domestic and industrial wells is discussed in 6.

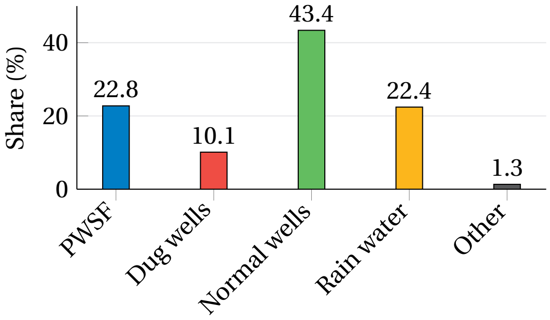


Figure 3.10: Distribution of water supply in RRB; (L. V. Anh, 2018)

4

Water

This chapter focuses on the water system of the Red River – Thai Binh Basin and the consequences of climate change and human interaction on the water system. It first examines the water levels (4.1). The second Section (4.2), elaborates on different types of flooding throughout the basin. The sediment budget is discussed in Section 4.3. The fourth section (4.4), discusses the freshwater availability. Finally, in the last Section 4.5 the key relations of the water system with other pillars of the WEFE-Nexus are summarised.

4.1. Water levels

This Section discusses the water levels in the main rivers of the Red River water system. It elaborates on the consequences on the water levels of climate change, a change in water use, and anthropogenic activities.

4.1.1. Rainfall variability

As explained in Section 3.2, within the Red River system, there is a seasonal rainfall pattern. These extreme seasonal dynamics can lead to drought events in the dry season and flood events in the wet season (Thai & Thuc, 2011). Furthermore, this seasonal pattern is visible in the river discharge, resulting in a significant variation between flood and low-flow discharges (about 20:1). This results in a large water level difference, ranging from 1–3 m above to 5–6 m below the floodplain, amounting to a total difference of 6–9 m (Quang et al., 2024). Section 3.3 elaborates that the seasonal dynamics are intensified by climate change, and the expectation is that the differences will only become greater. The climate change predictions indicate that by 2030 the dry season may decrease by 10.3%, while the wet season will increase by 20.9%. This change in precipitation influences the discharge and therefore the water levels in the Red River system (Thai & Thuc, 2011). In line with these projections, multiple climate scenarios indicate that droughts in Hai Duong province will increase in both frequency and intensity between 2021 and 2050, with extreme drought events occurring approximately every 9–10 years (Dao et al., 2022).

4.1.2. Water use

However, this increase in precipitation is not properly reflected in the discharge levels of the river. In the period 1991-2015, the annual Red River discharge decreased by 9.1% while the precipitation increased by about 4.4%. Due to increasing water use in upstream regions (Tam & Nga, 2018). This increased water use is the result of an increased water demand in several sectors (H. T. Tran, 2010). Due to the rapid growth, both reflected in urbanisation and population growth (as explained in Section 1.4). The precipitation change and water use change are not directly visible in the measured levels; they cancel each other out. However, it does not mean that they have no influence individually. It is important to be aware of this in order to understand the water system.

4.1.3. Anthropogenic activities

In addition to precipitation, anthropogenic activities strongly influence the water level of the river system. In the past decades, the discharge in the key rivers of the system has changed slightly, 5–15 %. While the water level varied 10–40% (Quang et al., 2024).

Dam-reservoir system

The build of the dam-reservoir system (discussed in Subsection 3.4.1) is a key factor of this water level change. Quang et al. (2024) researched the relation of the dam construction and water levels at several locations in the river system. Here, a further focus is placed on the system change caused by the construction of the Hao Bihn Dam. This is accomplished by comparing trends in water level and discharge at gauging stations located upstream (TB) and downstream (HB) (visible in 4.1) of the Hoa Binh Dam over a time period that includes its construction.

The TB gauging station is now a days located within a reservoir, therefore it does not exist any more. These locations are therefore only used to illustrate the concept.

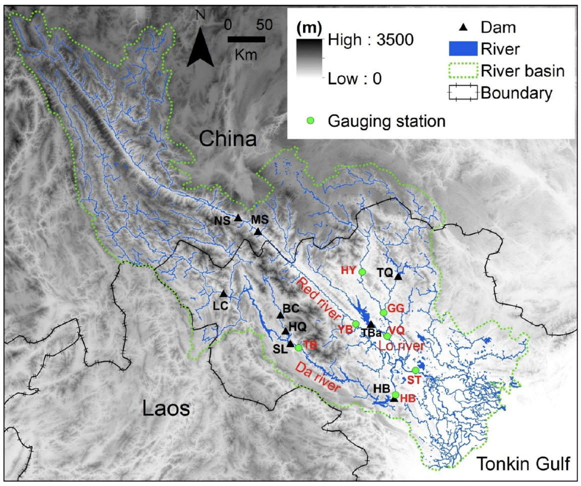


Figure 4.1: Overview of locations of gauging stations (Quang et al., 2024).

In figure 4.3 The non-parametric Mann–Kendall (MK) test conducted by Quang et al. (2024) is illustrated. In both gauging stations, the discharges tend to decrease. However, these trends are not statistically significant. Simultaneously, the water levels at the two stations show opposite trends: at TB, the water level increases ($Z = 5.65$), whereas at HB, the water level decreases ($Z = -7.35$). At the TB station, this increase is a result of an event identified in the early 1990s, while at HB, no statistically significant changes were observed in the water level time series. The event in the early 1990s was likely due to the construction of the Hoa Binh Dam, which took place from 12/1979 to 12/1988.

In further analysis, the time series is split into two periods: the pre-dam and the post-dam period. Figure 4.2 shows a clear upward shift in water levels upstream and a downward shift downstream following the dam construction. Furthermore, before the dam construction, water levels were strongly correlated with water discharge ($R^2 = 0.91$), whereas a weak relationship was observed afterwards ($R^2 = 0.05$). This highlights an important consequence of the dam: water levels are no longer solely influenced by changes in discharge but also by dam operations.

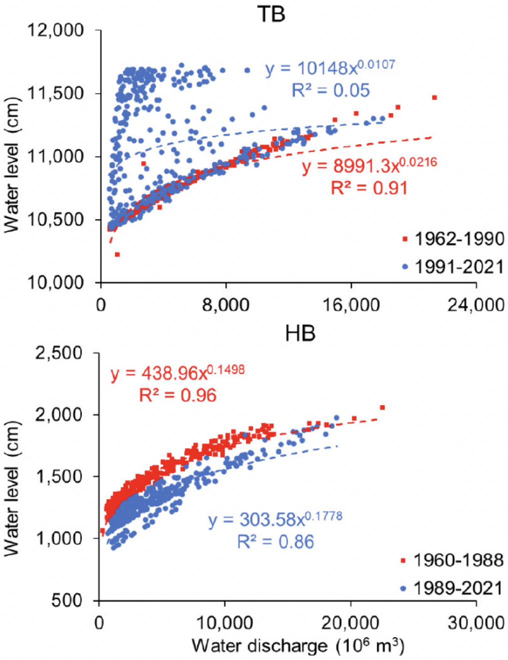
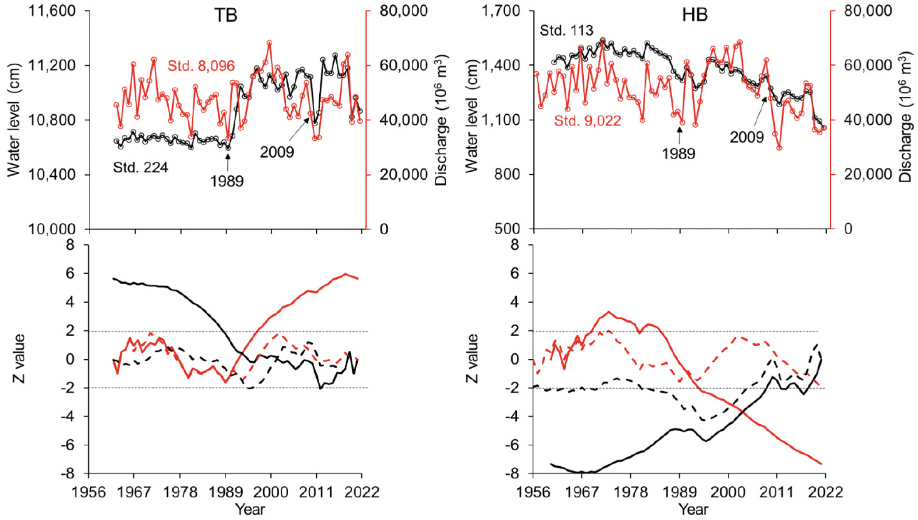


Figure 4.2: Rating curves of monthly water level vs. water discharge. Analysis conducted by Quang et al. (2024).



(a)

Figure 4.3: Inter-annual variations (upper panel) and Mann-Kendall analyses (below panel) for the water discharge and water level conducted by Quang et al. (2024)

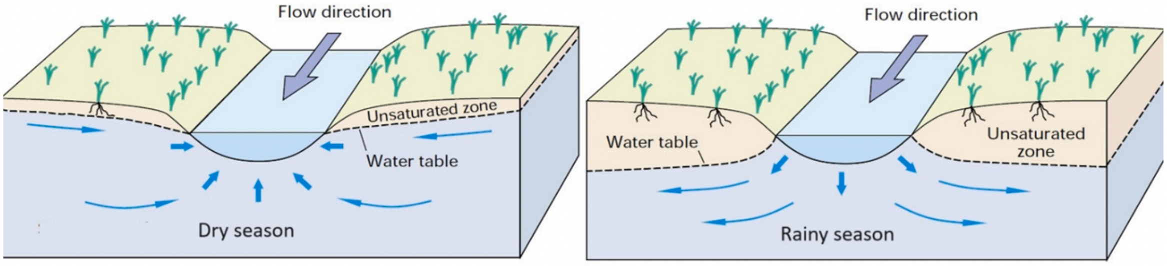


Figure 4.4: Illustration of water gain and loss due to interaction between groundwater table and river water between different seasons (Trinh et al., 2025).

Sand mining

Next to the construction of the dam-reservoir system, sand mining also influences the water levels. The anthropogenic activity sand mining is explained in the Subsection 3.4.2. The exploitation of sand is one of the reasons the riverbed is lowering. Together with the reduced water supply from upstream, and erosion (elaborated in Section 7.1), the water levels are decreasing (Quang et al., 2024). However, next to a decrease in water levels, sand mining in the Red River has also enhanced groundwater discharge into the river. Trinh et al. (2025) claims that this is due to a rapid riverbed lowering, a change in the groundwater flow during the dry season has occurred, resulting in discharge instead of recharge (fig. 4.4).

4.2. Floods

As explained in the Section 3.1, the Red River – Thai Binh Basin consists of two types of landscapes that are vulnerable to floods. Due to the steep slope, high-density network of rivers and streams, and extreme rainfall events the Northern mountain area is vulnerable to flash floods. Simultaneously, the delta is low-lying and an area that is regularly affected by storm surges. Making the delta vulnerable to coastal floods.

4.2.1. Land use change

As discussed in Subsection 3.4.3, more land is required for agriculture and aquaculture. The land reclamation has caused the area of intertidal flats to decrease over the past decades (Fan et al., 2019). These land reclamation has a significant impact on coastal flooding. Due to the land reclamation, intertidal areas lost their value as a protection zone (Xu, Ding, Nitivattananon, & Tang, 2021). Next to that, it magnifies the extent of coastal flooding and increases the exposed area and population (Silveira, Lopes, Pinheiro, Pereira, & Dias, 2021).

Furthermore, flash floods are also influenced by changes in land use. Land use change disrupts natural hydrological processes, which significantly affects the surface run-off. For example, areas with a vegetation cover below 20% are associated with a high risk for flash floods. Dense vegetation reduces run-off by slowing down the water and stabilising the soil. Other major human activities that influence the flow patterns and consequently increase flash flood risks include deforestation, agriculture, and urban development (H. G. Pham & Kieu, 2025).

4.2.2. Climate change

Due to climate change (3.3), the rain season is predicted to become wetter. Resulting in more frequent and intense peak rainfall events that may cause flash floods in the northern region. In addition, storm surges are likely to occur more frequently and with greater intensity. This will increase the frequency of storm surge events and, consequently, the exposure of the delta to coastal floods. This is exacerbated by sea-level rise, since both the exposed area and affected population will increase (Silveira et al., 2021).

4.3. Sediment budget

Formerly, the Red River was one of the most sediment-rich rivers of the world, with an annual suspended sediment flux at Son Tay estimated at 100–160 million tons per year (Vinh, Ouillon, Thanh, & Chu, 2014b). This sediment is essential for maintaining delta elevation, nourishing floodplains and compensating for natural subsidence and sea-level rise.

4.3.1. Dam-reservoir system

In addition to changing water levels, the construction of dam–reservoir systems has a substantial impact on the sediment budget of a river. Approximately 30% of the global sediment flux is trapped in large dam–reservoir systems. Reservoirs trap the majority of the bedload and a significant portion of the suspended load. This results in a substantial reduction in sediment budget in the downstream river parts Hao Quang et al. (2023). (Hao Quang et al., 2023) focuses on two locations, Son Tay and Hoa Binh station. The concept of sediment trapping is described here using the example of the Hoa Binh station (downstream of the Hoa Binh dam) to fully understand the influence of the Hoa Binh dam.

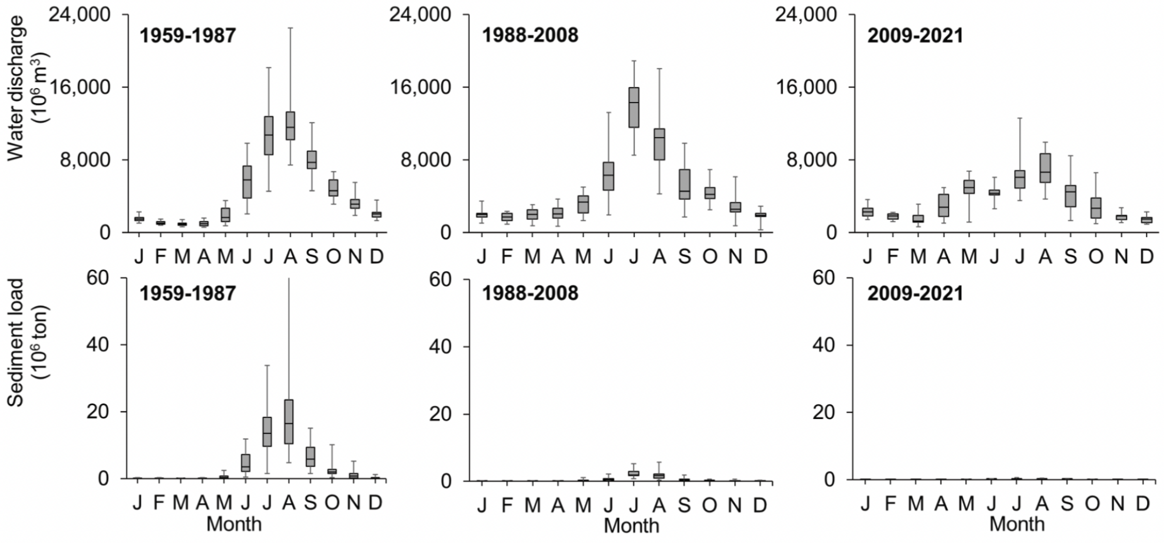


Figure 4.5: Inter-annual variations of monthly water discharge and sediment load in the three periods 1958–1987, 1988–2008, and 2009–2021 for the Hoa Binh station Hao Quang et al. (2023).

Figure 4.5 shows the sediment load at the Hoa Binh station monthly in different time periods. From 1959 - 1987 (no dams), 1988 - 2008 (Hoa Binh dam), and 2009-2021 (Hoa Binh, Son La, Ban, Chat, Huoi Quang, and Lai Chau dam). This figure shows that the sediment load becomes nearly zero after 2008. Figure 4.6 illustrates that before the construction of the Hao Binh dam, high monthly discharge is accompanied by a large monthly sediment load. Once the Hao Binh dam went into operation, high discharge periods are no longer accompanied by a large monthly sediment load. This difference has been exaggerated further by a series of operating dams upstream.

Before the construction of the dams, rainfall was the primary driver of variations in water discharge, resulting in corresponding fluctuations in sediment load. Once the Hoa Binh Dam was constructed, sediment became trapped in the reservoir. Therefore, both rainfall and dam operation became the main factors influencing the sediment load. After the construction of several additional dams, the relationship between natural forcing and sediment load weakened, as the dam–reservoir system increasingly controlled changes in sediment load and discharge Hao Quang et al. (2023).

4.3.2. Sand mining

In addition to sediment trapping by dams, sand mining (discussed in Subsection 3.4.2) further disrupts the sediment budget. Within the Red River, sand mining is illegally done to extract sand for construction purposes, among others (Chinh, 2018). According to Rentier and Cammeraat (2022), sand mining, through pit excavation and channel-wide instream mining, creates deep excavation pits which locally trap sediment. The consequences of downstream sediment starvation are explained in Section 7.1.

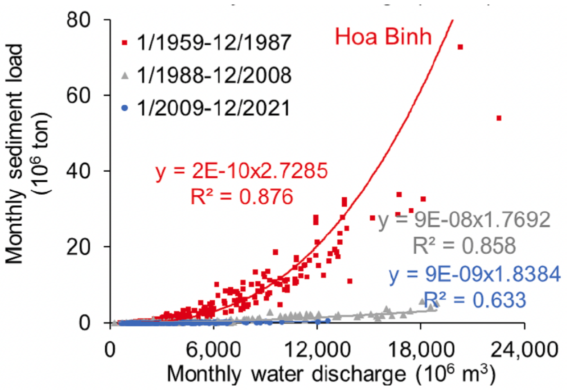


Figure 4.6: Rating curves of sediment loads and water discharges. Period 1958–1987: Before the Hoa Binh dam operating, period 1988–2008: Hoa Binh dam started its operating, and period 2009–2021: A series dams operating upstream Hao Quang et al. (2023).

4.4. Fresh water availability

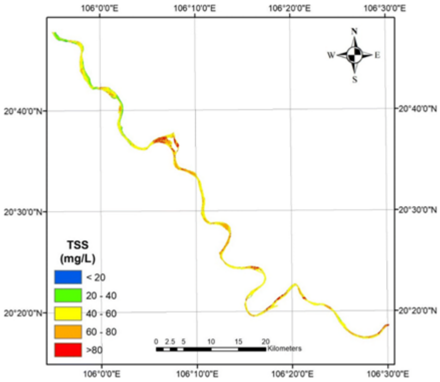
In Subsection 3.4.4, it is stated that the demand for water supply increases. Simultaneously, there are several causes for the decline in the freshwater supply.

4.4.1. Water pollution

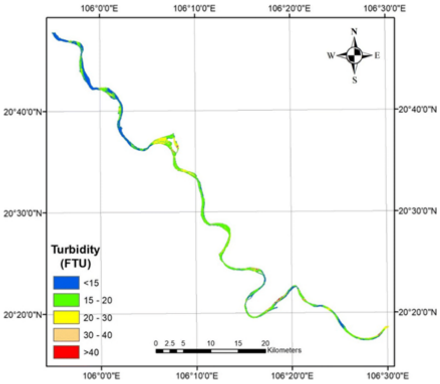
Primarily, the most downstream surface waters are heavily polluted. Polluted surface waters will not justify as drinking water or irrigating fields. The pollution in surface water is caused by intensifying agriculture, resulting in the discharge of wastewater further downstream in the rivers. The intensification of agriculture is a direct result of urbanisation, the change in land use described in Section 3.4.3. There is less room for agriculture, while the food production for export and domestic use still stays equal or higher. The irrigated water on crops flows back into the system but is now carrying residuals of pesticides, fertilisers, waste discharge, industry parks, etcetera. (Duc Viet, 2018). Wastewater is dumped into river systems and carried further downstream. General waste is also found along the river during the fieldtrip (Figure 4.7), causing pollution of water systems even more besides agriculture. Pollution due to aquaculture in rivers or water bodies is caused by fish feces. Where large amounts of fish are farmed in small cages within or alongside the rivers. The waste these farms produce is increasing the concentration of feces within the water. These pollutants deteriorate water quality and contribute to a feedback loop affecting food security, where bad water quality has a negative effect on crop yield resulting in a decrease in food security.

In Figure 4.8a and 4.8b the worsening quality of water downstream in the Red River is shown, in terms of turbidity and Total Suspended Solid (TSS). The location within the Red River of this analysis is shown in Figure 4.8c. Both TSS and turbidity say something about the clarity of the water and the concentration of suspended particles. A higher value for both can indicate pollution, higher water temperatures or algae bodies.

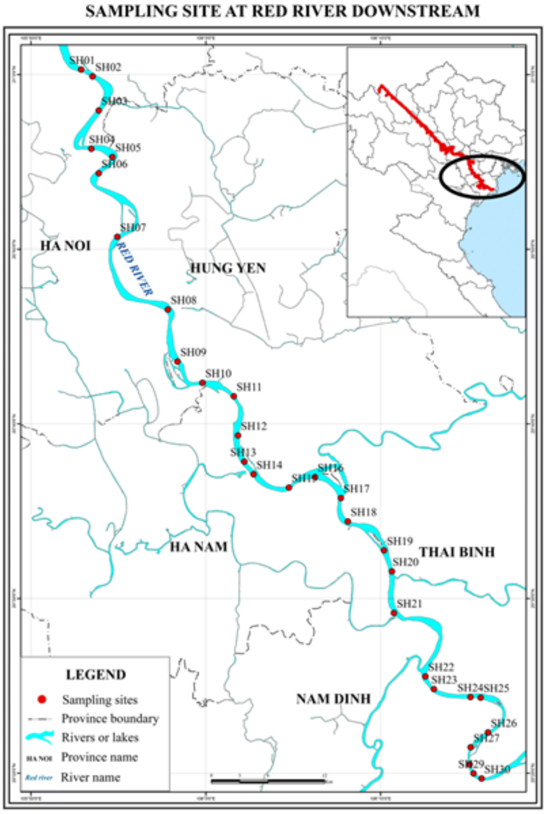
Figure 4.7: Garbage next to the Red River (taken during field trip)



(a) Total Suspended Solids (TSS) concentrations



(b) Turbidity levels in the Red River



(c) Sampling sites in the Red River

Figure 4.8: Surface water quality indicators and sampling locations in the Red River.

4.4.2. Groundwater resources

Secondly, there is a large reduction in groundwater resources (Tam & Nga, 2018). This is caused by a decline in the groundwater recharge, mainly due to a decrease in the Red River discharge and water levels resulting from increasing water use in upstream regions for hydropower, for example (Tam & Nga, 2018). During the dry season, it can even happen that groundwater flows towards the Red River instead of vice versa, as explained in Section 4.1. A decline in groundwater levels naturally results in seawater intrusion (Van Pham & Lee, 2015). Adding to that, the groundwater extraction increases (Section 3.4.4). This is a result of the increased water demand and the worsening of the surface water quality.

However, over-pumping of groundwater from the coastal aquifers enhances the effect of saltwater intrusion. This is caused by the variation in the density of freshwater and seawater. The high-density seawater moves into the coastal aquifer and forms a wedge shape. Depending on the intensity of pumping, this wedge can extend for several kilometres inland. These affected aquifers are characterised by high concentrations of chloride, bromide, and sodium. So the fresh water bubble will be overexploited such that the bubble "shrinks" and the deeper lying wells start extracting saline or brackish water instead of fresh water. The figure 4.9 below illustrates saltwater intrusion close to the coast due to heavy pumping. The freshwater bubble shrinks, and when it shrinks enough, saline water will be pumped instead of freshwater. Also, the effect of heavily constructed buildings on top of the soil is illustrated. Causing sinking due to compression of the soil as a result of overexploitation of groundwater.

This reduction in groundwater resources results in less available fresh water, which will be further exacerbated by rising sea levels (Section 3.3).

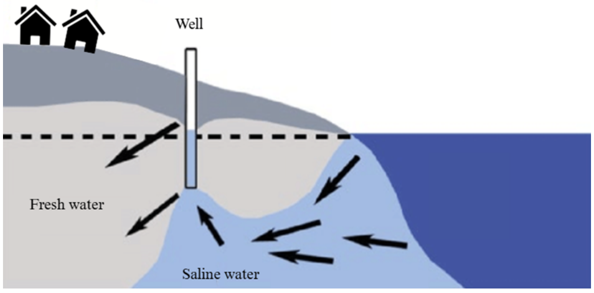


Figure 4.9: Salt water intrusion due to heavy pumping; land subsidence due to depression cone. figure edited from (Etikala, Adimalla, Madhav, Somagouni, & Keshava Kiran Kumar, 2021)

4.4.3. Sand mining

Thirdly, the main riverbed changes caused by sand mining are: an increase in channel capacity, a lowering of the average riverbed elevation, a deepening of the water depth, and a decrease in the longitudinal riverbed gradient (Jia, Luo, Yang, Ou, & Lei, 2007). Jia et al. (2007) has explored the effect of changing riverbed morphology due to sand mining on the tidal dynamics in the lower reaches and delta of the Dongjiang River in China. It can be expected that similar effects occur in the Red River delta.

Jia et al. (2007) shows that the enlarged channel capacity, lowering of the average riverbed elevation, and increased water depths increase the tide accommodating capacity of rivers. Enabling more tidal currents to enter the rivers leads to the strengthening of tidal dynamics.

In addition to an increased tide accommodating capacity of the rivers, sand mining causes a decrease in the riverbed gradient, triggering the tide move upstream. Thus, the tidal limit, tidal current limit, and saltwater limit to move upstream. Which can cause difficulties in the freshwater supply land inwards (Jia et al., 2007). Although the magnitude of these changes in the Red River Delta remains uncertain, sand mining likely alters tidal dynamics and may consequently affect freshwater availability.

4.5. Key WEFE-Nexus relations

In summary, the key WEFE Nexus relations identified in this chapter are:

- The operation of dam–reservoir systems for hydropower generation may conflict with downstream water level requirements.

- Land-use change associated with economic growth alters hydrological processes and increases the exposed area, consequently increases flood frequency and damage.

- Rising freshwater demand driven by Vietnam's growth is increasingly met through groundwater abstraction, leading to groundwater depletion and long-term declines in freshwater availability.

- The growing demand for construction sand intensifies river sand mining, which negatively affects freshwater resources.

5

Energy

This chapter analyses Vietnam's energy system. Section 5.1 presents an overview of important statistics. Section 5.2 examines total energy use, the primary energy mix, sectoral consumption, and energy dependency. The electricity sector is analysed in Section 5.3, focusing on generation structure, imports, and efficiency. Section 5.4 evaluates national transition targets and compares projected developments with historical trends. Finally, section 5.5 assesses the role of renewable energy sources, discussing both their potential and structural constraints. At last in Section section 5.6 the challenges are summarised.

5.1. Overview

To provide an overview of Vietnam's energy use and associated emissions, Table 5.1 presents statistics on energy consumption, electricity generation, and CO_2 emissions.

Indicator	Value
Primary energy consumption	14 618 kWh per capita
Primary energy consumption (total)	1 476 10^9 kWh
Total electricity generation	303.6 10^9 kWh
Population with access to electricity	99.8%
Electricity consumption	2 624 kWh per capita
Electricity generation	3 006 kWh per capita
Emission intensity	0.66 tCO_2e/MWh
Total CO_2 emissions	370.93 Mt

Table 5.1: Key energy statistics for Vietnam (2023/2024) (Our World in Data, 2025)

5.2. Energy consumption

Vietnam used 540 TWh in 2010 and in the past 15 years this has increased to 1 476 TWh (Our World in Data, 2025). This is caused by the rapid growth in energy demand over recent years, reflecting the country's strong economic expansion.

5.2.1. Energy mix

In Figure 5.1 the energy consumption of Vietnam is made visible. Currently fossil fuels add up to more then 70% of all the energy consumption in Vietnam.

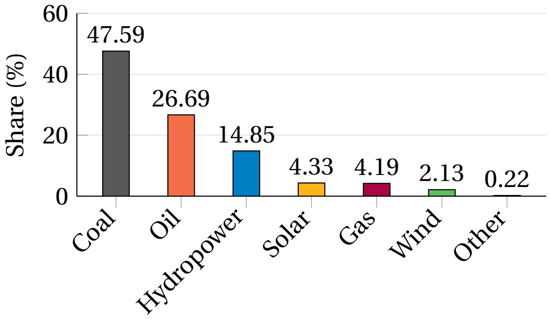


Figure 5.1: Energy consumption (%)

5.2.2. Sectorial consumption

Industrial activities account for approximately 50% of total energy consumption. This is caused by the energy-intensive nature of Vietnam's current economic structure (IEA, 2024).

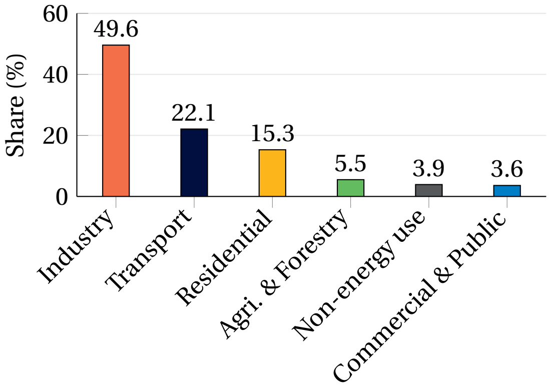


Figure 5.2: Total energy consumption per sector (2023)(IEA, 2024)

5.2.3. Energy Dependency

Vietnam became a coal importer in 2015. Its reliance on imported coal has grown sharply, from 7 Megatonnes in 2015 to 67 Megatonnes in 2024. The country mainly imports coal from Indonesia, Australia, and Russia. At the same time, coal exports have fallen. They dropped from 20 Megatonnes in 2010 to 0.7 Mt in 2024 (Enerdata, 2024). Since the energy consumption has risen rapidly, Vietnam needs all its coal to meet its own demand.

5.3. Electricity sector

This section discusses key characteristics of Vietnam's electricity sector, including the generation mix, electricity imports, and efficiency challenges.

5.3.1. Generation Mix

The electricity generation has tripled in the past 15 years. It can be seen in Graph 5.3 that the electricity production out of coal plays a big role. The second most important factor in electricity production is hydropower (Our World in Data, 2025).

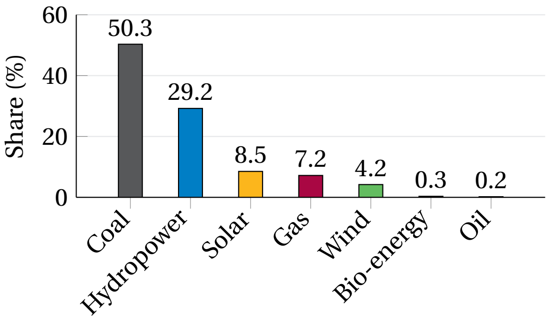


Figure 5.3: Electricity production (%)

5.3.2. Imports and Capacity

In addition to its own electricity production, Vietnam plans to import 9 360–12 100 MW of electricity from Laos and China over the next five years. This is more than five times the current level. The move aims to meet growing demand as the country targets double-digit economic growth. Currently, Vietnam imports about 1 600 MW from Laos and 550 MW from China. This equals roughly 2.4% of total electricity capacity. By 2030, imports are expected to reach 4–5.1% of total capacity. They could be increased earlier or further to meet rising demand in the north (VNS, 2025).

5.3.3. Low efficiency

Despite high output, electricity use is inefficient. Vietnam consumes about 652 kWh to produce $1,000 of GDP. For comparison, this is roughly 2.8 times more than Indonesia and 2.4 times more than the Philippines. High consumption is driven by an energy-intensive economic structure. Industries like steel, cement, and raw material processing rely heavily on electricity. Outdated production technologies further reduce efficiency. In addition, low electricity prices also distort incentives, as they discourage energy-saving investments and improvements. To resolve this inefficient electricity use, the industrial technologies need to be modernised and the electricity prices need to be adjust to match the true cost (Hung, 2025).

5.4. Government targets

Vietnam's energy and climate policy framework sets a long-term transition pathway. The government targets a renewable share of 74–75% in the power mix by 2050, alongside bigger deployment of biofuels and energy efficiency measures. Institutional reforms accompany these goals with the reintroduction of nuclear power and the implementation of an emissions trading scheme to support decarbonization objectives. According to the current Power Development Plan (PDP8) and the Master Plan for Energy Development (2021–2030), renewable energy is planned to account for 15–20% of total primary energy supply by 2030, increasing substantially toward 80–85% by 2050 (Enerdata, 2024). In parallel, total installed power capacity is projected to expand to approximately 183–236 GW by 2030.

Figure 5.4 compares the projected electricity portfolio (PDP8, 2020–2040) with historical generation data. The comparison indicates a substantial increase in total electricity generation over the coming decades. Crucially, this expansion is not intended to be driven by additional coal capacity. Instead, projected growth is concentrated in gas (particularly LNG), wind, solar, and biomass. Hydropower remains relatively stable, suggesting saturated implementation. The implications of this transition are examined in the following Section 5.5.

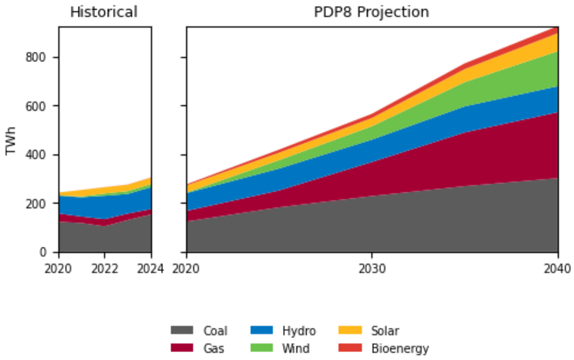


Figure 5.4: Electricity Generation, policy versus historical data Our World in Data (2025), Sasges and Ziegler (2023a)

5.5. Renewable Energy sources

In this section, the renewable energy sources are discussed. Both the advantages and disadvantages are addressed, as well as their future role in Vietnam's energy transition.

Figures 5.5 and 5.6 illustrate the contrast between currently installed renewable capacity and estimated technical potential in Vietnam. While hydropower dominates present renewable generation, biomass and wind show significantly larger potential (X. P. Nguyen et al., 2021). The gap between deployment and potential shows constraints related to financing, grid capacity, regulatory stability, and environmental trade-offs, which will be further explored in the next sections.

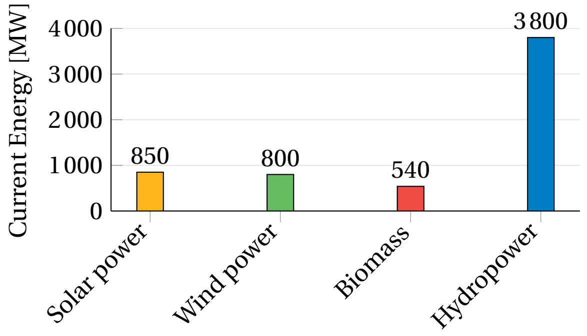


Figure 5.5: Current energy generation by renewables(X. P. Nguyen et al., 2021)

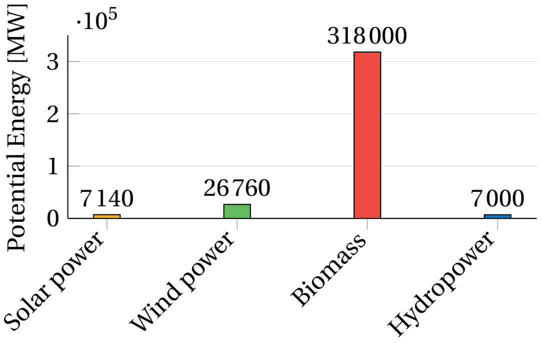


Figure 5.6: Potential energy generation by renewables(X. P. Nguyen et al., 2021)

5.5.1. Hydropower

As explained in Section 3.4.1 hydropower plays an important role in the energy production in Vietnam.

Trade-offs

Hydropower provides a renewable and relatively low-carbon source of energy for Vietnam. It has supported economic growth and has contributed to poverty reduction in several regions. The dams and reservoirs also play an important role in flood control, irrigation, and water storage. In addition, hydropower can supply electricity to remote and mountainous areas where grid access is otherwise difficult. The sector also creates employment opportunities and can stimulate local economic activity and recreation.

However, hydropower also has environmental and social downsides. The construction of dams can lead to land degradation, displacement of agricultural land, and damage to sensitive ecosystems. River systems are also affected: fish migration routes are interrupted, streamflow dynamics change (See Section 4.1), and sediment transport is reduced (see Section 4.3). These alterations affect downstream areas and can create long-term impacts (Sasges & Ziegler, 2023a). Downstream effects include negative impacts on agriculture, increased salt intrusion (Section 4.4),(Section 4.2), reduced hydropower performance in connected systems (Sasges & Ziegler, 2023a) and altered flood risk. The dam constructions can breach or have unexpected releases, causing a higher flood risk. So the flood risk is improved, as well as sometimes increases due to dam construction.

For example, before the impoundment of the Hoa Binh Dam, the suspended sediment flux of the Red River at Son Tay was estimated at 100–160 × 10^6 t yr^{-1}. The Da River was the main sediment source until the dam was constructed in the 1980s. After impoundment, sediment flux decreased sharply to about 40 × 10^6 t yr^{-1} during the period 1997–2004. This reduction in sediment supply contributes to coastal erosion, as sediment deposition no longer compensates for sea-level rise and tectonic subsidence. Although the Hoa Binh Dam improved flood control, irrigation, and electricity production in northern Vietnam, it also significantly reduced water discharge and sediment delivery from the Red River basin to the delta and coastal areas. The construction of the Hoa Binh Dam also had major social consequences. Approximately 58,000 people were displaced. The towns of Cho Bo, Van Yen, and Suoi Rut were flooded. Around 11,000 hectares of agricultural land were submerged, including 5,000 hectares of rice fields. Most affected communities belonged to ethnic minority groups, including the Muong, Tay, White Thai, and Black Thai. Following the flooding, reported cases of diseases such as malaria increased significantly (Hirsch et al., 1992).

Hydropower management in Vietnam

In Vietnam, regulations governing dams prioritise water security, fair distribution, and the maintenance of minimum river flows. This limits hydropower plants from focusing solely on electricity generation (Prime Minister of Vietnam, 2019a).

Hydropower management in Vietnam is regulated by inter-reservoir coordination rules, particularly in major basins such as the Red River basin. The legally binding operation procedures are issued by the Prime Minister. This regulates water releases, flood control functions, and dry-season water allocation. In the Red River basin, major reservoirs such as Hoa Binh, Son La, Tuyen Quang and Thac Ba are operated under coordinated rules designed to balance multiple objectives: flood mitigation for the Red River Delta, electricity generation, and downstream water supply.

During the flood season, reservoir levels are required to remain below specified thresholds to preserve flood storage capacity. Controlled water release mechanisms are put in use when water levels exceed regulatory limits. This ensures downstream safety while maintaining the structural integrity of the dams. During the dry season, reservoir water releases are coordinated to guarantee minimum downstream flows. This happens to support agricultural irrigation and prevent salt intrusion in the delta. These operational rules reflect the multi-purpose character of Vietnam's hydropower dams, where electricity production is constrained by water management priorities (Government of Vietnam, 2019).

However, extreme weather events continue to create challenges. Historic rainfall in 2025 forced 93 out of 122 reservoirs nationwide to discharge water simultaneously, in small and medium-sized hydropower plants. Many reservoirs were kept near full capacity to maximise power production, leaving a limited storage buffer for flood control. This was caused by outdated operating rules. In steep mountainous catchments, rapid inflows required urgent water releases, at times putting downstream communities at risk. As a result, experts and policymakers have called for stronger dam-safety governance, improved inter-reservoir coordination, modern forecasting systems, and the expansion of pumped-storage hydropower to stabilise the grid and reduce pressure on conventional reservoirs (Vietnam News Service, 2025).

Small vs big hydro-plants

Large and small hydropower plants differ significantly in scale, impact, and purpose. Large dams, such as the Hoa Binh Dam, generate high electricity output and play an important role in national energy supply, flood control, and irrigation. However, they also cause major environmental and social impacts as discussed in the previous section.

Small hydropower plants, on the other hand, have a much lower generation capacity and are often developed to supply regional or rural areas. Their reservoirs are smaller and usually cause less large-scale displacement. In some cases, they can support local agricultural income by improving irrigation reliability. However, small hydropower plants still affect river flow and water availability, especially at the local level. Downstream households gain from improved water regulation, while upstream communities are unaffected. According to Seewald, Grote, and Nguyen (2025), the small hydropower plants should be encouraged.

In reality, the downstream household can experience negative consequences. In the Bien La commune, the construction of multiple small hydropower plants led to loss of farmland, declining fish catches, reduced irrigation water and lower rice production. Many households reported income losses, however the compensation for lost land was limited. These changes forced part of the population to migrate in search of work, particularly affecting ethnic minority communities. This example shows that although individual small hydropower plants operate on a smaller scale than large dams, their local impacts can still be substantial (Esterman, 2025).

Future development potential

Perspectives on the remaining hydropower potential in Vietnam differ considerably. Most assessments suggest that the economically feasible capacity is already largely exploited. In 2014, the International Hydropower Association estimated Vietnam's feasible potential at 19–21 GW, which was close to the installed capacity at that time (just over 17 GW). This implies that only limited additional large-scale development would be possible. More recent research, which uses more conservative criteria estimates that only around 3.9 GW of additional capacity remains. In contrast, Electricity Vietnam (EVN) presents a more optimistic outlook. The corporation estimates the exploitable hydropower potential at 30–38 GW, PDP8 largely follows this projection. The plan forecasts total hydropower capacity, including pumped storage, reaching around 40 GW. However, given the current density of hydropower facilities, these optimistic projections should be treated cautiously. Vietnam already has more than 700 hydropower plants in operation or under construction, which corresponds to roughly one plant per 459 km^2 or per 135 000 inhabitants. In this sense, Vietnam's hydraulic resources are already highly developed (Sasges & Ziegler, 2023a).

5.5.2. Solar

Solar energy has expanded rapidly in Vietnam over the past few years and plays an increasing role in the electricity mix. The country benefits from high solar irradiation levels, especially in the southern and central regions. This makes solar power technically attractive. However, several structural challenges limit its long-term integration into the energy system.

One of the main barriers is the high initial investment cost. Although technology prices have decreased globally, the upfront installation costs remain significant for households and small businesses. Long payback periods and limited awareness of long-term benefits can discourage private investment (X. P. Nguyen et al., 2021).

In addition, solar energy is inherently intermittent. Electricity production depends on sunlight availability, which creates fluctuations during the day and across seasons. Large-scale deployment therefore poses challenges for grid stability and real-time system balancing. When solar output suddenly drops, the system must rely on backup capacity or imports to maintain supply security. Related to this issue is the limited availability of energy storage. Vietnam currently lacks sufficient large-scale storage capacity to save excess generation during peak sunlight hours and release it when production declines. As a result, grid congestion can occur in regions with high solar penetration X. P. Nguyen et al. (2021).

5.5.3. Wind

Vietnam has nine wind power plants with a total installed capacity of 304.6 MW (X. P. Nguyen et al., 2021). Due to its coastline of more than 3 200 km and average wind speeds of around 6 m/s at 65 m height, the country has favourable natural conditions for wind power development. According to the World Bank, the technical potential of onshore wind power is estimated at around 30 GW, in addition offshore potential could reach approximately 100 GW (Meier, Vagliasindi, & Imran, 2015).

Wind energy has the advantage of requiring less direct water than hydropower or thermal power plants, which reduces pressure on freshwater systems. However, large-scale onshore and offshore deployment raises other trade-offs, including land use conflicts and impacts on coastal ecosystems. Despite the strong resource base, actual installed capacity remains limited compared to the estimated potential. Key constraints include grid congestion, high upfront investment costs, regulatory uncertainty, and slow permitting procedures. Consequently, while wind energy represents a major pillar of Vietnam's future decarbonisation strategy, its expansion depends on institutional reform, grid reinforcement, and improved policy stability. X. P. Nguyen et al. (2021)

5.5.4. Biomass

Biomass represents an underused component of Vietnam's renewable energy portfolio. The country benefits from substantial feedstock availability due to its large agricultural and agro-industrial sectors. Immediately exploitable resources are widely available, including rice straw, surplus bagasse from sugar production, dedicated energy crops such as elephant grass, municipal solid waste in urban centres, livestock waste, residues from agro-forestry, and seafood processing activities (X. P. Nguyen et al., 2021).

Estimates of technical potential indicate that by 2030 biomass energy could reach approximately 14.6 Mtoe (million tons oil equivalent) from wood resources, 20.6 Mtoe from agricultural residues, and 1.5 Mtoe from urban waste streams. Agricultural waste thus constitutes the dominant share of biomass potential.

Despite this considerable technical potential, biomass currently plays a small role in Vietnam's electricity mix. Whereas biomass accounts for roughly 2% of electricity generation across Asia on average, Vietnam's share remains around 0.3% (Our World in Data, 2025). This gap suggests that the constraint is not resource availability but rather institutional, logistical and economic.

Biomass also has a few disadvantages, firstly, direct combustion can release carbon dioxide. Secondly, over-collecting wood can destroy the forests and make the soil more vulnerable to erosion and flooding. Thirdly, when plant and animal waste is used as biomass it can not be used for fertilizer any more and this will make the production of crops harder. Devanshu, Mamta, and Brijendra (2019)

5.6. WEFE Nexus relations

To conclude this chapter, the main challenges are summarised.

- Vietnam's rapid energy expansion has increased fossil fuel dependence. Coal remains central to the energy mix, contributing heavily to rising CO_2 emissions, air pollution, and long-term climate risks. Growing coal imports further lock the country into carbon-intensive infrastructure. However, the expansion of renewable energy could help slow this trend if deployment continues to increase.

- Hydropower is the main renewable energy source in Vietnam and plays an important role in electricity generation. It supports economic development and water management, including flood control and irrigation. However, hydropower development also causes ecological and social impacts, such as altered river flows, disrupted fish migration, coastal erosion, and the displacement of local communities.

- Solar and wind energy reduce direct emissions and water use but introduce new environmental tensions. Wind power expansion, particularly offshore, may affect coastal ecosystems and require transmission infrastructure. Both technologies also increase pressure on grid systems. The grid system will need to be improved if the growth of solar and wind energy continues. Also, both technologies are dependent on fluctuating factors such as wind speed and sunlight availability.

- Biomass offers considerable renewable energy potential but raises environmental concerns related to emissions from combustion, deforestation from excessive harvesting, and soil nutrient depletion when agricultural residues are not used as fertiliser.

6

Food

For this part the Food aspect of the WEFE-nexus will be discussed. Food plays a central role in the Red River Delta (RRD), often referred to as the “second rice bowl” of Vietnam after the Mekong Delta due to its high rice productivity. The delta forms the agricultural and aquacultural core of Northern Vietnam and supplies both domestic markets and export chains. Increasing water scarcity, groundwater depletion, pollution and climate variability are placing pressure on food production systems, while intensification strategies aim to maintain output under declining land availability.

6.1. Agriculture

The delta contributes approximately 18% of national rice output and 26% of vegetable production (Food & Organization, 2019). Agricultural land in the delta covered approximately 674 000 ha in 2021, with a reduction of 27 760 ha between 2015 and 2024 due to urbanization and industrial expansion (Wageningen University & Research, 2024). Main crops in the basin conclude:

- rice (dominant water consumer)
- vegetables (cabbage, carrots, tomatoes, sweet potatoes, soybean)
- fruits (lychee, longan, oranges, bananas)
- flowers (roses, chrysanthemums, lilies)

According to General Statistics Office of Vietnam (2024a), the following land use structure is determined in the Red River Basin. Visible in figure 6.1, the structure in area for 2024. These values are based on statistics and the numbers are attached in appendix A.3, table A.8.

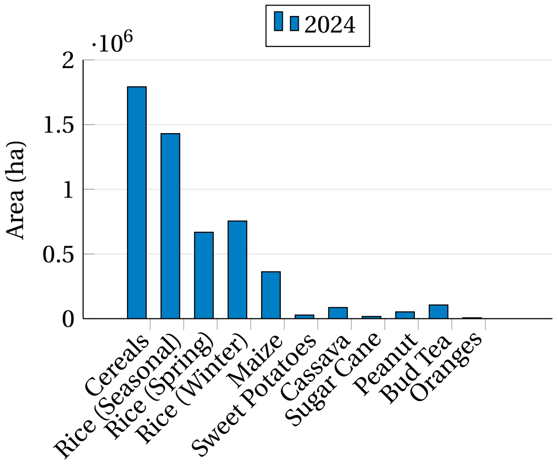


Figure 6.1: Crop area in the Red River Basin (ha)

Perennial crops are plants that live for several years and do not need to be replanted and stay all year long like orange trees. Insufficient data lead to only Oranges and Tea as perennial crop. Cereals and other crops than rice are dry-field crop. They grow in drained conditions and therefore are grown outside of the rice season, most of the time. The season refers to the hydrological context and time of the year (Table 6.1)

Term	Period	Hydrological Context
Spring crop	Dry Season (Feb–May)	High irrigation demand
Season crop	Early wet season	Moderate demand
Winter crop	Post-rice dry season	Irrigation dependent

Table 6.1: Differences between crop seasons and irrigation demands

The total rice area is larger than the physical agricultural land area because it represents the area across multiple growing seasons. This indicates a high cropping intensity, particularly the dominance of double-cropping systems.

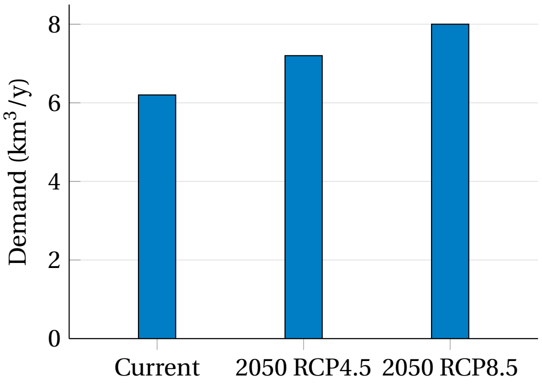


Figure 6.2: Projected agricultural water demand under current and future climate scenarios based on GCAM outputs

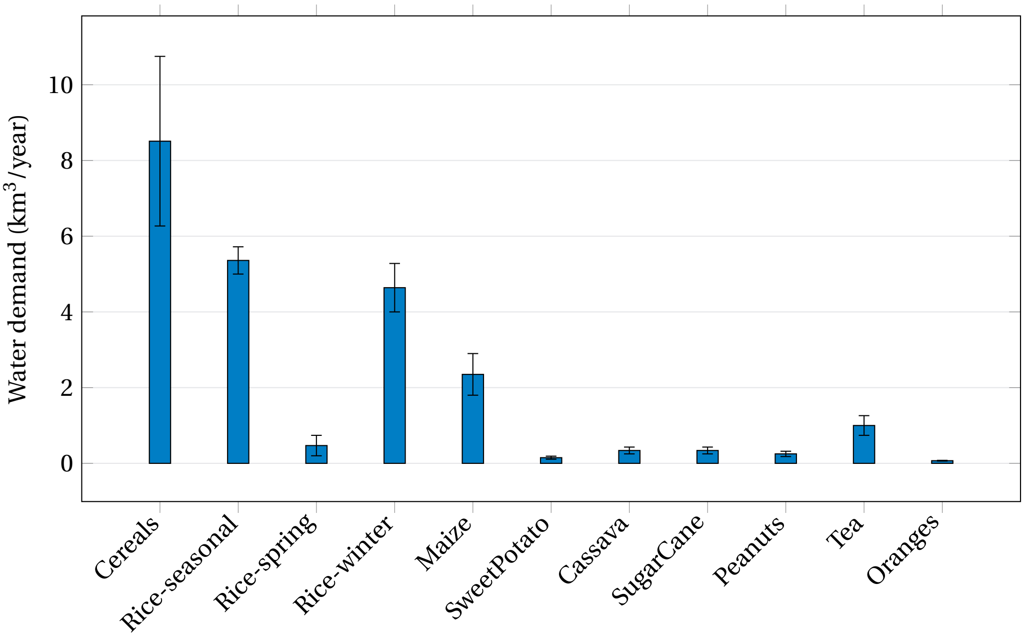


Figure 6.3: Estimated irrigation water demand per crop based on cultivated area in 2024 and crop water requirements. Bars represent mean demand while error bars indicate the uncertainty range derived from minimum and maximum irrigation requirements.

Water demands (table A.11 in the Appendix) can be obtained by using the area per type of crop, from figure 6.1 with the detailed values in the Appendix A.3, in combination with the irrigation demand per crop (table 6.2). This total water demand per crop is shown in 6.3

Table 6.2: Estimated irrigation water demand per crop type based on FAO crop water requirement guidelines (Allen, Pereira, Raes, & Smith, 1998). Crop water requirements are typically expressed in millimetres per growing season and can be converted to volumetric water demand per hectare, where 1 mm corresponds to approximately 10 m³ ha^{-1}.

Crop	Water demand (m^3/ha)
Rice (seasonal)	3500–4000
Rice (spring)	300–1100
Rice (winter)	5300–7000
Cereals	3500–6000
Maize	5000–8000
Sweet potato	4000–7000
Cassava	3000–5000
Sugar cane	15000–25000
Peanuts	3500–6000
Tea (perennial)	7000–12000
Oranges (fruit trees)	9000–12000

To illustrate the change of water demand for 2050 the paper and discussion in 6.5.4 is used, where figure

6.9 shows the demands for different RCP scenarios. Looking at the scenario for RCP4.5 and RCP8.5 (A mediocre emission and heavy emission scenario), values of $7.2km^3/y$ and $8.0km^3/y$ respectively can be estimated (average). Calculating the current demand, using the crop type (the average demand) and the area of crops we obtain the diagrams visible in figure **??**.

Crop water requirements derived from irrigation guidelines represent total evapotranspiration demands and do not directly correspond to irrigation water use. According to the FAO framework, irrigation water requirement is defined as the difference between crop evapotranspiration and effective precipitation Allen et al. (1998). In monsoon-dominated regions such as northern Vietnam, a substantial fraction of crop water demand is supplied by rainfall, with annual precipitation ranging between approximately 1600 and 2000 mm.

As a result, only a fraction of total crop water requirements must be met through irrigation. Previous studies and FAO-based assessments indicate that irrigation typically accounts for approximately 20–40% of total crop water demand in such regions, depending on seasonal conditions and irrigation practices. In this study, a representative average value of 30% is adopted to estimate irrigation demand from total crop water requirements. This assumption provides a reasonable approximation while remaining consistent with FAO guidelines and regional hydrological conditions. In This way, the current values for water demands in agriculture are obtained. This, to get an overview of the current demand compared to future demands.

6.2. Aquaculture

Next to agriculture the production of fish is a source of food in the delta, mainly produced via aquaculture. The total freshwater area in 2024 dedicated to aquaculture was 94 336 ha (Dang, 2025). This can be within reservoirs or along the rivers. The goal for 2025 was to expand this area to 115 000 ha (Dang, 2025), which shows the drive to keep expanding and intensifying the aquaculture. Table 6.3 shows the provinces with the leading area of aquaculture.

Province	**Area aquaculture (ha)**
Hanoi	24 700
Hai Duong	12 555
Ninh Binh	11 457

Table 6.3: Area of aquaculture in hectares in the three leading provinces.

A large variety of species are cultivated: tilapia, hybrid carp, grass carp, eels, giant freshwater prawns, snails, turtles, and snakehead fish. The total production of the Red River Basins in 2025 is projected to be 850 000 tons of fish which is 42.6% of the total fish output in Vietnam (Vietnam Association of Seafood Exporters and Producers, 2025). These numbers are just an indication in showing the scale and intensity of aquacultural fisheries related to the Food nexus. Comparing the 18% of the national rice output and the 42.6% of the national fish output, shows how important the aquaculture is in the Red River Basin.

Aquacultural fisheries need a constant water supply for deacidification and creating an environment for aquatic growth and development. Therefore, fisheries in

- Rivers and reservoirs have this continuous natural water flow.
- Ponds or created basins need continuous irrigation, demanding more water during dry periods due to higher evaporation and abundant rainfall (Duc Viet, 2018).

Aquaculture water demand is estimated at 8 000 – 12 000 m³/ha/year (Duc Viet, 2018). This estimation is on average for the Red River Basin and does not conclude local aspects or processes. The wide range indicates the large uncertainty. In appendix A.3 the area of aquaculture for every province in Red River Basin is calculated, with a total of $161.45 * 10^3 ha$. This corresponds to 1.29 - 1.94 km^3/year.

Again, looking at the GCAM resuls in 6.5.4, an estimation for aquaculture demands can be conducted. For scenario RCP4.5 and RCP8.5, respectively $2.4km^3/y$ and $2.6km^3/y$ are the demands.

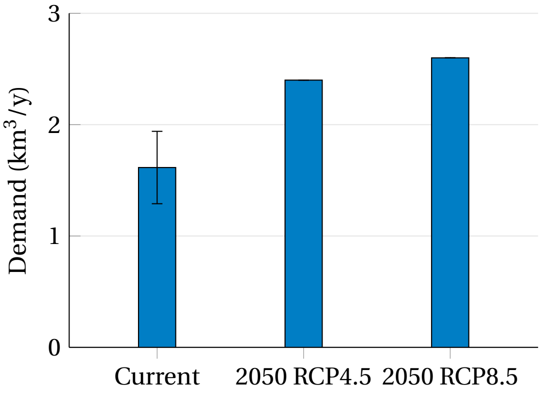


Figure 6.4: Projected aquaculture water demand under current and future climate scenarios based on GCAM outputs

6.3. Livestock

Livestock production constitutes a critical but often under represented component of the food system in the Red River Basin. The region is characterized by high densities of pigs and poultry, reflecting the strong domestic demand for animal protein (Food and Agriculture Organisation of the United Nations, 2022). Northern Vietnam, including the Red River Basin, is a core region for:

- Pig production
- Poultry farming
- Cattle (mixed crop–livestock systems)

The sector has transitioned from smallholder backyard systems toward more intensive semi-industrial production (T. H. Nguyen et al., 2018). Cattle refers to multiple types of mammals (buffalo, horse, dog), which are raised both as food source and for functional roles on the farmland.

Stage	**Buffalo** (10^3 **heads**)	**Cattle** (10^3 **heads**)	**Pigs** (10^3 **heads**)	**Poultry** (10^3 **heads**)
Current	999.79	1336.09	9 913.70	403 242.65
2050	593	1174	21 431	1 113 000

Table 6.4: Current and projected livestock numbers in the Red River Basin.

The head count in 6.4 for the current stage is according to General Statistics Office of Vietnam (2024) Livestock (Appendix A 6.4). The projections for 2050 were estimated using species-specific exponential growth rates applied to 2024 provincial headcounts. Based on observed trends in Vietnam, buffalo and cattle populations are assumed to decline at annual rates of −2% and −0.5%, respectively, reflecting reduced reliance on draft animals and increasing land constraints. In contrast, pig and poultry populations are projected to grow at +3% and +4% per year, driven by rising demand for affordable animal protein and the ongoing intensification of livestock production systems. These assumptions are consistent with recent evidence showing expanding pig and poultry sectors alongside stagnating or declining cattle numbers The Pig Site (2025) and broader structural changes in Vietnam's livestock industry Vietnam Briefing (2023), supported by increasing feed demand linked to intensification Grand View Research (2024). The projections were calculated using $N_{2050} = N_{2024} \cdot (1+r)^{26}$, where r is the species-specific annual growth rate.

Livestock water demand consists of multiple components, including direct drinking water, water used for cleaning and processing, and the indirect water embedded in feed production. Due to limitations in available data, this study considers only the direct drinking water requirement of livestock. The average drinking water demand for livestock in the Red River Basin is estimated as follows: (Duc Viet, 2018).

Livestock	Demand (l/day/unit)	Total Demand (2024) (km^3/year)	Total Demand (2050) (km^3/year)
Buffalo	135	0.0492	0.0292
Cattle	135	0.0658	0.0578
Pig	60	0.217	0.469
Poultry	11	1.619	4.468
Total	-	1.951	5.024

Table 6.5: Estimated livestock water demand in the Red River Basin.

Notice that these estimates do not include the indirect annual water demand associated with feed production. The predicted numbers are based on recent trends in the livestock changes, So there is a large uncertainty to get an estimation in 2050. The poultry and pig numbers will likely balance out when the population in the Red River Basin also levels out, in other words the water demand will not keep increasing with the current values.

6.4. Land use changes

The change of land use has an influence on water and land availability for agriculture. An overall overview of land use change and the coverage in the Red River - Thai Binh Basin is discussed in 3.4.3. Land use changes in river basins are reducing the ability to regulate river flows, decreasing the proportion of water bodies, reducing surface water resources, and reducing groundwater recharge during the rainy season. The increasing groundwater depletion during the dry season puts even more pressure on existing water resources. Farmers will face more uncertainty in water security due to changes in land use. Therefore, it is important to take into account the changing land cover. Effective regulation of water resources and river basin flows in Vietnam remains challenging due to institutional limitations and insufficient coordination between water management and land use planning (Q.-N. Pham, Nguyen, Ta, & Tran, 2023).

6.5. Water availability for Agriculture

6.5.1. Water supply

Table 6.6 summarizes the estimated annual water demand per sector. Agriculture accounts for the largest share of total water consumption, while aquaculture and livestock account for significantly smaller proportions. Figure 6.5 illustrates the percentage contribution of each sector to the total water demand for both the current situation and the 2050 scenario.

Sector	**2024(km^3/y)**	**2050(km^3/y)**
Agriculture	6.2	7.2*
Aquaculture	1.615	2.4*
Livestock	1.951	5.024
Total	**9.766**	**14.624**

Table 6.6: Estimated annual water demand by sector in the Red River Basin.

*The 2050 value is chosen for RCP4.5 since this is the most likely scenario, which has a moderate emission pathway.

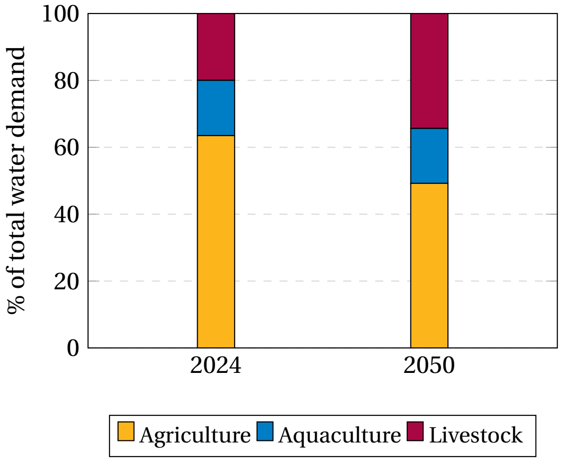


Figure 6.5: Percentage contribution of each sector to total water demand for the current situation and the 2050 scenario.

To meet irrigation demand, farmers obtain water from several sources:

1. Surface water (rivers and canals)
2. Reservoir releases (regulated surface water)
3. Shallow groundwater (renewable aquifer)
4. Deep groundwater (limited and slowly replenished aquifer)
5. Direct precipitation (rainfall contribution)
6. Irrigation scheme supply (pumping stations and canal systems)

Other potential sources, such as desalinated water and Public Water Supply Facilities, are not used for irrigation in the Red River Basin.

6.5.2. Groundwater extraction for Agriculture

The distribution between water supply was visible in Chapter 3 system characteristics, in the Section groundwater extraction 3.4.4. Concluded from this, more than half of the people use groundwater extraction as their water supply. Table 6.7 shows more detailed numbers on where water extraction rates are shown. Notable is that domestic wells also play a big role in the extraction. Domestic wells most of the time are not well monitored or controlled, which easily results in an imbalance of the groundwater recharge and extraction. Farmers pump water when they need it, especially during dry periods. During these periods groundwater is not being recharged by precipitation with overexploitation as result. These numbers are mostly likely an estimate, since not all pumping rates from farmers are known as well as the amount of wells in use. In the same paper groundwater modelling with MODFLOW was executed. With the recharge based on rainfall, irrigation return flow and waste water, shown in figure 6.6.

Province/city	**Extraction (m^3/day)**		
	Industrial wells	**Domestic wells**	**Total**
Hanoi	670931	124180	795111
Vinh Phuc	25900	52361	78261
Hung Yen	114490	7800	122290
Bac Ninh	42000	55118	97118
Hai Duong	18200	64259	82459
Ha Nam	5508	24492	30000
Hai Phong	-	-	34000
Thai Binh	9546	39454	49000
Nam Dinh	-	-	120000

Table 6.7: The extraction of groundwater per Province in the Red River Delta, for domestic wells and industrial wells (V. H. Le et al., 2024b)

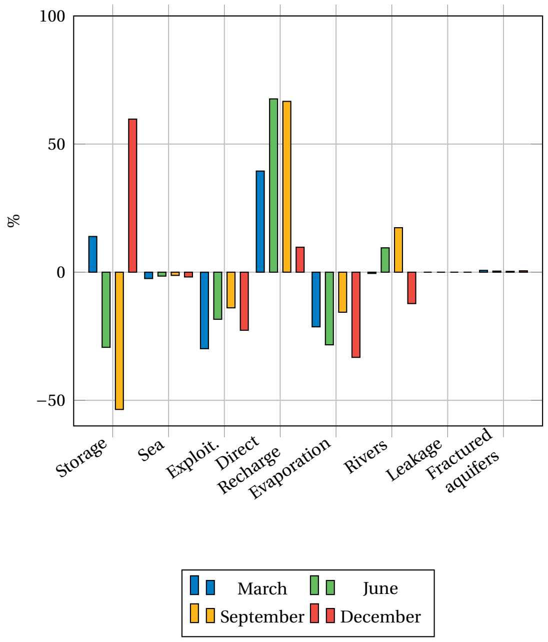


Figure 6.6: Distribution of Groundwater Balance components. Inflow and outflow are shown by positive and negative percentages for that period of time (V. H. Le et al., 2024b).

Following from the same paper, the groundwater balance assessment results in:

- Rainy season recharge: 5 607 868 m^3/day
- Dry season recharge: 664 326 m^3/day

According to V. H. Le et al. (2024b) the total estimated water extraction per day is 1 408 239 m^3, remaining roughly constant throughout the year. Showing an imbalance during the dry period:

$$\begin{aligned} 664\,326 - 1\,408\,239 = -743\,913\ \mathrm{m}^3/\mathrm{day} \\ Groundwater_{\mathrm{extraction}} \approx 2.1 * Recharge \end{aligned} \tag{6.1}$$

With the large seasonal fluctuations in groundwater recharge (4 943 542 m³/day) there is a lot of uncertainty in groundwater availability. This dry-period imbalance in recharge and extraction results in storage depletion and the formation of depression cones (3.4.4) across the delta V. H. Le et al. (2024a).

6.5.3. Irrigation and declining water levels

In the upstream regions of the Red River - Thai Binh basin, farmers are often able to irrigate their fields using gravitational flow. Precipitation in the higher elevations is captured through locally constructed irrigation systems consisting of pipes, small channels and storage tanks. These systems transport water from higher parts of the catchment towards agricultural fields located further downstream.

However, the efficiency of these irrigation systems is generally low. Water distribution is often poorly controlled, which means that water continues to flow even when fields no longer require additional irrigation (Figure 6.7a). In addition, infrastructure is frequently poorly maintained (Figure 6.7b). The photographs were taken near the town of Sapa, located in the mountainous upstream region of the Red River basin.

In this area, households also maintain small aquaculture ponds for domestic use (Figure 6.7c). While these ponds contribute to local food production, they may further increase water demand in a region where water availability is already seasonally constrained.

(a) Drowned rice field due to uncontrolled irrigation.

(b) Broken irrigation tube causing water losses.

(c) Small aquaculture basin in upstream Sapa.

Figure 6.7: Examples of inefficient water use in upstream agricultural systems near Sapa. Photo by the author.

Further downstream, around Hanoi and in the lower parts of the basin, irrigation conditions are different. These areas largely depend on regulated discharge from upstream dam operations. In addition the water levels are further influenced by riverbed lowering. Over the past decades, river water levels in the middle and lower reaches of the Red River system have dropped by several meters. Due to the low topographic gradient in the delta, the natural head difference between rivers and agricultural land is often insufficient for gravity-driven irrigation. Consequently, pumping stations are required to lift water (higher) from the river system to the surrounding agricultural fields.

Lower water levels reduce the operational capacity of pumping stations. For example, the Phu Sa pumping station was designed to operate at a river water level of 5.25 m. However, during the spring crop season of 2017, the average water level was only 3.38 m. When water levels fall below operational thresholds, entire irrigation systems may fail. In extreme cases, up to 233,400 hectares of farmland across 12 provinces in the Red River Delta could face drought conditions VietnamNet (2017). Consequences of declining river water levels include:

- Increased energy demand for pumping
- Greater reliance on groundwater extraction
- Higher risk of saline intrusion in coastal areas
- Reduced navigability of rivers
- Increased pollutant concentrations due to lower dilution capacity

VietnamNet (2017)

At the same time, land subsidence (see Chapter Environment, section 7.3) alters the local hydrological dynamics. Water may accumulate in low-lying areas where drainage becomes difficult, while peak run off can occur more rapidly after rainfall events. This results in a shorter hydrological response time and higher peak discharges, requiring additional pumping capacity to remove excess water. A conceptual illustration of this response behaviour during rainfall events is shown in Figure 6.8, adapted from Oke, Mills, Christen, and Voogt (2017).

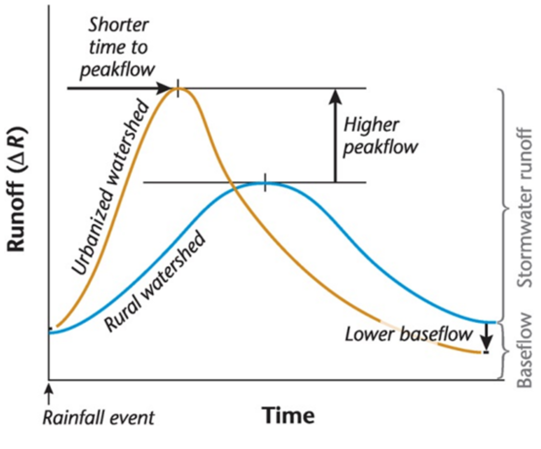


Figure 6.8: Change in peakflow discharge and response time for different watersheds. Oke et al. (2017)

6.5.4. Changing climate and changing demands

The report from T. Pham, Ludwig, et al. (2022) applies the Global Change Assessment Model (GCAM) to estimate future water demand in the basin. In this model, agricultural and aquaculture water demands are calculated using the following formulations:

$$W_{\text{irr}} = ET_c + L_{\text{prep}} + P_{\text{rep}} - P_{\text{eff}} \tag{6.2}$$

$$W_{\text{aq}} = EP_c + S_{\text{prep}} - P \tag{6.3}$$

Where irrigation demand depends on crop evapotranspiration, land preparation requirements, percolation losses and effective precipitation, while aquaculture demand depends on pond evaporation and preparation water.

In addition to these demand equations, the GCAM framework incorporates several input variables. These include socio-economic drivers such as population growth and urbanization (downscaled to the basin level), sectoral water consumption for rural, town and urban areas, and climate variables such as precipitation, temperature, solar radiation and humidity. Water supply sources include renewable surface water, renewable groundwater, non-renewable groundwater, and desalinated water. Future projections are simulated using different climate scenarios (RCPs) and socio-economic pathways (SSPs).

The results are illustrated in Figure 6.9. Each point represents a projected scenario for 2050, with colours indicating different Representative Concentration Pathways (RCPs). The horizontal axis shows the change in temperature relative to historical conditions, while the vertical axis represents the ratio between future and historical precipitation. The colour scale indicates the resulting water demand. Scenarios with higher temperature anomalies generally correspond to higher irrigation water demand, as increased temperatures enhance evapotranspiration. Consequently, the highest water demands occur under the RCP8.5 scenario, which is associated with the largest projected temperature increases in the model ensemble. The figure illustrates how combined changes in temperature and precipitation influence water demand in both agriculture and aquaculture.

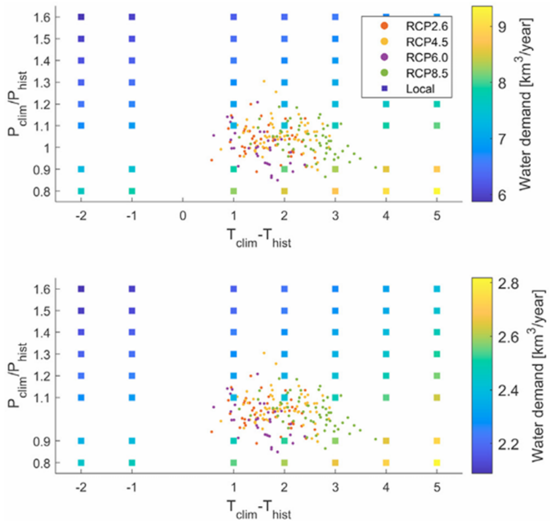


Figure 6.9: rojected water demand in the Red River Basin for different climate scenarios towards 2050. Each point represents a scenario characterized by temperature change relative to historical conditions ($T_{clim} - T_{hist}$) and the precipitation ratio (P_{clim}/P_{hist}). Colors indicate the resulting water demand. Source: T. Pham et al. (2022). T. Pham et al. (2022)

Based on these projections, and considering the currently observed decline in agricultural land area in the Red River Delta, the long-term outlook for water demand can be summarized as follows. Although agricultural water demand is projected to decrease due to increased precipitation and a reduction in cultivated area, total water demand in the Red River Basin is expected to increase significantly towards 2050. This increase is mainly driven by urbanization (population growth), economic development and the expansion of water-intensive sectors such as aquaculture. Combined with the already documented seasonal groundwater deficits, this trend suggests increasing competition between water-use sectors, particularly during dry-season conditions.

The water demand for agriculture in 2050 is projected to range from 5.9km^3/y - 9.4km^3/y, Aquaculture 2.1km^3/y - 2.8km^3/y.

6.6. Natural Hazards

Food production in the Red River - Thai Binh basin is exposed to climatic extremes. The area is characterized by strong seasonality in precipitation as already known, with approximately 70–80% of annual precipitation occurring during the monsoon period (May–October), and a pronounced dry season from November to April. Natural hazards affecting food production in the Red River -THai Binh basin include:

- Seasonal droughts
- Riverine and pluvial flooding
- Typhoons and tropical storms
- Saltwater intrusion in coastal areas

These hazards interact with increasing water demand, land-use change, and groundwater depletion, amplifying systemic vulnerability within the WEFE-Nexus and thereby increasing the risk of water scarcity and production losses in agricultural and aquaculture systems.

6.6.1. Seasonal Droughts

During dry months, extraction exceeds recharge, resulting in storage depletion and formation of depression cones (the circular area around a well where groundwater levels are influenced). Reduced river levels may limit pump station operability, increasing reliance on groundwater extraction. In years of severe drought, irrigation schemes operate below design capacity, raising pumping costs and energy consumption The drought impacts include:

- Yield reduction
- Increased salinity intrusion risk
- Vulnerability of irrigated systems (agriculture and aquaculture) and livestock water supply.

6.6.2. Riverine and pluvial flooding

While drought constrains dry-season production, the monsoon season brings flood risk. Monsoon season is characterized by extreme rainfall events and shortly after one another as explained in section 3.3.4. Depending on response time of the system and the state of the saturation degree of the soil, water levels and run off discharge may be high. Due to land subsidence and channel control (explained earlier), low lying areas are in danger of flooding. Flooding affects food systems differently as shown in Table 6.8.

Sector	Flood Impact
Rice	Submergence damage; lodging (breaking of the stems)
Vegetables	High sensitivity; crop loss; crop destruction
Aquaculture	Pond overflow; stock escape; cage destruction
Livestock	Infrastructure damage; disease spread

Table 6.8: Flood impacts by the agricultural sector

6.6.3. Saltwater Intrusion

In coastal provinces of the delta, dry-season low river discharge facilitates saline intrusion as explained in Chapter Water, section 4.4. Saltwater intrusion leads to:

- Reduced freshwater irrigation quality
- Soil salinization
- Constraints for freshwater aquaculture

- Livestock drinking water stress

This risk increases when upstream discharge is insufficient and when groundwater extraction lowers piezometric heads. Flood events combined with saltwater intrusion in the Red River Delta contaminated roughly 40 000 hectares of farmland and caused food losses exceeding 100 000 tons, during the period 1976–2005 (Neumann, Emanuel, Ravela, Ludwig, & Verly, 2015).

6.6.4. Typhoons and Tropical Storms

Northern Vietnam experiences several tropical storms annually. Impacts on food production include:

- Wind damage to crops (destruction of vegetation)
- Infrastructure destruction (pond dikes, livestock sheds, cages, rice field cascades)
- Coastal aquaculture loss due to waves
- Disruption of transport and markets

Aquaculture is particularly vulnerable to dyke failure and sudden salinity fluctuations during storm surges.

6.7. WEFE-Nexus relations

This section demonstrates that food production in the Red River Basin is strongly interconnected with water availability, energy use and environmental conditions. These interactions form several feedback mechanisms within the WEFE-Nexus.

Water → Food

- Water availability is a key determinant of agricultural productivity in the Red River Delta. Declining river water levels reduce the ability of irrigation systems to operate using gravity-fed intake. As a result, irrigation systems increasingly depend on pumping to deliver sufficient water to agricultural fields.
- Lower river discharge also facilitates saltwater intrusion in the coastal parts of the delta. Salinity intrusion reduces freshwater availability for irrigation and degrades soil quality, limiting crop productivity and constraining freshwater aquaculture systems.
- Seasonal droughts further exacerbate water scarcity during the dry season. When river discharge and groundwater recharge are insufficient, irrigation schemes may operate below design capacity. This directly affects the agricultural output.

Food → Water

- Agricultural intensification increases pressure on water resources. Irrigated rice cultivation, aquaculture expansion, and livestock production all require significant volumes of water. As demand grows, farmers increasingly rely on groundwater extraction to supplement surface water shortages.
- Agricultural activities also influence water quality (see also 4.4. Run off containing fertilizers, livestock waste, and agricultural residues can enter rivers and canals, leading to nutrient pollution and reduced water quality. This degradation further limits the availability of clean water for irrigation and domestic use.

Food → Energy

- Agricultural production also drives energy demand. Irrigation pumping, mechanization of farming practices, and fertilizer production all require significant energy inputs. As irrigation systems rely more heavily on pumping, the energy consumption of the agricultural sector continues to increase.

Energy → Food

- Food production in the delta increasingly depends on energy availability. Declining river water levels require irrigation systems to rely on pumping stations to supply water to agricultural fields. Without sufficient energy supply, irrigation infrastructure cannot operate effectively, directly affecting agricultural productivity.
- In low-lying areas of the delta, pumping is also required to drain excess water after heavy rainfall events. This demonstrates the growing dependence of agricultural production on energy-intensive water management infrastructure.

Environment → Food

- Environmental changes strongly affect food production in the basin. Land subsidence caused by groundwater extraction alters local hydrological conditions, increasing flood risk in low-lying agricultural areas and facilitating saltwater intrusion in coastal zones.
- Extreme weather events such as typhoons can damage crops, destroy aquaculture ponds and disrupt livestock production systems. These environmental pressures reduce agricultural productivity and increase vulnerability of food systems.

Food → Environment

- Food production can also affect environmental conditions. Intensive agricultural practices often involve increased fertilizer use and livestock waste production. These substances can enter rivers through run off, contributing to water pollution and ecosystem degradation.
- Excessive groundwater extraction for irrigation contributes to groundwater depletion and land subsidence. These environmental changes may ultimately feed back into the agricultural system by reducing land productivity and increasing flood and salinity risks.

7

Environment

This chapter focuses on the environmental dynamics of the Red River - Thai Binh basin and the impacts of climate change and human activities on the natural system. First, processes of erosion are discussed (7.1), including soil erosion (7.1.1, river erosion (7.1.2) and coastal erosion (7.1.3). Subsequently, Section 7.2 addresses landslides and Section 7.3 land subsidence, which are increasingly observed in the basin. Section 7.4 explores soil and water quality. Finally, impacts on biodiversity are discussed in Section 7.5. Section 7.6 concludes the chapter by highlighting the key interactions between environmental processes and the other components of the WEFE nexus.

7.1. Erosion

Under natural conditions, there is a dynamic balance between sediment supply and erosion. However, climate change and human interventions have increasingly disrupted this balance, resulting in a net increase in erosion in the Red River - Thai Binh basin (T. P. Q. Le, Le, Dao, et al., 2018). These changes in erosion rates are reflected in different processes across the basin, including soil erosion in the mountainous areas, erosion within the river system, and coastal erosion along the deltaic coastline.

7.1.1. Soil erosion

As described in Section 4.2, the mountainous northern part of the basin is prone to flash floods due to intense rainfall events. In addition, expansion of agriculture has contributed to widespread deforestation in the basin (Section 3.4.3) resulting in a loss of vegetation. Vegetation loss reduces the infiltration capacity of soils and increases surface run-off. Ranzi, Le, and Rulli (2012) demonstrated that by converting 35% of forest area into agricultural land, sediment production could increase to 28%. This increase can be explained by the higher surface run-off flowing over steep slopes, which enhances the detachment and transport of soil particles and thereby intensifies soil erosion (Wang et al., 2016).

7.1.2. River erosion

As described in Section 4.3, both dams and sand mining trap sediments and reduce sediment concentration in downstream parts of the Red River (Le Van, Ranzi, & Rulli, 2018). Sediment starved water, or so-called 'hungry water', creates severe erosion of the riverbed because the flow is not saturated with sediment and therefore erodes and entrains sediment from the river's bed and banks (Motta & Koehler, 2025)(Quang et al., 2024).

From 2000 till 2018, Quynh, Hieu, Dang, Quang, and To (2020) observed this continuous riverbed incision:

- Red River: 0.81-4.22 m lowering

- Duong River: 3.3-6.67 m lowering

The stability of a river channel can be assessed using the ratio between channel width (B) and average depth (h), expressed as the B/h ratio. Riverbed incision increases the average depth (h) of the channel, resulting in a decrease of the B/h ratio over time (Quynh et al., 2020). Besides this, the 'hungry water' further destabilises the river channel by undercutting the base of the riverbank (Rentier & Cammeraat, 2022)(G.J. Klaassen, 2005). This destabilisation can lead to the collapse of riverbanks, which in turn results in a widening of the river channel. Along the Da River, both the left and right riverbanks have been observed to erode at rates of approximately 8 cm per year (Quang et al., 2024). In addition, the riverbank can further erode in the downstream reaches by stronger flow velocities associated with tidal amplification, as described in Section 4.4.

7.1.3. Coastal erosion

As discussed in the previous sections Red River system contains sediment starved water. This results in less sediment being transported to the delta and deposited along the coast, leading to an increased sediment deficit and enhanced coastal erosion. In addition, sea-level rise contributes to shoreline retreat. Estimates suggest that sea-level rise alone may increase erosion rates by approximately 0.14-0.31 m per year. Furthermore, tropical cyclones frequently affecting the region can increase the coastal erosion rate as well, with 7.1 m when the wave height is 4.25 m and the duration is 2.4 hours (Nhuan, Van Ngoi, et al., 2012). Human activities like land reclamation also disturb coastal dynamics, adding to the coastal erosion (Ve, Fan, Van Vuong, & Lan, 2021).

7.2. Land slides

Extreme rainfall, typhoons and flashfloods, described in Sections 3.3.3, 3.3.4 and 4.2, could act as important triggers for landslides (B. T. Pham, Prakash, & Bui, 2018). These mechanisms trigger rapid water infiltration into slopes, which increases the pore water pressure and therefore changes the stress distribution within the slope. This rapidly reduces slope stability and therefore causes landslides (Zheng et al., 2025). As described in Section 3.1.1, the mountainous region of the Red River - Thai Binh basin is vulnerable to these landslides because of its steep slopes and V-shaped valleys.

Figure 7.1: Landslide observed during a field visit to the Hmong Hoa valley.

Recent events illustrate the scale of this hazard. Following extreme rainfall between the 4th and 6th of August 2023, Toan, Duc, Quynh, Khang, and Van Dong (2025) identified 346 landslides in Ho Bon commune in Yen Bai province. Typhoon Yagi in 2024 triggered the Lang Nu landslide in Lao Cai province, a deep and rapidly moving landslide that caused 60 fatalities and destroyed 37 houses (Tien et al., 2025). Figure 7.1 shows an example of a landslide observed during a field visit to the Hmong Hoa valley.

7.3. Land subsidence

Section 3.4.4 discusses the extent of groundwater extraction in the Red River - Thai Binh basin. When groundwater extraction occurs in an uncontrolled way, it can lead to land subsidence. Considering an aquifer system, the subsidence mechanism from exploiting groundwater will be briefly explained by four steps according to (Kulasza, 1983).

1) When pumping from a well, water levels are lowered. This is called the cone of depression. Now, within the pores of the sediments from which the groundwater is withdrawn, the water pressure decreases. Because the water pressure in the pores helps support the weight of overlying sediments or buildings constructed on top of the soil, the decrease of pore pressure causes more of the weight of the overlying sediments to be transferred to the intergranular skeleton of the sediments. In other words, the sediments compresses and pores now filled with air are (partly) filled with sediments.

2) Clay and silt beds, that is, aquitards, in aquifer systems commonly are very compressible and will compact when the weight of the overlying sediments is transferred to the intergranular skeletons. Compaction is essentially irreversible. Water level recoveries will not cause the clay and silt beds to expand to their original thickness. Compaction may lag years behind water-level declines measured in sand beds because it may take years for water to drain out of aquitards.

3) As an aquitard compacts, the sediment and land surface above the aquitard move vertically downward. The land subsidence equals the amount of compaction because the lateral extent of aquitards typically is much greater than their depth.

4) Confined aquifers compact more than unconfined aquifers given equal declines of water level.

This phenomenon can also be observed in Hanoi, where cumulative land subsidence has reached up to 23.1 cm (Q. Zhao et al., 2025). Land subsidence has several important consequences. First, water obtained from clay and silt beds during their compaction is a limited water resource because the compaction process is irreversible. In addition, the lowering of the land surface increases the risk of flooding and amplifies the impacts of relative sea-level rise, particularly in low-lying areas near surface water bodies.

7.4. Soil and water quality

Section 3.4.3 describes that between 2000 and 2020, the area used for agriculture decreased, while the area of settlements increased. This indicates that more food needs to be produced while agricultural land becomes more limited. To compensate for this, farmers are practising more intensive agriculture. This intensification, combined with rising temperatures, increases the occurrence of pests and diseases. At the same time, soil quality declines due to reduced sediment deposition. This all together causes farmers to rely more on pesticides and fertilisers. These chemicals contribute to the pollution of surface water, groundwater, and surface sediments (Yuen et al., 2021). T. Le et al. (2022) showed that the sediments of the Red River are influenced by both natural characteristics and human activities within the basin. Their results indicate that the sediments are polluted by As and moderately polluted by Cu, Pb, Cd, and Hg. Untreated domestic and industrial wastewater continues to degrade the quality of water ((VietnamPlus), 2025). Tham et al. (2022) investigated water quality in the Red River delta. Although water quality was generally classified as moderate to good at most locations, several sites located near health facilities and industrial zones were found to be heavily polluted. Salt intrusion, mentioned in Section 4.4, also further degrades the quality of water.

7.5. Biodiversity

In addition to pollution, the Red River delta's ecosystem is also experiencing a decline in biodiversity. While the delta used to host many bird species, mangrove forests and aquatic plants and animals, human activities, such as agriculture, industry and construction, have destroyed many natural habitats (Thanh, 2003) (Pedersen, Thang, Dung, & Hoang, 1996). Saltwater intrusion also degrades wetland ecosystems by killing less salt-tolerant species and increasing soil salinity, which decreases habitats for birds, fish and other animals (USDA, n.d.). More upstream, hydropower plants fragment ecosystems and thereby threaten several species, like rhinos and monkeys (Carew-Reid, Kempinski, & Clausen, 2010). Besides this, the reforestation efforts mentioned in Section 3.4.3 often involved planting the same tree species, resulting in monocultures. Such monocultures reduce habitat diversity and lead to a decline in biodiversity.

7.6. WEFE Nexus relations

To conclude this chapter, the main WEFE nexus relations between the environment and the other pillars are summed up:

- Hydropower dams and sand mining reduce the sediment supply in the river system, creating sediment-starved water that increases riverbed and coastal erosion and alters the morphology of the river.
- Deforestation associated with agricultural expansion reduces vegetation cover and infiltration capacity, increasing surface run-off and thereby raising the amount of soil erosion and landslides in mountainous areas.
- Groundwater extraction lowers groundwater levels and leads to compaction of aquifer sediments, resulting in land subsidence.
- Urbanisation and more intensive agricultural practices increase the use of fertilisers and pesticides, contributing to the pollution of surface water, groundwater and soils.
- Increased saltwater intrusion and the construction of dams degrade natural habitats and fragment ecosystems, contributing to a decline in biodiversity.

8

Actor Scan

This chapter provides an overview of the key actors within the North Vietnam WEFE nexus policy arena. The goal is to establish which actors are relevant and must be accounted for in the broader system analysis. This is particularly important given that Vietnam's political and governance structures differ significantly from those of countries like the Netherlands.

The chapter first looks at the governance structure of Vietnam and then at what actors are relevant, with a brief description. Subsequently, a Power-Interest Grid and analysis is done that gives an overview of the influence of the different actors on the arena. Note that the actor descriptions are brief and are meant to give a general idea of the actor rather than going into detail about how and what motivates them.

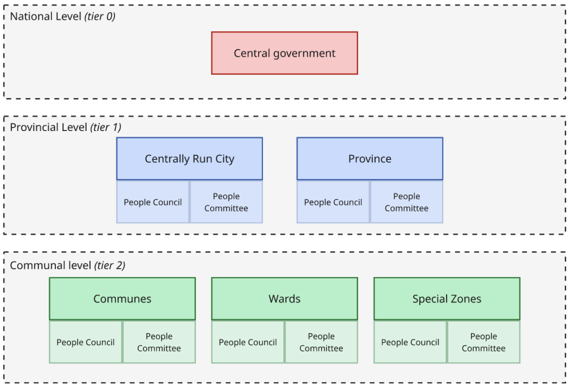


Figure 8.1: Two tier governance structure Vietnam based on (Vietnam News Agency, 2025)

8.1. Governance structure of Vietnam

Vietnam has recently drastically restructured its provincial governance. Moving from a three-tier system to a two-tier system. As stated earlier, the restructuring aims to reduce bureaucratic overhead and streamline administrative processes and efficiency (Vietnam News Agency, 2025). Vietnam's administrative units now comprise the provincial level (provinces and centrally managed cities) and the commune level (communes, wards, and special zones under the provincial level). Communes represent rural areas, wards correspond to urban zones, and special zones refer to strategically important islands tailored to geographic, demographic, and socio-economic needs as well as national defence and security (Thuong, 2025).

Each of the governmental units has a representative organ (People's Council) and an executive organ (People's Committee).

This new structure gives the provincial leaders more influence and allows them to directly intervene at the commune level. Beyond their current duties, provincial governments now have expanded powers, especially in issuing local policies related to planning, finance, budgeting, and investment, reflecting an ongoing decentralisation from central authorities (Thuong, 2025). Provincial governments are required to delegate responsibilities to commune governments, which will now handle both district and commune-level tasks. They are also empowered to issue legal regulations within their jurisdiction (Thuong, 2025). Some argued against reinstating People's Councils in wards, citing the efficiency of current urban models in Hanoi and Ho Chi Minh City. However, the Government confirmed that the inclusion of both councils and committees reflects Party directives and maintains a distinction between urban, rural, and island governance (Thuong, 2025). In the long run, this could result in a more efficient governance system, but in the short term this restructuring might cause uncertainty and vagueness as to which province or department has what specific tasks in what region.

8.2. Government Actors

This section concerns the ministries or national organisations that are relevant to the WEFE Nexus arena.

Vietnamese Communist Party (VCP)

Vietnam operates under a one-party system led by the Communist Party of Vietnam (CPV), which holds supreme authority over all state institutions. The CPV sets political direction, manages personnel, and exercises leadership through embedded party committees in every layer of government. Below the Party, the National Assembly functions as the highest formal state organ, responsible for legislation, electing key leaders, and supervising state activities. The State President serves as head of state and commander of the armed forces, while the Government, led by the Prime Minister, handles day-to-day executive administration (Vietnam Government Portal, 2026). The judiciary operates independently in hearings, but remains under the National Assembly's oversight. In practice, all institutions function within the boundaries established by the Party, making the CPV the true centre of power.

Ministry of Agriculture and Environment (MAE)

In 2025, Vietnam implemented a major government restructuring, merging the Ministry of Agriculture and Rural Development (MARD) with the Ministry of Natural Resources and Environment (MONRE) to form the Ministry of Agriculture and Environment (MAE). This consolidation also aims to streamline operations and improve the government's capacity to manage agricultural and environmental policies at the same time. It now covers water management, irrigation, food production, land use, and environmental protection in one ministry (Vietnam Government Portal, 2026). This means that the MAE is one of the most important actors in the decision-making arena since it oversees most of the WEFE Nexus sections.

Ministry of Industry and Trade (MOIT)

This Ministry is responsible for energy policy, electricity regulation, and industrial water use. It oversees the national electricity company, EVN, and sets the national energy strategy. The tension between MOIT's hydropower expansion goals and MAE's water management mandate could be one of the most important governance dynamics for further analysis. (Vietnam Government Portal, 2026)

Ministry of Planning and Investment (MPI)

The MPI sets the national development priorities and allocates budgets across sectors. This is relevant because it coordinates between ministries and determines which projects get funded (Vietnam Government Portal, 2026). This could have an influence on which project contributes to the Nexus and gets funding and will be realised. Smart spending is one of the foundations on which the WEFE nexus can be built.

8.3. Quasi-Government Actors

Quasi-Government Actors concern companies that operate independently but are owned by the state. This puts them in a position where these hybrid institutions hold a public purpose but with the flexibility of a private company.

Vietnam Electricity (EVN)

Electricity of Vietnam (EVN) is a state-owned enterprise with a central and at times dominant role in water-related decision-making. Since 1995, responsibility for hydropower development has gradually shifted to EVN. Today, EVN not only manages the national electricity grid but, through its subsidiaries, also operates hydropower and coal-fired power plants, together accounting for more than half of Vietnam's installed electricity generation capacity (Vietnam Electricity (EVN), 2024).

Irrigation and Drainage Companies

Irrigation management companies are responsible for the operation, maintenance, and oversight of hydraulic infrastructure within irrigation networks. Their core functions include ensuring reliable water delivery for agricultural use, managing drainage systems, preventing flooding, and collecting irrigation service fees in accordance with national regulations. These companies operate as state-owned entities.

The Bac Hung Hai irrigation system offers an illustrative example: it is governed by a central Irrigation & Drainage Management Company, with each province hosting a subsidiary or representative body responsible for overseeing local irrigation works (N. T. Hang, 2023).

However, the management of such complex systems is hampered by a range of institutional and operational deficiencies. Environmental oversight lacks dedicated departmental structures or specialist personnel. Waste source monitoring is conducted irregularly, compounded by inadequate equipment and insufficient technical expertise. Furthermore, no clear assignment of responsibilities or coordination mechanism exists between wastewater management units, relevant sectoral authorities, and local government bodies across administrative levels (N. T. Hang, 2023).

Farmers

Farmers are an important actor both within the Water-Energy-Food-Environment (WEFE) nexus and for Vietnam more broadly. The majority of Vietnamese farmers operate as small-scale individual holdings rather than larger commercial enterprises, making them particularly vulnerable to external pressures such as climate change and market volatility. To address this, farmers are organized into two distinct but complementary collective institutions: agricultural cooperatives, which function similarly to a business entity by pooling resources to support investment, market access, and climate resilience; and the Farmers' Union, which operates as part of the government structure and acts as an advocacy bridge between national authorities and individual farmers to represent their broader interests.

Farmers Cooperatives

Agricultural cooperatives are member-owned business organizations where farmers pool their resources collectively to access shared services such as bulk purchasing of inputs, collective selling of products, and shared equipment and technology.

A paper by Vu, Phi, Nguyen, and Tran (2023) looked at the role of these cooperatives in helping farmers adapt to climate change, specifically examining cooperatives in the Son La region in North West Vietnam. The study found that individual smallholder farmers face several barriers that prevent them from adapting on their own, including lack of finance, limited access to weather forecasting, poor knowledge of new farming techniques, and inadequate connections to markets and government support programs.

Cooperatives were found to address these barriers in four main ways: promoting environmentally friendly farming through certifications, introducing advanced technologies like drip irrigation and drought-resistant crops that individual farmers could not access alone, and acting as a bridge between farmers and government to channel funding and translate national policies into practical action on the ground.

Farmers Union

The Farmers' Union operates as a recognized part of the government structure, functioning primarily as a bridge between national authorities and individual farmers. Unlike cooperatives, which operate more like independent business entities focused on providing direct commercial services to their members, the Farmers' Union is an advocacy and political organization. Its main role is lobbying governments, negotiating with policymakers, and campaigning on issues that broadly affect the farming community, such as trade policy, subsidies, and land rights. While cooperatives tend to be locally or regionally organised around specific crops or production types, the Farmers' Union typically operates at a national scale, representing farmers across many sectors and ensuring their collective voice is heard at the highest levels of government.

Industrial Companies

Large industrial companies are a sword that cuts both ways. On the one hand, they drive the economy and produce on a large scale, but on the other hand they pollute the environment and water. A paper by Linderhof, Meeske, Diogo, and Sonneveld (2021) demonstrates how industrial run-off affects both water quality and food consumption patterns in Northern Vietnam, finding that "pesticides and fertiliser end up in surface water used for drinking water, crop irrigation, and in fish tanks," creating interconnected risks where water pollution influences food safety and consumption choices for the population.

They influence policy not directly through official channels but according to T. T. Nguyen (2022) they influence policy and decision making through non-compliance and causing environmental incidents that force policy adaptations.

8.4. International Development Institutions

This section concerns the actors who influence decision-making by conditionally investing money and assisting with country development.

World Bank

The World Bank Group is an international development organisation with 189 member countries. It works to reduce poverty and boost shared prosperity on a liveable planet by providing policy advice, technical expertise, and financing to the governments of low- and middle-income countries. As one of the world's largest sources of funding and knowledge for developing countries, it plays a key role in promoting sustainable development for people and the planet. The main goal of the World Bank is to help Vietnam achieve its high-tech ambitions and its goal of high-income status by 2045 (World Bank, 2025).

Asian Development Bank (ADB)

ADB is a leading multilateral development bank supporting inclusive, resilient, and sustainable growth across Asia and the Pacific. Working with its members and partners to solve complex challenges together, ADB harnesses innovative financial tools and strategic partnerships to transform lives, build quality infrastructure, and safeguard our planet (Asian Development Bank, 2024). The ADB is supporting Vietnam on climate-resilient transportation, sustainable urban development, improved rural connectivity, and poverty reduction in remote areas. The bank's assistance portfolio has also recently expanded to include sustainable coastal forest management, green transition policies, and enhanced private sector engagement. The support strategy of the ADB has two main pillars. The first pillar focuses on supporting Vietnam's transition to a green economy. The second pillar concentrates on harnessing the country's private sector and promoting social equity. The strategy is further supported by four cross-cutting priorities: gender equality, governance, digital transformation, and regional cooperation and integration (RCI). (Asian Development Bank, 2023). The ADB is especially relevant since its investment projects explicitly cover the Water, Food and Energy topics that are also relevant to the WEFE nexus.

Note On Development Banks

World Bank project documents are a useful source for identifying governance gaps in the Vietnamese WEFE nexus. When the World Bank designs a project, it has to justify why the intervention is needed, which means Project Appraisal Documents often explicitly describe institutional weaknesses, coordination failures, and policy gaps in the sectors they target. This could make them a practical tool for mapping governance gaps, particularly given the limited availability of transparent institutional assessments from Vietnamese government sources directly. Implementation Completion Reports are similarly useful, as they reflect on what did and did not work institutionally after a project has ended. Nevertheless, it is important to note that these development banks do not solely act with the greater good of Vietnam in mind but have their own agenda for the country as well. Therefore, it is important not see them as a neutral actor but rather a wealthy actor that uses its influence for its own gain while also helping developing countries.

8.5. International Actors

These actors concern international actors outside of Vietnam that still have influence in some form in the country.

China, Yunnan Province (upstream)

Vietnam has very limited leverage over China's upstream dam operations, despite significant downstream impacts. China shares little to no information about dam operations upstream, so Vietnam has a passive position in this. After the Sino-Vietnamese war, all cooperation stopped. The two countries restored official relations in 1991, but China has not resumed sharing of its hydro-meteorological data (L. Pham, 2021).

8.6. Power Interest gird

A Power Interest Grid is a visual representation of the actors in the policy arena and their ability to influence the decision-making process.

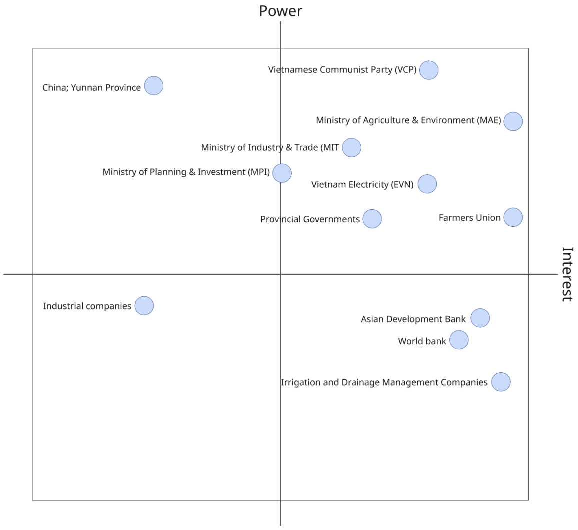


Figure 8.2: Power Interest Grid of key actors in the WEFE nexus of Northern Vietnam

High Power, High Interest: Core Decision-Makers

The highest authority in Vietnam is the Vietnamese Communist Party (VCP), which sets the country's direction and determines national priorities. Under its authority, the government operates through various ministries. Of the three ministries that influence the process, the Ministry of Agriculture and Environment (MAE) is the most important, as it oversees the largest share of the WEFE nexus and therefore holds the highest level of interest. The Ministry of Industry and Trade (MOIT) and the Ministry of Planning and Investment (MPI) hold similar levels of power but less interest, as they only influence the nexus indirectly and have other areas of focus. EVN holds significant power because it is responsible for the majority of the electricity grid, meaning smaller actors must operate within the conditions it sets. The Asian Development Bank and the World Bank both have interests and investments in Vietnam and want to see it succeed. They can influence decision-making through conditional investments in the country. Although provincial governments hold less formal power than the ministries, they have more direct influence on the WEFE nexus in practice, since they are responsible for implementing the laws and policies set at the national level.

High Power, Low Interest: Actors to keep satisfied
China's Yunnan Province and the Ministry of Planning and Investment (MPI) hold significant power but lower direct interest. MPI's influence over investment allocation means it shapes WEFE infrastructure indirectly, without necessarily prioritising nexus, which can disturb possible future Nexus Policy changes. Because of this, they need to be taken into account when making policy decisions. Yunnan's upstream dam operations on the Mekong/Red River directly affect downstream water availability in North Vietnam, yet it operates outside Vietnamese governance reach.

Medium Power, High Interest: Operational and Financial Actors
The Development Banks are important financing levers with growing sustainability mandates and potential allies for nexus-integrated investment. It is important to note that these banks are not necessarily working for the greater good and have their own agenda as well.

Low Power, High Interest: Small but Critical actors

Farmers and Irrigation and Drainage Management Companies are directly dependent on WEFE outcomes, yet hold minimal power. Farmers bear the consequences of water stress, shifting seasons, and food insecurity. Their low position signals a governance gap: end-users of the system are mostly excluded from decision-making, which undermines policy effectiveness in the long term.

Medium Power, Low Interest: Important but indifferent to the Nexus

Large industrial companies are important economic drivers but have limited direct interest in the WEFE nexus. Their main stake could grow in the future, however, if they are held more accountable for the environmental damage they cause. That said, it is important to keep them informed, as sudden policy changes could deter future investment in the country and slow economic growth.

9

Concluding Remarks

The WEFE Nexus literature shows that there is not one definitive methodology for assessing the interdependencies between water, energy, food, and the environment. Existing studies rely on various combinations of analytical methods, indicators, and modelling tools, but frequently suffer from practical limitations: many current Nexus tools are designed for large-scale or national application, lack spatial mapping capabilities, and fail to incorporate local stakeholder perspectives.

Because Nexus interactions are tied to specific geographic and environmental conditions, overly aggregated frameworks risk stripping away the detail required for actionable resource management. The literature therefore suggests that Nexus insights matter most at the local level, where communities, governance, and resource trade-offs physically intersect. These trade-offs shows in the literature are visible in both case studies.

Water systems are under pressure from altered river flows, reduced groundwater recharge, and changing precipitation, with Thac Ba managing highly variable inflows and Bac Hung Hai struggling to secure clean freshwater intake due to lowered riverbeds and saltwater intrusion. Energy production through hydropower is crucial for Vietnam's energy independence but carries severe trade-offs, including sediment trapping and disruption of river ecologies; the Thac Ba case illustrates the balance between maximising electricity generation and safely managing reservoir levels during extreme weather.

Food production depends heavily on the other pillars, and the Bac Hung Hai case shows how farmers' livelihoods and regional food security are increasingly threatened by declining water availability and pollution across its 110 000 hectares of irrigated crops and extensive aquaculture.

Environmental health underpins all three sectors but is degrading due to sand mining, deforestation, and chemical runoff, with Thac Ba facing landslides and erosion from extreme rainfall, and Bac Hung Hai suffering ecological degradation from untreated wastewater.

Moving from generalised Nexus studies to localised case studies makes it possible to gain a deeper system understanding without losing the unique information embedded in local contexts. Combining multiple case studies builds a detailed picture of each subsystem, which can then be integrated with broader system-wide knowledge, creating a multi-level understanding useful for both national policy makers and local authorities.

To bridge this gap between high and low level, the second part of the report uses two case studies in the Red River Basin: the Thac Ba reservoir and the Bac Hung Hai irrigation system. Together, these cases illustrate how the four Nexus pillars interact in a more localised setting, with the aim of understanding two very different parts of a larger system. By examining these contrasting contexts, it becomes possible to identify which WEFE indicators are most relevant in each setting and how they vary with local conditions. These insights can then be used to extrapolate to the broader context of the Red River–Thai Binh basin.

Thac Ba Case study

The Thac Ba region in Yen Bai province hosts Vietnam's oldest hydropower reservoir. The case study examines how the system balances hydropower, flood protection and agricultural water supply under climate change, combining water balance modelling, climate scenario analysis, and stakeholder mapping to assess WEFE trade-offs.

Bac Hung Hai Case study

The Bac Hung Hai system is the largest irrigation network in northern Vietnam, covering 215 000 hectares across four provinces and supporting 2.8 million people. The case study addresses growing water insecurity from pollution and scarcity, combining field surveys, actor analysis, water balance modelling, and system dynamics modelling to evaluate policy responses.

10

Thac Ba

10.1. Introduction

10.1.1. System characteristics

The Thac Ba reservoir, located in Yen Bai province in northern Vietnam, represents the oldest hydropower project in the country and plays a key role within the Red River Basin. The reservoir is fed by the Chay River, which originates in Ha Tao (China) and drains a catchment area of approximately 6,500 km^2, of which 1,920 km^2 lies within Chinese territory. The river has a total length of 319 km, with a mean basin elevation of 858 m and an average slope of 24.6% (UNESCO International Hydrological Programme, 2004).

Constructed in 1971, the Thac Ba dam created a reservoir with a storage capacity of 2.49 km^3 and an installed hydropower capacity of 120 MW, making it one of the largest reservoirs in the Red River Basin (EVNEIC, 2023; N.-T. Nguyen, Nguyen, Tran, Nguyen, & Pham, 2023). Beyond energy production, the reservoir supports multiple functions, including flood regulation, downstream water supply, aquaculture, and emerging ecotourism activities.

The system boundaries adopted in this study encompass the entire upstream Chay River catchment, as illustrated in Figure 10.1b. This boundary captures the key hydrological processes governing reservoir inflow, including precipitation, runoff generation, and upstream land use dynamics. While the downstream area up to the confluence with the Lo River (approximately 30 km) is not included in the quantitative analysis, it is considered in the stakeholder perspective to assess the impacts of reservoir operations on downstream communities.

The local economy in the region is primarily based on small-scale agriculture, with approximately 42.5 × 10^3 ha of rice cultivation and 2.6 × 10^3 ha of aquaculture (General Statistics Office & United Nations Population Fund, 2019). These activities are highly dependent on water availability and are therefore directly influenced by reservoir management.

10.1.2. Problem statement

The Thac Ba reservoir system is increasingly challenged by the need to balance multiple, and often competing, functions within a context of growing hydrological variability. While hydropower generation remains the primary operational objective, reservoir management must simultaneously ensure downstream water availability, flood protection, and support for local livelihoods.

Climate change is intensifying this challenge by amplifying both hydrological extremes and system uncertainty. During the wet season, increased frequency- and intensity of rainfall events, combined with upstream landslides, lead to higher sediment inflows and elevated risks of extreme reservoir levels and potential dam safety concerns (SGGPO, 2024)(Toan et al., 2025). These conditions require careful regulation of reservoir storage to prevent downstream flooding while maintaining structural safety.

Conversely, during dry periods, reduced inflows constrain water availability, forcing trade-offs between hydropower production and water releases for agricultural and domestic use. In extreme cases, reservoir levels may fall below the threshold required for electricity generation (EVNEIC, 2023).

These dynamics highlight a fundamental WEFE Nexus challenge: optimizing reservoir operation under increasing climate variability while balancing water, energy, food, and environmental objectives. As such, the Thac Ba system provides a representative case for analysing cross-sectoral trade-offs in hydropower-dominated river basins.

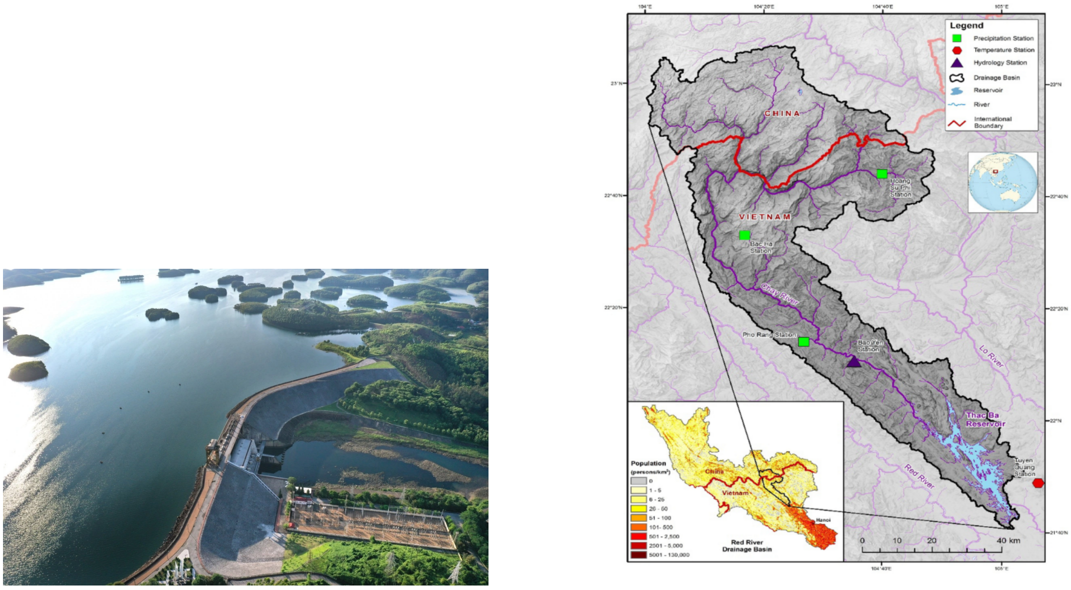
10.1.3. Simplified Causal Loop Diagram (CLD)

To structure the analysis, a simplified Causal Loop Diagram (CLD) was developed to conceptualize the key feedback mechanisms within the system (Figure 10.1c). The CLD synthesizes insights from the preceding literature research and identifies the main interactions between hydropower generation, climate change, reservoir dynamics, agricultural production, and local socio-economic conditions.

A central feature of the diagram is the reinforcing loop (R1), in which population dynamics influence local income, which in turn affects population growth and regional development. At the same time, climate change acts as an external driver, intensifying both droughts and extreme precipitation events, thereby propagating impacts across the water, energy, food, and environment sectors.

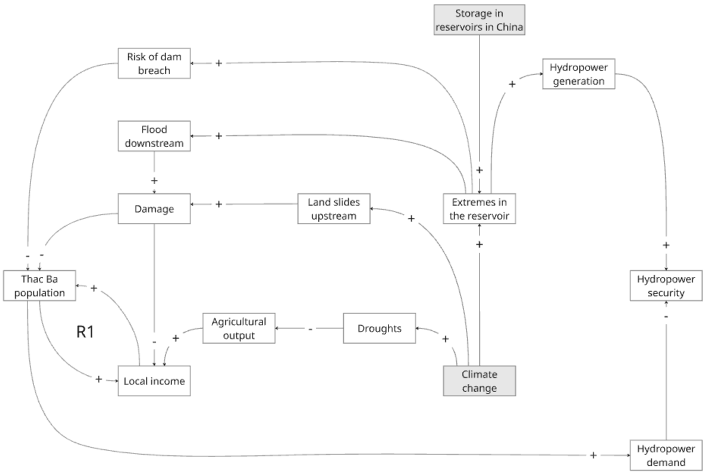
The CLD serves as a guiding hypothesis for the subsequent analysis. Based on this conceptual framework, a combination of methods is applied, including a water balance model, scenario analysis, and stakeholder analysis. These approaches are used to evaluate the strength and relevance of the identified relationships and to assess system behaviour under different future conditions.

The following sections present the methodology, results, and discussion of this integrated assessment.



(a) Thac Ba dam (VOV, 2024)

(b) System map (N.-T. Nguyen et al., 2023)



(c) Causal Loop Diagram

Figure 10.1: Overview of the Thac Ba system

10.2. Methods

10.2.1. Water balance

The objective of this model is to simulate the monthly water balance of the study area, including reservoir storage dynamics and groundwater fluxes. This provides insights into how water availability influences energy production and food systems.

For the water balance, the following principle is used:

$$\Delta S = P - ET - Q \tag{10.1}$$

The system is conceptualised as a two-reservoir model consisting of a groundwater storage and a reservoir storage. Precipitation is partitioned into two components: rapid surface runoff contributing directly to the reservoir storage, and groundwater recharge contributing to the groundwater storage. When the groundwater storage reaches its maximum capacity, excess water is generated and routed to the rapid runoff component. In addition, a baseflow from the groundwater storage contributes to the reservoir storage.

The outflows from the system consist of evapotranspiration from the groundwater storage, as well as evaporation losses and dam discharge from the reservoir. The model schematisation is shown in Figure 10.2.

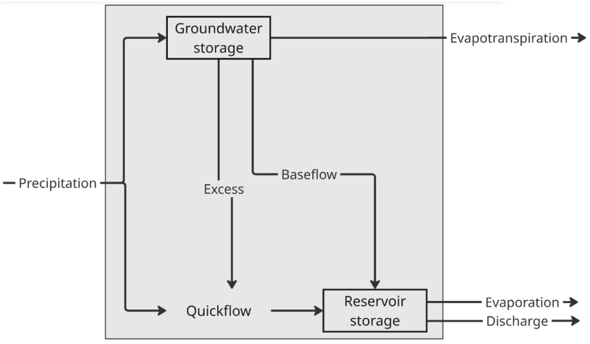


Figure 10.2: Schematisation water balance model

The precipitation partitioning is controlled by a dimensionless factor α, representing the fraction of precipitation contributing to groundwater recharge, while the remaining fraction contributes to rapid surface runoff.

The groundwater storage is updated according to:

$$S_{GW,t+1} = S_{GW,t} + \alpha P_t - Q_{BF,t} - ET_t \tag{10.2}$$

Baseflow from the groundwater storage is calculated using an exponential recession function:

$$Q_{BF,t} = S_{GW,t}\left(1 - e^{-k}\right) \tag{10.3}$$

The reservoir storage is updated as:

$$S_{R,t+1} = S_{R,t} + P_{quick,t} + Q_{BF,t} - E_t - Q_{out,t} \tag{10.4}$$

In these equations, S_{GW} is the groundwater storage, S_R is the reservoir storage, P is precipitation, P_{quick} is the rapid runoff component of precipitation, Q_{BF} is the baseflow from groundwater to the reservoir, ET is evapotranspiration from the groundwater storage, E is evaporation from the reservoir, and Q_{out} is the dam discharge. The parameter α is the precipitation partitioning factor, k is the baseflow recession constant, and t denotes the discrete time step. All storages and fluxes are expressed in units of water depth [mm] per time step, representing spatially averaged values over the catchment area.

Input data

The precipitation, evaporation and evapotranspiration data are derived from daily remote sensing products. Multiple datasets are combined to reduce uncertainty and account for dataset-specific biases. Climate data were accessed and processed using the Climate Engine platform (Climate Engine, 2026) ; (Huntington et al., 2017). Precipitation data are obtained from CHIRPS (Funk et al., 2015), ERA5 (European Centre for Medium-Range Weather Forecasts (ECMWF), 2023), and TerraClimate (Abatzoglou et al., 2018), while evapotranspiration is derived from FLDAS (NASA Goddard Space Flight Center, 2020), GLEAM4.2 (Miralles et al., 2025), and TerraClimate (Abatzoglou et al., 2018). Evaporation data are obtained from WaPOR (FAO WaPOR, 2023).

Observed reservoir storage is derived from water level measurements Nguyên (2021). This is done using an empirical storage–elevation relationship. This relationship is based on data provided by reservoir operation guidelines (Prime Minister of Vietnam, 2019b).

The outflow of the reservoir data is obtained from observed data from Nguyên (2021).

Parameters

Furthermore, some parameters that were used can be found in Table 10.1

Parameter	**Description**	**Value**
α	Land fraction	0.9
k	Recession constant	0.06
$GW_{\max}$	Maximum groundwater storage	70 mm
k_{ET}	Hargreaves calibration coefficient	0.0023

Table 10.1: Model parameters

The infiltration factor is based on the area covered by water bodies. The area of our catchment covered by waterbodies is estimated at around 10%.

The recession constant is 0.06 based on research from Beck et al. (2013).

The maximum groundwater storage is assumed by taking the first 10 cm of the ground and assuming it can be filled with water for 70%.

The Hargreaves equation is used for the potential evapotranspiration (based in differences between daily maximum and minimum air temperature), the equation also includes a calibration coefficient which is 0.0023 (k_{ET}), determined by Hargreaves and Samani (1985)

The model is initialised with a start storage known from data and a groundwater storage of half the GW_{max}.

Validation

This model is validated using the observed data, as can be seen in Graph 10.3. After this, the data is aggregated monthly.

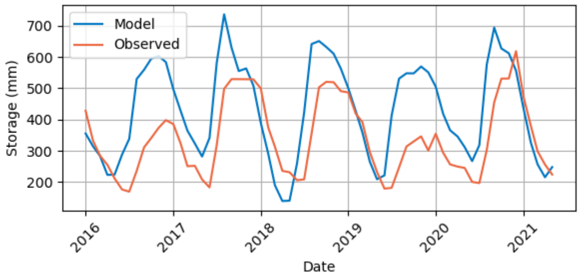


Figure 10.3: Validation

Water Stress Index (WSI)

To assess water availability and potential water stress in the system, a Water Stress Index (WSI) is calculated. The WSI is defined as the ratio between actual evapotranspiration (AET) and potential evapotranspiration (PET) (S. Zhao, Huang, Liu, Liu, & Tang, 2024):

$$WSI = \frac{AET}{PET} \tag{10.5}$$

Potential evapotranspiration (PET) represents the atmospheric demand for water and is estimated using a temperature-based formulation (Hargreaves & Samani, 1985):

$$PET = k_{ET} \cdot (T_{mean} + 17.8) \cdot \sqrt{T_{max} - T_{min}} \cdot R_a \tag{10.6}$$

where k_{ET} is a crop factor, T_{mean}, T_{max}, and T_{min} are the mean, maximum, and minimum temperatures, respectively, and R_a is the extraterrestrial radiation.

Actual evapotranspiration (AET) is limited by water availability and is therefore scaled based on the relative groundwater storage:

$$AET = PET \cdot \min\left(1, \frac{GW}{GW_{\max}}\right) \tag{10.7}$$

The WSI indicates water stress:

- $WSI \approx 1$: No water stress (water supply meets atmospheric demand)
- $WSI < 1$: Increasing water stress
- $WSI < 0.5$: Severe water stress

A critical threshold of $WSI = 0.5$ is used in this study to identify periods of significant water limitation. This threshold indicates that only half of the atmospheric evaporative demand can be met, which may have implications for vegetation health and water resource availability (S. Zhao et al., 2024).

10.2.2. Scenario analysis

A scenario analysis was performed to evaluate the impact of future climate conditions on the water balance and water stress in the Thac Ba reservoir. Four climate scenarios were considered (World Bank Group, 2026):

- SSP2 (2040–2059)
- SSP2 (2080–2099)
- SSP5 (2040–2059)
- SSP5 (2080–2099)

For each scenario, projected changes in temperature and precipitation were applied to the baseline data. These changes were used to recalculate precipitation and potential evapotranspiration (PET).

Subsequently, the WSI was computed for each scenario. To account for uncertainty in precipitation projections, three variants (minimum, mean, and maximum) were analysed, resulting in a range of WSI values.

Using these updated inputs, the monthly reservoir storage was simulated with the same model structure as the baseline case. In the first step, the discharge (Q) was kept equal to the observed values, allowing for an isolated assessment of the effect of climate change on storage. The results are presented as mean values with corresponding minimum–maximum ranges.

In a second step, reservoir outflow was no longer fixed. Instead, discharge was dynamically calculated by constraining storage to remain at the previously modelled storage from the water balance. Any excess storage was released as additional discharge:

$$Q_{\text{new}} = \max\left(0, S_{\text{scenario}} - S_{\text{baseline}}\right) \tag{10.8}$$

Initial discharge values are taken from observed data. The resulting adjusted outflows are then compared with historical discharge to quantify the changes in water release required to maintain baseline storage conditions under future climate scenarios.

10.2.3. Stakeholder analysis

To gain an understanding of the actors involved in and affected by the management of the Thac Ba dam and its reservoir, a stakeholder analysis was conducted. Following their identification through literature review, stakeholders were mapped using a stakeholder network map and a power–interest diagram, enabling an assessment of their relative influence and involvement.

Stakeholder identification

The literature research to identify stakeholders combined multiple sources: academic literature, Vietnamese news articles, official government publications and the annual report of the Thac Ba Hydropower Joint Stock Company (2025). The identified stakeholders were grouped by sector to enable a structured comparison between stakeholder categories.

Stakeholder network map

A stakeholder network map was constructed to represent the identified actors and the relationships between them within the geographical context. Each stakeholder was positioned relative to the Thac Ba dam and reservoir, with connections drawn to indicate the strength of their interactions. By highlighting key connections, weak links, and connecting actors, the network map provides context for understanding the social dynamics surrounding dam management.

Power-interest grid

Following identification, stakeholders were further evaluated using a power–interest diagram to determine their relative level of influence on decisions and their degree of engagement with the issues surrounding the dam and reservoir (Wong, 2024).

The diagram organises stakeholders into four quadrants, each corresponding to a recommended engagement strategy:

- **High power, high interest:** manage closely: these stakeholders have the greatest impact on project success and their expectations must be actively managed through close collaboration.

- **High power, low interest:** keep satisfied: these actors hold authority or resources and must be kept engaged, as dissatisfaction may lead them to use their power in an undesirable way.

- **Low power, high interest:** keep informed: directly affected parties who should be consulted regularly, as they can provide valuable insight into the details of the issue.

- **Low power, low interest:** monitor: limited engagement is required, but their position should be tracked in case their power or interest changes over time.

Stakeholder positions regarding dam safety, water availability, and energy production were mapped using the power-interest diagram. By doing so, actors who are essential for developing effective management strategies and actors who require further engagement were identified.

10.3. Results

10.3.1. Water balance

The monthly average results of the water balance model are shown in Figure 10.4. The figure presents monthly aggregated water balance components for both the groundwater and reservoir systems. In each panel, inflows are shown as positive values, while outflows are plotted as negative values, allowing a direct comparison of water inputs and losses within the system. The black line represents the simulated storage evolution over time, while the red line indicates the maximum storage capacity.

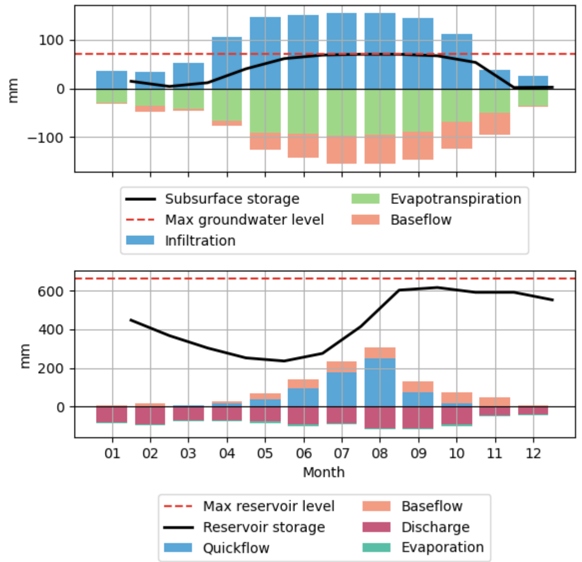


Figure 10.4: (a) Subsurface storage (upper panel), (b) reservoir storage (lower panel)

Groundwater storage exhibits a clear seasonal cycle. During the wet season, storage approaches its maximum capacity, while in the dry season it decreases due to reduced recharge and continued evapotranspiration. Reservoir storage also shows a seasonal pattern, but with a delayed decline compared to groundwater storage.

WSI

In Figure 10.5 the Water Stress Index (WSI) for the current climate conditions is shown. There is a strong seasonal variability. During the dry season, WSI values decrease significantly, indicating water stress for crops.

Only approximately three months per year exhibit conditions close to optimal (WSI ≈ 1), suggesting that water availability is sufficient to meet atmospheric demand during this period. Outside of these months, crops are subject to varying degrees of water limitation.

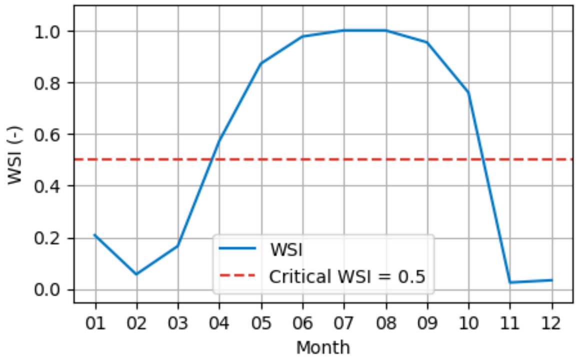
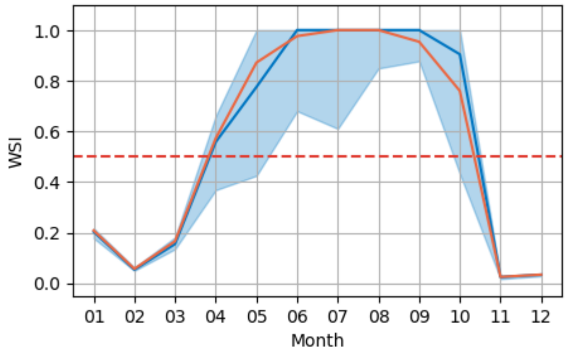


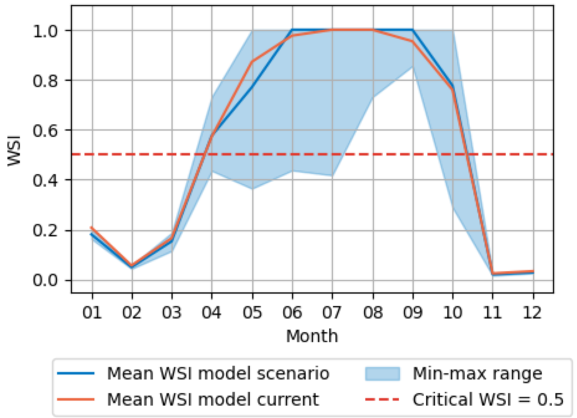
Figure 10.5: WSI

10.3.2. Scenario analysis

Under future climate scenarios, the mean WSI remains relatively similar to current conditions. To capture the range of potential system responses, two contrasting scenarios are presented: the SSP2 short-term scenario and a SSP5 long-term scenario (Figure 10.6a and 10.6b). These represent the upper and lower bounds of WSI variability. Additional scenario results are provided in the Appendix B.1.



(a) SSP2, 2040–2059



(b) SSP5, 2080–2099

Figure 10.6: Water Stress Index (WSI) under different climate scenarios and time periods.

The shaded p10–p90 range represents the 10th and 90th percentiles of different climate model projections, illustrating the spread and associated uncertainty in monthly storage estimates. The lower bound (p10) reflects drier conditions, and the upper bound (p90) represents wetter scenarios.

In particular, the minimum precipitation scenarios show substantially lower WSI values during the dry season, indicating that severe water stress may occur more frequently. Additionally, the period with favourable growing conditions is slightly reduced, from approximately three months to about two to three months per year.

Under future climate scenarios, when the outflow (Q_{out}) is kept at the same amount as the current model, all scenarios show a strong increase in storage during the wet season (Figure 10.7).

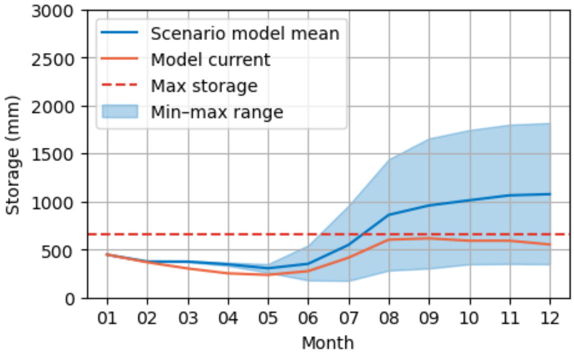


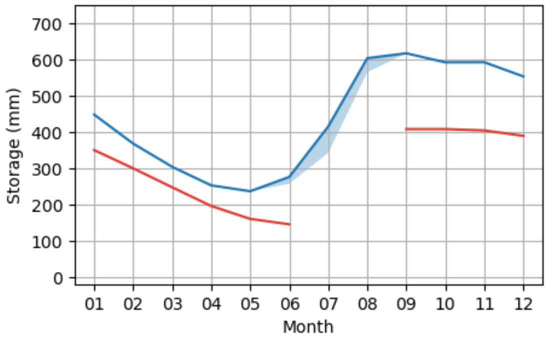
Figure 10.7: Monthly Reservoir Storage, SSP2 2040-2059

Over time, this leads to storage levels exceeding the maximum reservoir capacity in all scenarios, indicating that the current discharge regime is not sufficient to handle increased inflows under future climate conditions.

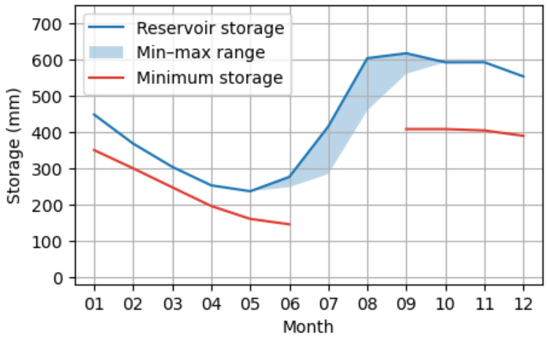
To address this, a second analysis was performed in which discharge is adjusted to maintain current storage levels.

The results show that even under minimum precipitation scenarios, the storage remains above the minimum water level requirements defined by operational guidelines (Figure 10.8). Where no min–max range is visible, this indicates that even the lowest precipitation scenario provides sufficient inflow to maintain storage at levels comparable to current conditions. In contrast, during the wet season, a small lower bound of the uncertainty range falls below the reservoir storage curve. This suggests that under the driest scenarios, inflows may be insufficient to fully replenish the reservoir.

However, maintaining current storage levels requires significantly higher discharge during the wet season. The simulated discharge shows pronounced peaks, particularly for the mean and maximum scenarios, driven by increased precipitation (Figure 10.9).

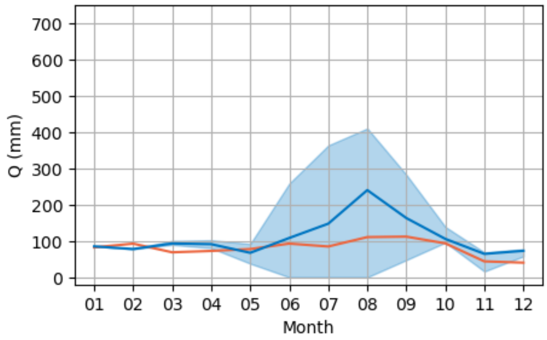


(a) SSP2, 2040–2059

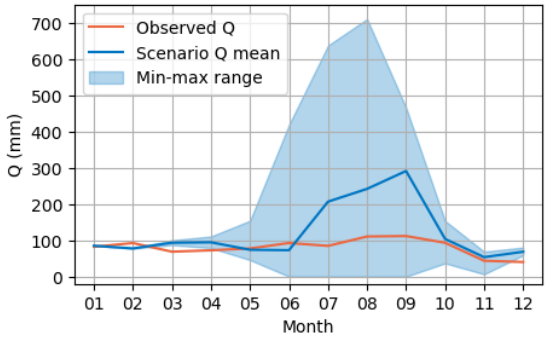


(b) SSP5, 2080–2099

Figure 10.8: Modelled storage for scenarios SSP2 and SSP5



(a) SSP2, 2040–2059



(b) SSP5, 2080–2099

Figure 10.9: Modelled discharge for scenarios SSP2 and SSP5

10.3.3. Stakeholder analysis

The literature search identified fifteen actors involved in or affected by the management of the Thac Ba dam and reservoir. These were grouped into six categories: energy, government, agriculture and aquaculture, local communities, ecotourism, and economy. The results are presented in the form of a stakeholder network map (Figure 10.10) and a power–interest diagram (Figure 10.11).

The Thac Ba Hydropower Joint Stock Company (TBC) holds a central position in the network. Its primary objective is to maximise energy production and revenue. Two major shareholders have controlling stakes in the company: Refrigeration Electrical Engineering (REE) JSC, which holds 60% of shares, and Power Construction Consulting JSC No. 2, which holds 30% (Thac Ba Hydropower Joint Stock Company, 2025). Electricity of Vietnam (EVN) is a state-owned enterprise that purchases all electricity generated by TBC through a Power Purchase Agreement, which determines the price at which electricity is bought (Connect, 2026). The Ministry of Agriculture and Environment holds regulatory authority over the dam's operational safety, with the power to order TBC to open or close the spillways for flood management purposes (News, 2025).

The dam and reservoir are situated in Yen Bai province, where a large proportion of the surrounding population consists of ethnic minorities (Don, 2024). These communities depend directly on the reservoir for their livelihoods, generating income through ecotourism, cage fishing in the reservoir, and agriculture on the surrounding land (Bui, 2016). Following the Prime Minister's approval of ecotourism development in the area, the Department of Culture and Information has invested in developing the region as a tourism destination (Tourism, 2019).

While most actors in the network are interconnected, some stakeholders operate independently from the rest of the system. At least four hydropower plants have been constructed upstream of the Thac Ba reservoir on the Chinese side of the border. These dams influence the volume and timing of inflow into the reservoir; however, their operations are not coordinated with the actors downstream, representing a significant gap in transboundary water governance. Similarly, no direct communication exists between TBC and the downstream provinces of Phu Tho and Vinh Phuc, despite the fact that these provinces would be directly affected in the event of a dam breach (Vinh, Ouillon, Thanh, & Chu, 2014c).

The power-interest diagram shows a clear picture of high power actors in the energy and government sectors, reflecting their authority over the dams operations and water management decisions. In contrast, local communities and actors in the agri-/aquaculture sector lack an overaching body, thereby their ability to influence decision making is limited while they dependent heavily on the reservoir.

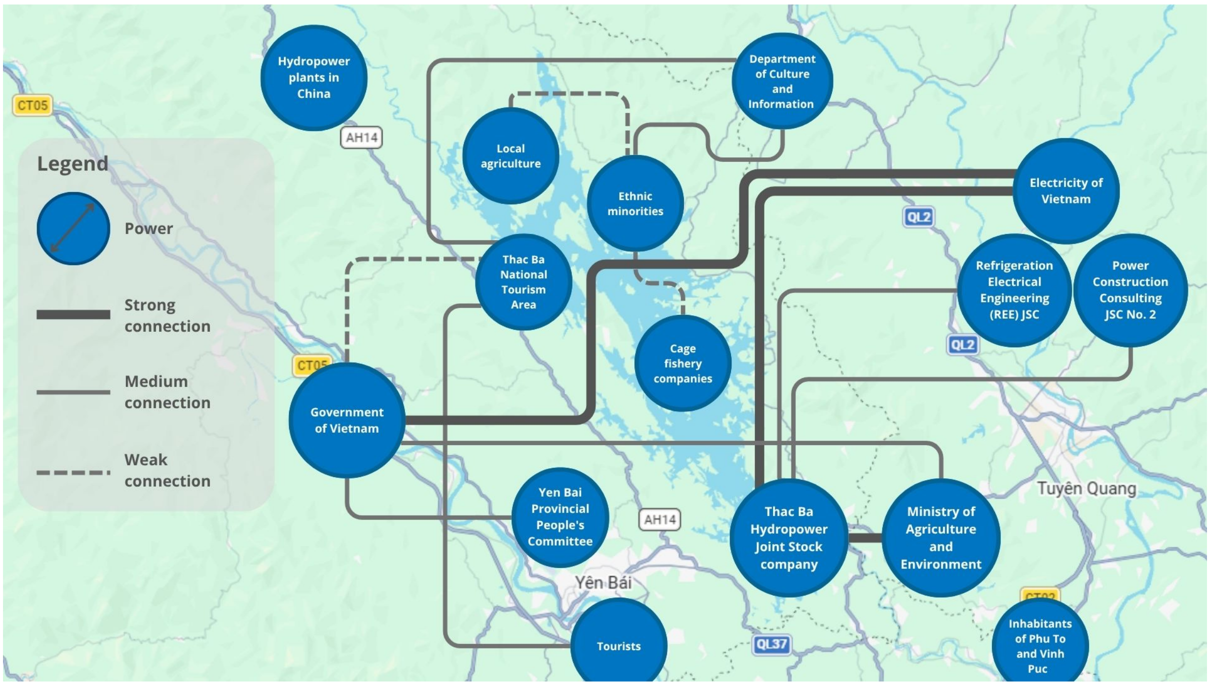


Figure 10.10: Stakeholder network map of management of Thac Ba dam and reservoir.

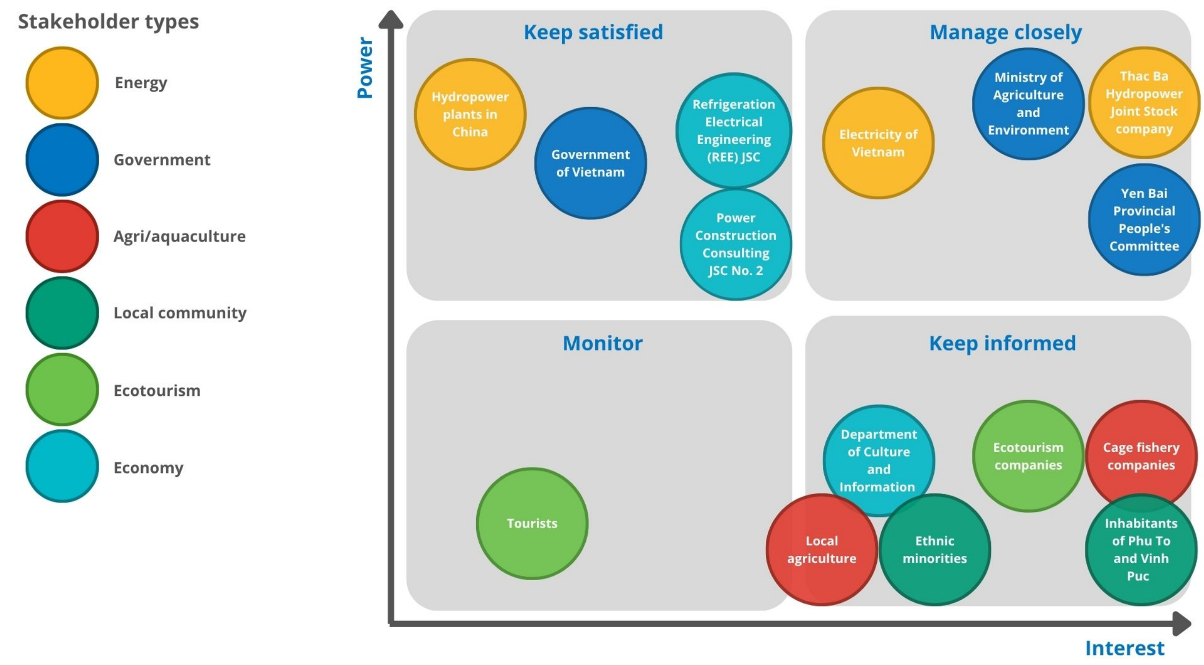


Figure 10.11: Power-interest grid of management of Thac Ba dam and reservoir.

10.4. Discussion

At the start of this case study, a CLD was developed to conceptualise the main interactions within the system. Several of the relationships identified in the CLD are supported by the methods, which are presented in this chapter. However, not all links could be quantitatively assessed within the scope of this study, due to time constraints and model limitations.

10.4.1. Energy & Water

A comparison between the baseline water balance and the scenario analysis indicates that water scarcity is unlikely to become a critical issue at the monthly scale. Under the modelled conditions, where current discharge rules are maintained, reservoir storage does not fall below baseline levels. This implies that the system is capable of meeting essential water amounts for energy generation and for downstream users.

However, there is a challenge during periods of high water availability. Increased inflows lead to higher hydropower production not only at a single reservoir but across multiple dams within the region. When many hydropower facilities generate large amounts of electricity simultaneously, the total energy supply on the market increases. This oversupply can lead to a reduction in electricity prices. As a result, revenues for hydropower operators may decrease. This dynamic can negatively affect the economic performance of hydropower systems and may influence future investment decisions.

To evaluate these interactions between water availability and energy production, key indicators include discharge and reservoir storage. Discharge reflects the amount of water released through the system, directly influencing hydropower generation potential, while reservoir storage indicates the system's capacity to buffer variability in inflows and maintain stable energy production over time.

10.4.2. Food & Water

The results show that the current WSI indicates moderate water stress during the dry season. In the scenario analysis, the mean WSI remains largely unchanged, suggesting no significant increase in average crop stress. However, WSI values decrease during extreme dry conditions. This leads to additional stress on crops.

These periods of intensified stress may negatively impact food security, particularly in already vulnerable systems. Moreover, actual stress levels may be higher than modelled, as discussed in the Subsection 10.4.5.

Key indicators used are the WSI and subsurface storage, which together reflect crop water availability and soil moisture conditions.

10.4.3. Environment & Water

Climate change is projected to change hydrological regimes, mainly through an increase in precipitation. When comparing the current water balance with future scenarios, there is a clear trend: higher rainfall leads to increased inflow into the reservoir system. Under the assumption that reservoir storage capacity remains unchanged from the current situation, this leads to an increase in discharge during the wet season.

The model results indicate that, across all considered future scenarios, reservoir discharge must be higher to maintain current reservoir water levels. For instance, in the month of August, discharge requirements under the SSP2 scenario for the period 2040–2059 are approximately twice as high as those observed under current conditions. This has important implications for downstream areas, where increased flow volumes may elevate the risk of flooding and associated damages. As highlighted in the literature, hydropower dams and regulated reservoir systems can enforce such risks by changing the natural flow regime.

In addition to changes in discharge, increased precipitation also raises the likelihood of secondary hazards such as landslides. Soil saturation reduces slope stability, making regions more susceptible to landslides. One sector that may be vulnerable is tourism, as landscape degradation and increased hazard frequency can reduce the attractiveness and accessibility of affected areas.

To evaluate these environmental and hydrological changes, key indicators include precipitation and discharge, which together provide insight into shifts in the water balance and system dynamics.

10.4.4. Cultural context

Water management in the study area is influenced by power asymmetries between stakeholder groups. Ethnic minority communities are being directly affected by hydrological changes, yet they tend to have limited influence in decision-making processes. This reduces their ability to shape water management strategies and advocate for their specific needs.

In addition, the tourism sector lacks formal representation, such as a unified association or governing body. As a result, it is difficult to include tourism-related interests in stakeholder discussion, even though the sector is very sensitive to environmental changes.

10.4.5. Research limitations

Water balance

The modelled water balance represents a strong simplification of reality, as several hydrological processes are not included. Validation against observed data indicates that reservoir storage is consistently overestimated. The representation of groundwater storage remains close to saturation throughout most of the simulation period, whereas in reality, groundwater levels are likely to fluctuate on shorter (e.g., daily) timescales.

In addition, the model operates on a monthly time step, which smooths temporal variability and masks short-term extremes. As a result, both peak discharge events and short-duration droughts are likely underestimated.

Furthermore, the model does not account for upstream dam operations in China, which control a significant portion of the inflow to the basin. This may lead to an overestimation of the effective precipitation contributing to reservoir storage and an underestimation of drought severity during dry periods.

Scenario analysis

The scenario analysis is subject to additional uncertainties. Evapotranspiration under future conditions was estimated rather than derived from observational or model-based datasets, due to data limitations. This introduces uncertainty in the water balance components.

Stakeholder analysis

The stakeholder analysis is based entirely on secondary sources, including literature and news articles, due to the absence of fieldwork. As a result, the findings may not fully capture local perspectives, informal institutions, or recent developments. Direct engagement with stakeholders would be necessary to validate and enrich the analysis.

11

Bac Hung Hai

This chapter focuses on the case study of the Bac Hung Hai (BHH) irrigation system. First, the case study is introduced, and the problem statement is defined (11.1). In Section 11.2, the methods used are presented and explained. The third section (11.3) presents the results obtained through these methods. Finally, the results are interpreted, and the limitations of the methods are discussed in Section 11.4.

11.1. Introduction

The introduction first describes the system characteristics. Next, it focuses on the problem statement. Finally, it presents the hypotheses using a causal loop diagram (CLD). The BHH irrigation system was selected as a case study because its characteristics and challenges are representative of many areas within the delta. Furthermore, its well-defined boundaries makes it particularly suitable for an analysis.

11.1.1. System characteristics

The BHH irrigation system is located in the middle of the Red River Delta. The Bac Hung Hai system was designed by Chinese engineers in 1958 and is subsidised by the government. The total area of the system is 214 932 ha, of which 192 000 ha lies within the dikes. Within the system, about 110 000 ha requires irrigation, while 70 000 ha is equipped with drainage infrastructure. The system is bounded by four main rivers: Duong, Luoc, Thai Binh, and the Red River. The system is characterised by free-flow conditions, with a general direction from north to south, from +1 m to -0.4 m.

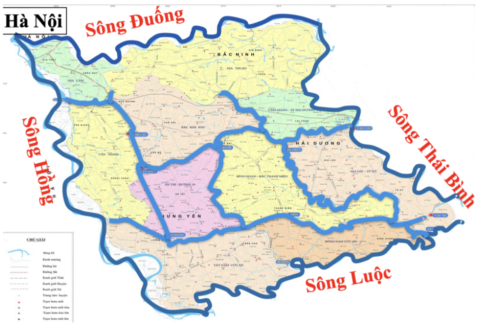


Figure 11.1: Bac Hung Hai Map (Grignard et al., 2020).

The Red River is the main water source of the BHH irrigation system. The water from the Red River enters the system through the Xuan Quan inlet. During the peak demand period, extra water is let in through the downstream outlet locks Cau Xe, Cau Cat, and An Tho. This water enters from the Thai Binh and Luoc river. At the Xuan Quan inlet pumps have been added to increase the inlet capacity during low water levels. The water leaves the system through free flow at the Cau Xe, Cau cat, and An Tho lock. In addition, to increase the drainage capacity, the Mi Dong pump is constructed. This helps achieve a higher drainage capacity during high water levels. The total population of the area is about 2.8 million people out of which about 2.2 million are working in agriculture. Farmers are increasingly growing high-value crops, such as vegetables, fruit trees, and flowers. However, paddy rice remains the major crop grown on 80% of the cropped area (Food and Agriculture Organization of the United Nations, 2010). Grignard et al. (2020) states the irrigation system plays an important role in the region by:

1. providing irrigation to 110 000 ha
2. providing water for livestock, poultry, and aquaculture
3. providing water for more than three million people and industrial zones

4. controlling flooding inside the dyke area to protect people's livelihoods and income

11.1.2. Problem statement

The BHH irrigation system is challenged by the risk of water insecurity. This is caused by the effects of pollution and water scarcity. This is amplified by the consequences of climate change and of multiple human interventions, which are explained in Section 3.3 and 3.4. Within the Bac Hung Hai irrigation system surface water is a vital part of life. Surface water is used in several sectors. Table 11.1 shows a summary of the average flow requirement per sector in m^3/s.

Sector	Flow requirement
Agriculture	40.46 m^3/s
Livestock	2.03 m^3/s
Aquaculture	8.36 m^3/s
Regional living activities	2.47 m^3/s
Industry	1.18 m^3/s
Maintain environmental flow	5.52 m^3/s

Table 11.1: Average water flow requirements per sector in the BHH irrigation system.

This results in an average total water flow requirement of 60.02 m^3/s calculated in 2016 (Nghia, 2016). Due to population growth and industrialisation, this flow requirement is expected to increase in the future. However, the quality of this surface water is very poor, and is expected to worsen. Wastewater is being discharged into the surface water system without any treatment. Large portions of this do not occur in a regulated manner. Consequently, this wastewater entering the surface water system often does not meet the required quality standards. This leads to a reduction in the amount of usable fresh water, consequently affecting households. Firstly, the accessibility to fresh water for households decreases because their old source is no longer usable. Secondly, the yield production reduces due to the limited irrigation water. Thirdly, the aquaculture productivity decreases. In conclusion, the polluted fresh water thus affects people both physically and economically. The wastewater is discharged by almost every sector in the Bac Hung Hai irrigation system. In total, about 438 899 m^3/day wastewater is discharged into the system. In the summary below, the sector with the percentage of the total wastewater that is discharged is stated (Linh, 2024).

- Domestic wastewater (72%)
- Industrial wastewater (18% of which 9̃1% treated)
- Agriculture, craft villages, healthcare (10%)

Most of these sectors have not invested in centralised wastewater treatment facilities; in almost all cases, this results in no wastewater treatment. Resulting in a poor water quality, in the period of 2017-2022 several locations have been monitored by Linh (2024). This monitoring showed that the requirements of the QCVN 08-MT:2015/BTNMT column B1 for irrigation and drainage or other uses (referred to as QCVN-08) are often exceeded.

- 90% of the locations have at least one parameter that does not meet QCVN-08.
- 90% of the days DO values do not meet QCVN-08.
- 70% of the days N-NH4+ and TSS values do not meet QCVN-08.

Next to the worsening water quality within the system, the quantity of water is also decreasing. The water flow from the Red River through the Xuan Quan sluice gate is currently only about 20% of the design capacity due to low water levels (Bao Chinh Phu, 2026).

The combination of declining water quality and reduced water availability places the Bac Hung Hai irrigation system under significant pressure. This pressure is further intensified by climate change and ongoing human interventions. As a result, the system's ability to meet the water demands of multiple sectors becomes increasingly uncertain. These interacting factors create a complex challenge in which water quantity, water quality, and external drivers are strongly interconnected, affecting not only environmental sustainability but also socio-economic stability within the region. Therefore, this case study aims to identify the most important challenges within the system and indicators that can help monitor these challenges.

11.1.3. Simplified Causal Loop Diagram (CLD)

To structure the analysis, a simplified Causal Loop Diagram (CLD) was developed to conceptualise the key feedback mechanisms within the system (Figure 11.2). The CLD synthesises insights from the preceding literature research and identifies the main interactions between a worsening water quality and the increasing pressure from human interventions and climate change.

The central focus is on the two reinforcing loops around water quality. The first loop shows the consequence of a worsening water quality that is expected to lead to less agriculture, which is expected to amplify the urbanisation trend, and therefore, in the end water pollution. The second reinforcing loop shows the result of a worsening water quality, which is expected to lead to an increase in groundwater extraction. This will increase the saltwater intrusion and therefore worsen the water quality. This loop is also amplified by climate change and sand mining.

The CLD functions as a conceptual basis for the analysis. Building on this framework, multiple methods are used, including a field visit, social survey, actor analysis, water balance modelling, and system dynamics modelling. Together, these methods are used to identify the importance of the relationships and to explore system behaviour.

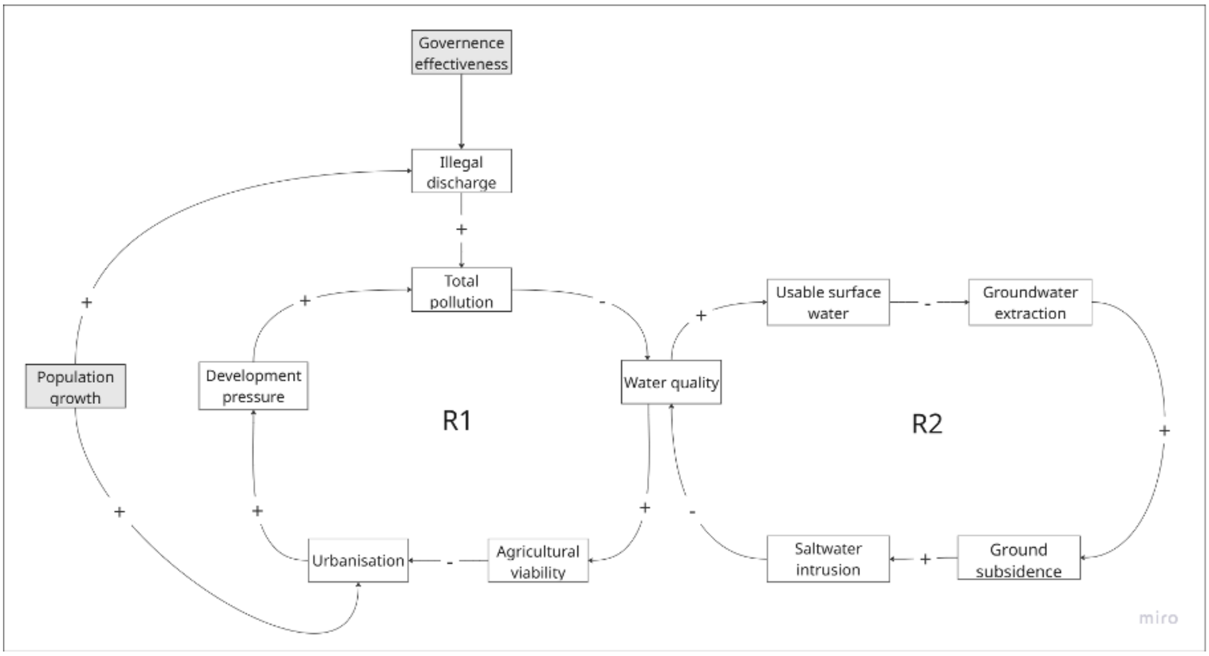


Figure 11.2: Causal Loop Diagram of the Bac Hung Hai irrigation system with the expected key problems.

11.2. Methods

This study used different methods to analyse the functioning of the Bac Hung Hai irrigation system, to eventually identify the main challenges. Multiple methods were combined to capture both the social and physical aspects of the system. A field visit and social survey were conducted to collect empirical data on stakeholder perspectives and on-the-ground conditions. Actor analysis was used to examine institutional relationships and governance structures within the system. In addition, a water balance and system dynamics model was developed to explore the behaviour of the system.

The combination of these methods provided a comprehensive understanding of the irrigation system, enabling the identification of the key problems.

11.2.1. Field visit

The aim of this method was to analyse the organisational structure of the Bac Hung Hai irrigation system through interviews across different institutional levels. The interviews were used to identify key challenges at each organisational layer and to examine how these challenges differ between levels. In addition, field observations were conducted to assess the scale of these challenges within the irrigation system.

For this method, interviews were conducted across different levels of the organisational structure. Interviews were conducted with staff members of the Xuan Quan lock, the Bac Hung Hai irrigation company, Hai Phong Province, Binh Giang District, and the Cau An Tho lock. These respondents represent the three main organisational levels as well as two key control points within the system. This selection ensured coverage across the full organisational structure. In addition, the lock operation teams provided specific knowledge on water inflow and outflow, which are critical for understanding water availability within the Bac Hung Hai irrigation system.

The interviews lasted approximately 60 minutes and were conducted with the assistance of an interpreter who translated between English and Vietnamese. The interviews were semi-structured and consisted of three main questions. Additional follow-up questions were asked to further explore relevant topics that arose during the interviews. The three main questions were:

- Which actors do you interact with within the Bac Hung Hai irrigation system, and what is the nature of these interactions?
- What actions do you take when poor water quality is observed?
- How do you perceive future challenges and developments?

Notes of the interviews formed the basis for the analysis, focusing on institutional interactions, response mechanisms, and perceived challenges across organisational levels. Field observations focused on visible indicators of water quality. The results of this method were used to confirm findings in other methods and to prioritise identified problems.

11.2.2. Actor analysis

The actor analysis was conducted through direct fieldwork as part of a field trip to the Bac Hung Hai irrigation system. Information was gathered by visiting sites across the system and interviewing experts and operators at three levels of management: the Bac Hung Hai irrigation company (tier 1), provincial operating companies (tier 2), and district operating companies (tier 3).

During these visits, structured conversations focused on two main themes: how each actor operates their infrastructure (including when and under what conditions sluices and pumps are activated), and how they communicate with actors above and below them in the management hierarchy. This allowed both operational procedures and inter-actor relationships to be mapped simultaneously.

11.2.3. Survey

To gain insight into the water use patterns of households, a survey was conducted among two different groups. The survey was developed in Qualtrics and covered three main themes:

1. General characteristics of respondents.
2. Daily experience with water, including water source, use, quality and supply.
3. Perceived problems and solutions regarding water management in the area.

Both groups received the same set of questions, combining open-ended and multiple-choice questions to capture both quantitative data and qualitative insights.

The first survey was targeted at local residents within the Bac Hung Hai area. To overcome the language barrier between the research team and local respondents, the questionnaire was translated into Vietnamese using DeepL and distributed via a QR code during the field visit. The QR code was brought to several water management organisations, posted in the city of Hai Duong, and displayed at various locations along the route through the Bac Hung Hai area.

The second survey was administered to a group of first-year English students at HUNRE, Hanoi, who completed the English version of the questionnaire during class. This group was included to provide a comparison with the perspectives of local residents.

The collected data were subsequently analysed using Microsoft Excel.

11.2.4. Water balance

The goal of this model is to simulate the monthly water balance of the studied area, with a focus on the water storage in Bac Hung Hai. This water storage is important for irrigation, which is one of the most important tasks of the Bac Hung Hai water system. Next to that, the water balance is used to gain insight into the in- and outflow of the water during the different seasons.

For the water balance, the following principle is used:

$$\Delta S = P - ET - Q \tag{11.1}$$

The system is modelled with two buckets: groundwater storage and reservoir storage. The model divides the precipitation into two parts: A quick surface runoff to the reservoir storage and a slower groundwater recharge. At the same time, water is lost by evapotranspiration and evaporation. The schematisation can be seen in Figure 11.3.

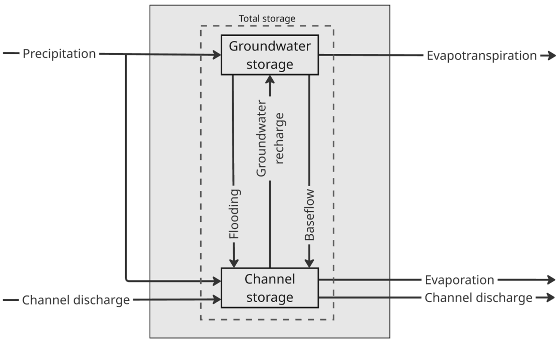


Figure 11.3: Schematisation of the water balance model

As visible in the schematisation, flooding, groundwater recharge, and baseflow are flows within the Bac Hung Hai system. For the total storage, these flows are not taken into account. Next each flow that enters or leaves the system is elaborated.

Precipitation and evapotranspiration

The monthly data from precipitation and evapotranspiration are daily remote sensing data of multiple data sets averaged to a monthly value. Multiple datasets are used to reduce uncertainties. Precipitation data are obtained from CHIRPS (Funk et al., 2015), ERA5 (European Centre for Medium-Range Weather Forecasts (ECMWF), 2023), and TerraClimate (Abatzoglou et al., 2018). In addition, evapotranspiration is derived from FLDAS (NASA Goddard Space Flight Center, 2020), WaPOR (FAO WaPOR, 2023), and TerraClimate (Abatzoglou et al., 2018). The precipitation is divided by a factor which represents the surface water area versus the ground area. The evaporation is calculated using a rule of thumb. The evapotranspiration is calculated by extracting the evaporation from the surface water of the evapotranspiration data.

Channel discharge

The channel discharge was estimated using lock operation logbooks combined with observed water levels and an estimated flow velocity.

The lock logbooks provide daily information on lock operations, including abbreviations describing the type of operation and corresponding operation times. To translate this into daily discharge estimates, each abbreviation was assigned a coefficient between 0 and 1, representing the fraction of the day the lock was open. A value of 1 indicates fully open conditions, while 0 indicates a fully closed lock. Since some locks are used for both inlet and outlet purposes, this information was combined with the planning logbook to determine the expected flow direction. Tables 11.2 and 11.3 show the resulting inlet and outlet coefficients. This method was preferred over using daily water level differences, as fluctuations throughout the day made them unreliable for determining flow direction.

Lock	Operations	Planning	Coefficient
Xuan Quan	MT	-	0.3
An Tho	M	LNN	0.1
Cau Cat	M	LNN	0.1
Cau Xe	M	LNN	0.1

Table 11.2: Lock inlet coefficients

Lock	Operations	Planning	Coefficient
An Tho	M	No LNN	0.3
Cau Cat	M	No LNN	0.3
Cau Xe	M	No LNN	0.3

Table 11.3: Lock outlet coefficients

Water levels, available at 3-hour intervals, were averaged to obtain daily means. These were used to compute the cross-sectional area based on channel bed elevation and width. Channel characteristics are based on the interactive map (*Bac Hung Hai Irrigation System - Google My Maps*, n.d.) and are shown in Table 11.4.

Channel	Width (m)	Riverbed (m)
An Tho	75	-4
Cau Cat	47.5	-2.5
Cau Xe	75	-4
Xuan Quan	47.5	-0.95

Table 11.4: Channel characteristics

Flow velocities per channel were calibrated by fitting discharge estimates for January–May 2025 to detailed discharge calculations based on 3-hourly data. The discharge is computed using Equation 11.2. The resulting velocities were then applied to the remaining days. For the Xuan Quan inlet, wet season velocities (June–November) were increased by a factor of 1.5. Estimated velocities are shown in 11.5.

$$Q = coef_{\text{lock}} \cdot (waterlevel - bed) \cdot w_{\text{channel}} \cdot v \quad (11.2)$$

Location	Velocity inlet	Velocity outlet
An Tho	0.05 m^2/s	0.4 m^2/s
Cau Cat	0.05 m^2/s	0.8 m^2/s
Cau Xe	0.05 m^2/s	0.5 m^2/s
Xuan Quan dry	0.8 m^2/s	-
Xuan Quan wet	1.2 m^2/s	-

Table 11.5: Estimated flow velocity at locks

In addition to the free flow channel discharge, there are also pumps constructed within BHH. Sixteen at the inlet lock Xuan Quan are used to increase the intake. In addition, there are ten pumps constructed downstream at Mi Dong that increase the drainage capacity. For the Xuan Quan pumps, there is daily data available for the year 2019. This data is copied to the other years that the pump was active. This resulted in days that the pump was active, days it was partly active, and days it was not used. Since the pump almost never works at full capacity, the estimation is made that on average, twelve of the Xuan Quan pumps are working. This is added to the free flow daily discharge.

For the Mi Dong pump, no operational data is available. Since this is a drainage pump, its operation was estimated based on monthly precipitation. If precipitation exceeds 400 mm, ten pumps are assumed to be active on average. For precipitation between 200 mm and 400 mm, 6.66 pumps are assumed to be active on average. For precipitation below 200 mm, no pumps are assumed to operate. This approach results in a monthly average discharge in m^3/s.

As a last step, these daily discharges were resampled to a mean discharge per month. To which the Mi Dong pump is added. This means monthly discharge is converted into mm of water entering and leaving the system through channel discharge, which is used in the water balance calculations.

This simplified discharge approach was selected because a more detailed discharge calculation would require converting the daily lock operation logbook into a 3-hourly time series, consistent with the resolution of the water level observations. As this process would require substantial additional effort, and since the water balance is intended primarily as a first-order indicator, the chosen method provides an appropriate balance between accuracy and feasibility.

Model validation

To validate the model the satellite total water storage difference data from GRACE is used (NASA Jet Propulsion Laboratory, n.d.). This is data is set to an unknown baseline. To ensure a validation can be done both the data and model are changed into a delta storage change compared to the previous month. This resulted in the following validation, visible in Figure 11.4.

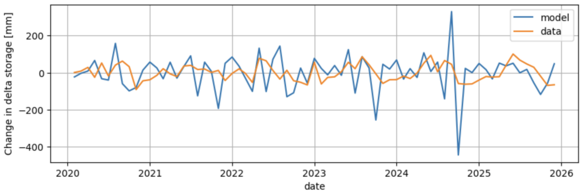


Figure 11.4: Change in delta Storage Relative Previous Month in BHH System. Used as validation for the system.

11.2.5. System dynamics model

System dynamics is a modelling approach used to study the behaviour of complex systems over time. It represents a system as a set of interconnected stocks, flows, and feedback loops, which together capture how variables accumulate, deplete, and influence one another. By making these relationships explicit, system dynamics makes it possible to simulate how a system evolves under different conditions and to explore how interventions propagate through the system as a whole.

One of the strengths of the approach is that it shifts the focus from isolated causal relationships to the structural dynamics that drive system behaviour. This makes it particularly well suited to problems where feedback, delays, and non-linear interactions play an important role, such as in environmental, economic, and social systems. In the context of this report, system dynamics provides a framework for examining how pollution, water quality, and economic activity interact over time, and for testing how different policies might influence these interactions.

Model setup

The model is a combination of stocks and flows and causal loops. There are four main components of the system.

Model is setup with rates rather than true values since data is limited and not alway as trustworthy. Therefore we have to the model more as a behavioural model more than looking at the specific values.

The model uses coefficients per pollution source to represent each source's impact on the WQI ratio, supported by a set of lookup tables that determine the strength of different effects. Most of these lookup tables follow an S-curve shape with drop-off points, and their values are largely educated guesses rather than empirically derived figures. The coefficients themselves have been tuned to produce realistic timing rather than calibrated against real-world data, which means they strongly steer the model's output. A key coupling in the model links ecological status and water quality to the regional GDP: degradation of the system accelerates GDP depreciation, since value stored in the system must be redirected towards recovery instead of generating new output.

A downside is that model also relies on several simplifying assumptions that limit its realism. Land-use conversions are one-way and final, meaning residential areas cannot revert to industrial use, nor industrial areas to residential. There is no feedback from the system to population health or demographics, even though such effects would be expected in reality. Similarly, the model contains no link between residential and industrial development, despite the real-world dependency in which people need to live near where they work.

For a clear overview of the model see Appendix B.5

Model Components

The model consists of four main components that are linked in a causal chain. Changes in land use stocks drive the accumulation of water pollution, which in turn affects the state of the environment. The environmental stock then feeds back into regional wealth accumulation that functions as a marker for the state of the region.

Land Conversion component

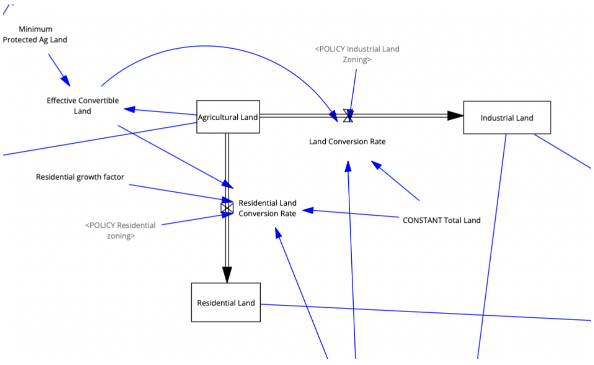


Figure 11.5: BHH System Dynamics model GDP component

The main driver of the system is the land conversion component. here we can see the stock for agriculture land that flows out to two other land uses, industry and domestic. The amount of how fast this land conversion happens depends on the influences from GDP.

Water Quality component

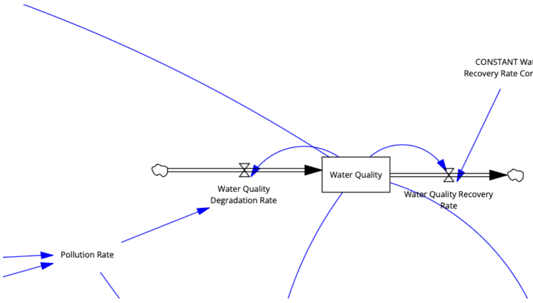


Figure 11.6: BHH System Dynamics water quality component

The water pollution from industry and domestic is aggregated in a overall pollution variable. The change in the pollution variable then used to determine the added pollution to the water system that effects the water quality. If the degredation rate is higher than the recovery rate of the water the water quality will get worse over time.The water quality then influences the ecological quality of the BHH system.

Environmental Quality component

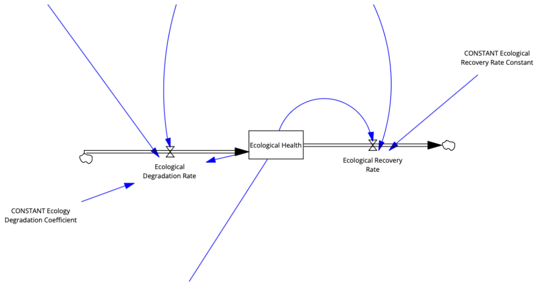


Figure 11.7: BHH System Dynamics environmental quality component

The environmental stock represents the overall ecological health of the system and responds to the state of water quality over time. As long as water quality remains poor, the environmental stock gradually degrades, draining out at a rate determined by the ecological degradation coefficient. Recovery is possible once water quality improves, but the recovery coefficient is deliberately set low, reflecting the fact that ecosystems tend to deteriorate faster than they recover. This asymmetry ensures that sustained pollution leaves a lasting imprint on the environmental stock, even after conditions begin to improve.

Regional Capital component

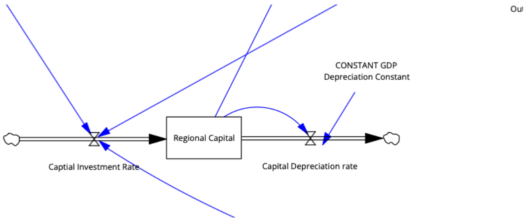


Figure 11.8: BHH System Dynamics model regional capital component

The regional capital stock represents the accumulated economic value of the region and serves as the link between environmental conditions and economic performance in the model. The stock functions as a tracker for the economic status of the region. Capital accumulates through an investment rate driven by GDP growth pressure, which reflects the gap between current capital and a reference level, and depletes through a depreciation rate influenced by a fixed depreciation constant. The stock is coupled to the environmental side of the model through an ecological health multiplier that decides the size of the effect of when ecological health declines, industrial output is reduced, which in turn lowers GDP growth pressure and slows capital accumulation

Policy Levers

The model includes several policy levers that allow the user to test how different interventions influence the system. Each lever reduces the impact of a pollution source or constrains land-use change, and their effects propagate through the model via the existing causal structure. The policy levers are water treatment for industyr and wate rtreamtent for domestic, also land zoning for industry and land zoning for domestic.

Industrial pollution, for example, is calculated as:

$$P_{\text{ind}} = L_{\text{ind}} \cdot c_{\text{ind}} \cdot (1 - P_{\text{treat}}) \tag{11.3}$$

where:

- P_{ind} = Industrial Pollution
- L_{ind} = Industrial Land
- c_{ind} = Industrial Pollution Coefficient
- P_{treat} = Policy Industry Water Treatment

A higher treatment value therefore reduces the total pollution generated per unit of industrial land.

Policy levers are not always on and are activated under a certain condition. In this case when the year is 2030 the policy starts to ramp up and starts influencing the system

Both are implemented using the following formulation:

$$P(t) = \begin{cases} 0 & \text{if } t < 2030 \\ \text{DELAY}(v,\ t) & \text{if } t \geq 2030 \end{cases} \tag{11.4}$$

where v is the target policy value and t the time it takes to reach it.

This means the policy is inactive before 2030 and then gradually ramps up to its target value over a delay period of t years, reflecting the time required for treatment infrastructure to take effect.

The second category concerns land-use zoning, again split between industrial and residential zoning. The levers all follow the same IF-THEN-ELSE structure

The zoning has a shorter delay of two years, since zoning decisions are assumed to take effect more quickly than large infrastructural investments.

A third lever is the the minimum agricultural land that acts as a floor for further land conversion, currently set at around 30 percent. This value was chosen based on available information but is not fixed by the model and can be adjusted to explore the effects of stronger or weaker agricultural protection. But because this lever is never changed in the model it is ignored as a policy.

Experimental Set-up

The ranges for the experimental setus are defined for parameters whose values are uncertain. Sampling across these ranges rather than using single deterministic values allows the model to give a distribution of possible outcomes that shows how input uncertainty propagates through the system.

The experimental design follows the XLRM framework (Lempert, Popper, & Bankes, 2003), a structured approach for policy analysis under deep uncertainty. It organises the study into four components: external factors (X), policy levers (L), relationships (R), and performance metrics (M).

An overview of how the framework is applied is shown in Figure 11.9.

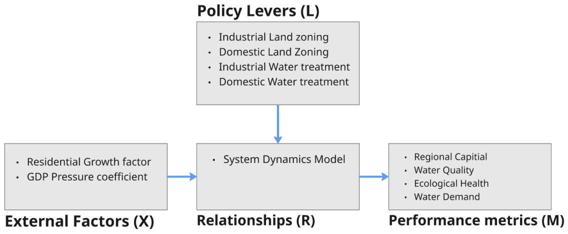


Figure 11.9: XLRM Framework Lempert et al. (2003)

Policy levers

- **Industrial Land Zoning**: constrains the conversion of land into industrial use, limiting the expansion of industrial activity and its associated pollution.
- **Domestic Land Zoning**: constrains the conversion of land into residential use, controlling the growth of domestic activity and its impact on the system.
- **Industrial Water Treatment**: reduces the pollution load generated per unit of industrial land, representing investment in treatment infrastructure for industrial pollution discharge.
- **Domestic Water Treatment**: reduces the pollution load generated by domestic activity, representing investment in treatment infrastructure for residential wastewater.

Performance metrics

- **Regional Capital**: represents the accumulated economic value of the region and serves as the primary indicator of economic performance over time.
- **Water Quality**: expressed through the WQI ratio, captures the state of the water system as influenced by industrial and domestic pollution sources.
- **Ecological Health**: reflects the overall condition of the environment and responds to sustained water quality over time, with slow recovery dynamics.
- **Water Demand**: represents the total water requirement of the region, driven by residential and industrial activity.

External factors

- **Residential Growth factor**: influences the rate at which residential land expands, reflecting demographic and development pressures outside the model's control.
- **GDP Pressure coefficient**: determines the strength of the economic growth drive in the model, influencing how strongly the system pushes towards capital accumulation.

The following settings are used for the simulations

Model Settings

Method	Euler
Time step	0.03125
Save steps	0.25
# Runs	1000
Seed	1234
t_0	2000
t_T	2100

Table 11.6: Model settings used for the simulation.

11.3. Results

This section presents the results of the analysis. The findings are organised based on the different methods applied in this study: the field visit, social survey, actor analysis, water balance, and system dynamics model. Together, these results provide insights into the key challenges within the Bac Hung Hai irrigation system.

11.3.1. Field visit

As explained in the method section 11.2.1 several locations within Bac Hung Hai were visited. At every location, three main questions in combination with follow-up were asked. The follow-up questions vary per location, the three main questions are:

- Which actors do you interact with within the Bac Hung Hai irrigation system, and what is the nature of these interactions?
- What actions do you take when poor water quality is observed?
- How do you perceive future challenges and developments?

Xuan Quan lock

The Xuan Quan lock is the main inlet structure of the Bac Hung Hai irrigation system. It regulates the inflow of water from the Red River, from where water can enter the system and be distributed through gravity-fed flow.

Which actors do you interact with within the Bac Hung Hai irrigation system, and what is the nature of these interactions? The operation team of the Xuan Quan lock is part of the Bac Hung Hai Irrigation Company. Therefore, the operation team are only in contact with the company, and other staff members of the company have contact with the provinces.

What actions do you take when poor water quality is observed? The Red River generally has good water quality, while poor water quality is mainly observed within the irrigation system itself. As a result, the Xuan Quan lock does not directly deal with water quality issues.

How do you perceive future challenges and developments? The key future challenge is the decreasing water level at the inlet point. Due to this decline, gravity-fed intake is not always possible. This situation is occurring more frequently, which has led to an increase in the demand for pump capacity. Resulting in the construction of more pumps at the Xuan Quan inlet point (see Figure 11.10). The lowering of water levels is a result of the declining riverbed level, which operators believe is mainly caused by extensive sand mining activities in the Red River.

Figure 11.10: Construction of extra pump capacity at the Xuan Quan lock.

The Bac Hung Hai Irrigation Company

The Bac Hung Hai Irrigation Company is the main operator of the irrigation system. The system was designed by Chinese engineers in 1958 and is subsidised by the government. The total area of the system is 200 000 ha, of which 192 000 ha lies within the dikes. Within the system, about 110 000 ha requires irrigation, while 70 000 ha is equipped with drainage infrastructure. The system is bounded by four main rivers. The system is characterised by free-flow conditions, with a general direction from north to south, from +1 m to -0.4 m. The system lies within four provinces. The Bac Hung Hai Irrigation Company is the umbrella organisation that the four provinces are part of. They are responsible for the 13 main structures within the system.

Which actors do you interact with within the Bac Hung Hai irrigation system, and what is the nature of these interactions? They are mainly in contact with the provinces. The four provinces inform the Bac Hung Hai Irrigation company about the water demand throughout the year. Based on that information, the Bac Hung Hai Irrigation Company determines the inlet's operations. Next to that, they inform the provinces when important changes happen.

What actions do you take when poor water quality is observed? The province informs the Bac Hung Hai Irrigation company when the water quality within the system worsens. The Bac Hung Hai irrigation company will then try to flush the system with fresh water, resulting in an increase in water quality.

How do you perceive future challenges and developments? There are several challenges that the Bac Hung Hai Irrigation Company faces. First, the decrease in water intake (explained above). In addition, they also face downstream saltwater intrusion. The salt levels are sometimes nine times the permitted levels. Consequently, they have to close the locks during these times, which results in less intake. Second, an insufficient drainage capacity. The drainage capacity is once built only for irrigation, but now also needs to drain water from houses and industry. This insufficient drainage capacity increases flood damage. Because of this, they sacrifice an area which they allow to flood to save the other areas. This flood damage is exacerbated by unauthorised building on the banks of the water, and decreasing the room for the river. Lastly, the poor water quality. Currently, there are limited treatment facilities and people have no other place to leave their wastewater. Therefore, they try to increase the quality by flushing the system with fresh water. They have several future plans to tackle these challenges:

- Building a drainage pump downstream with a capacity of 170 m^3/s
- Extra pump capacity at the Xuan Quan inlet, to increase the water intake
- Building wastewater treatment plants

Hai Phong Province
Provinces are responsible for the second & third order channels. Tries to meet the demand of the districts. Informs Bac Hung Hai with messages of the districts.

Which actors do you interact with within the Bac Hung Hai irrigation system, and what is the nature of these interactions? The province acts as a link between the districts and the Bac Hung Hai Irrigation Company. They collect the information of all the districts within their province and then inform the Bac Hung Hai irrigation company about the demands and reports of poor water quality. Next to that, they bring the districts together during, for example a flooding emergency.

What actions do you take when poor water quality is observed? Once a poor water quality is observed they can close the lock to prevent this water from entering the irrigation areas. Once this happens, they inform the Bac Hung Hai Irrigation company and ask for flushing.

How do you perceive future challenges and developments? The key challenge the province notices is the poor water quality. Because of this they can not always supply the requested demand to the districts.

Binh Giang District
The district is responsible for the supply of irrigation water to farmers, as well as for the drainage of agricultural land.

Which actors do you interact with within the Bac Hung Hai irrigation system, and what is the nature of these interactions? The district acts as a link between the province and the farmers and is the only organisational level directly in contact with farmers. Each year, the district and farmers develop an irrigation plan, which is communicated to the province. The province integrates the plans from all districts and submits a plan to the Bac Hung Hai irrigation company. If the company is unable to comply with this plan, it informs the province, which then communicates this back to the district.

What actions do you take when poor water quality is observed? When poor water quality is observed by district operational staff, the intake lock is closed and the province is informed. The province then submits a request to flush the system to the Bac Hung Hai Irrigation Company. Farmers may also report poor water quality to the district, after which the same procedure is followed.

How do you perceive future challenges and developments? A key challenge identified at the district level is poor water quality, which limits the ability to meet irrigation demand. In addition, drainage demand has increased in recent years, resulting in a higher frequency of flooding events. The district operation staff expect this to increase further in the future.

Cau An Tho lock
The Cau An Tho lock functions as the main outlet structure of the Bac Hung Hai irrigation system. In addition, it facilitates gravity-fed inflow during periods of high tide.

Which actors do you interact with within the Bac Hung Hai irrigation system, and what is the nature of these interactions? The operational staff of the lock are employed by the Bac Hung Hai Irrigation Company. They operate the lock in accordance with system-wide water demands and operational requirements. Therefore, the operation staff is only in contact with other departments within the Bac Hung Hai Irrigation company.

What actions do you take when poor water quality is observed? When poor water quality is observed within the system, efforts are made to discharge water through the lock to improve conditions. When poor water quality is detected outside the system, the lock is closed to prevent inflow. At this location, poor water quality is typically caused by high salinity levels instead of chemical pollution.

How do you perceive future challenges and developments? A key future challenge is saltwater intrusion during periods of high tide. Salinity levels have been observed to reach up to nine times the permitted concentration. These high salinity events are occurring more frequently and are expected to increase further in the future. According to the operators, this trend is caused by sand mining, as well as sea level rise.

Visual observations

In addition to the interviews with stakeholders, visual observations were conducted at several locations within the system. At the Dap Xuan Thuy lock, multiple photographs were taken to document local conditions. This lock receives wastewater from Hanoi.

Figure 11.11 shows the accumulation of solid waste and pollution associated with this inflow. The lock blocks the solid waste from entering the system, and polluted water is able to pass through. Resulting in visibly dark water within the Bac Hung Hai system (see Figure 11.12). Consequently, this contaminated water enters the irrigation channels.

Figure 11.13 illustrates the limited mixing between polluted and cleaner water. This is likely due to differences in density and composition, which reduce mixing and contribute to low flow velocities. These conditions are associated with a strong smell and may indicate high levels of sediment contamination.

Figure 11.11: Picture taken during the field visit that shows the garbage in the channels before Bac Hung Hai due to the waste of Hanoi city.

Figure 11.12: Picture taken just behind the lock within the system. The dark colour of the polluted water is visible.

Figure 11.13: Picture taken during the field visit that shows the separation of the fresh and polluted water due to the composition of the water.

11.3.2. Actor analysis

Relevant Actors in Bac Hung Hai

Province
The irrigation system consists of parts of 4 different provinces. The irrigation system is not a real governing entity itself.

District
The districts fall under the province that governs the villages and farms in their districts

BHH Irrigation company
The Irrigation company provides water to the system and punishes farmers if they pollute too much or use forbidden chemicals

Farmers/Farmers cooperatives
Use the water for agriculture and make food for the population

businesses & industry
More and more industry and business are coming to the area as a result of the economic development of Vietnam.

The BHH System

The Bac Hung Hai irrigation system is subdivided between four provinces as can be seen in figure 11.14.

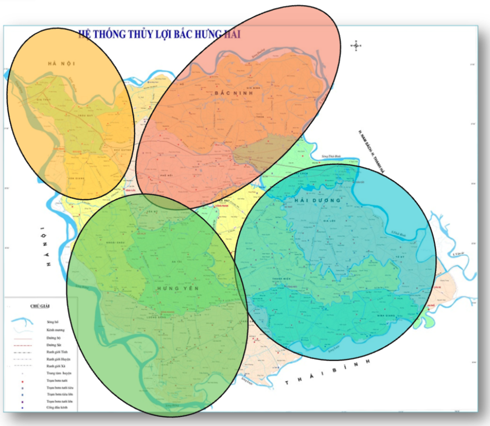


Figure 11.14: BHH map and province subdivision

Each province has multiple districts under their jurisdiction that communicate their water needs to the provinces. The province than combines the water needs and sends this to the BHH irrigation company. The company than decides when to open the water intake sluice.

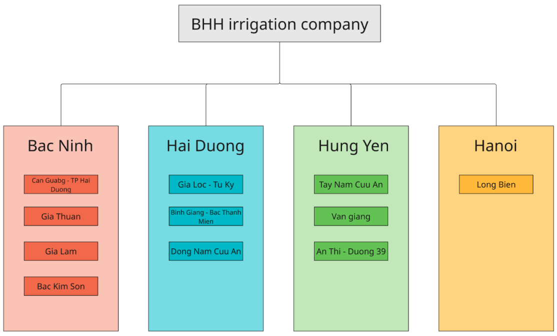


Figure 11.15: BHH Organogram

The hierarchical structure for water management communication is shown in Figure 11.15. For decisions concerning water management, the Bac Hung Hai Irrigation Company holds authority over the provinces, placing it above them in the decision-making hierarchy. They are also responsible for enforcing water policies and giving out fines when this is necessary. How much of this is done in practice is not clear.

Formal Communication lines

The communication structure that was identified during the field trip is strictly hierarchical, flowing bottom-up for requests and top-down for implementation:

Farmers - Districts

Farmers communicate their water needs directly to the district operating company. Together they draw up an annual water plan, which can be adjusted throughout the year. If water quality is too poor to use, farmers signal this to the district.

Districts - Provinces

Districts aggregate farmer demands and relay them upward. In emergencies (e.g., flooding or pollution), districts coordinate with other districts in the province and escalate to the provincial company. For pollution specifically, the district informs the province, which can then request flushing.

Provinces - Bac Hung Hai Company

Provinces combine district information and pass it to the Bac Hung Hai company. They have no direct contact with water users themselves. Water quality issues are flagged to the company, but it falls outside their direct operational scope.

Bac Hung Hai Company

Sits at the top, managing the 13 primary structures and inlets. It receives provincial requests and informs provinces about important system changes (e.g., water availability, flushing decisions). It also fields complaints about pollution from people, industry, and provinces, though its ability to act on them is limited by the lack of wastewater infrastructure.

These relations are formulated in a formal chart in figure 11.16 that shows the communication lines of water management within the BHH irrigation system. A formal chart visually maps the official hierarchy and responsibilities between actors, making it easy to see who communicates with whom and where authority sits within the system.

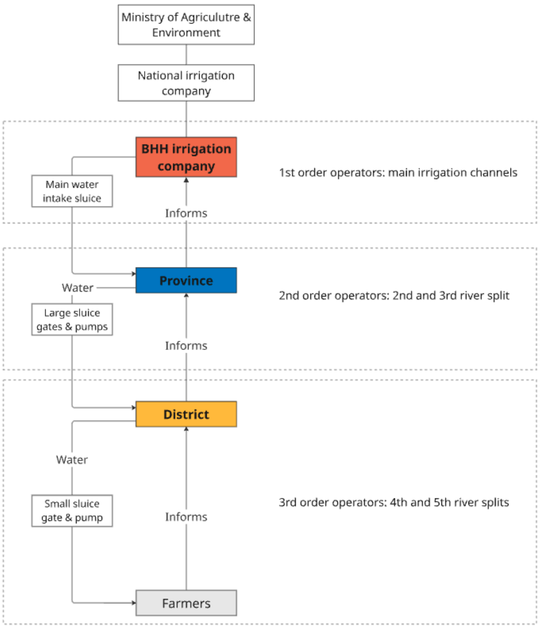


Figure 11.16: BHH formal chart

Actors within the system only communicate with those directly above or below them in the hierarchy.

As a result, a farmer's application must pass through multiple layers of bureaucracy before reaching the relevant authority. This also means, for example, that districts have no direct communication with the BHH company. It is important to note that the BHH irrigation company is not a governance actor since its primary role is to supply water and impose penalties on farmers. The core idea is that information flows up, water management decisions flow down.

Farmers submit their water requests to the districts. Districts combine these requests in a single request and then submit their water requests, after which the province consolidates these from all its districts into a single plan. The BHH company then reviews this plan and determines how much water each province will receive. The province and districts are subsequently responsible for ensuring the water reaches the right places. The province also plays a proactive monitoring role: if water quality is already insufficient, it can decide to close a sluice gate preemptively, before the situation worsens.

The key difference between a district and a province lies in the scope of usage data they handle. While districts report their own water usage, the province works with aggregated usage data collected from all its districts. At the operational level, districts are limited to basic controls, and they can only open or close sluice gates and switch pumps on or off.

Water management operations

The transport of water through the BHH system is organised hierarchically across three operational levels, mirroring the splits in the irrigation network shown in Figure 11.17. At the top, the BHH Irrigation Company controls the main intake from the Red River and manages the largest sluices that distribute water beyond the first split. Below this, the provinces operate the medium-sized sluice gates and pumps that direct water through the second and third splits towards their respective districts. At the bottom, districts run smaller pumping stations that deliver water to individual farmers upon request, corresponding to the fourth and fifth splits in the network. This layered structure is reflected in the formal chart in Figure 11.16, which shows how each operational level is matched to a specific tier in the communication hierarchy.

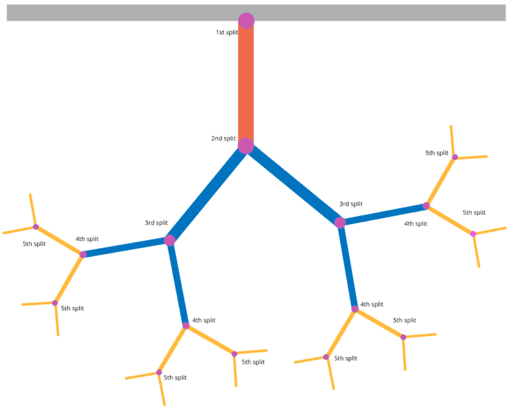


Figure 11.17: BHH splits in the network

Main takeaways

The actor scan highlights some governance issues in the region. Communication and water delivery operate on parallel tracks, with provinces and districts that cannot coordinate separately with the BHH Irrigation Company. The large number of smaller operators invites local optimisation, while the resulting fragmentation of responsibility means that actors tend to look to one another rather than addressing system-wide issues such as pollution. The structure is robust under stable conditions but poorly prepared for a more turbulent future. A possible improvement would be to shorten the upward chain of communication by allowing districts to talk more directly with the BHH Irrigation Company.

11.3.3. Survey

This section presents the results of the survey conducted among the local residents in the Bac Hung Hai area and first-year English students at HUNRE. The results are organised by group, covering the general characteristics of respondents, their daily experience with water, and their perceived problems and solutions regarding water management in the area.

11.3.3.1. Bac Hung Hai

General characteristics

A total of 17 responses were collected and included in the data analysis. Of the respondents, 11 had been living in the Bac Hung Hai area for more than 15 years, four for less than five years, and one between 5 and 15 years. One respondent indicated not living in the area; however, as this respondent did specify living in Hung Yen province, they were included in the analysis. In terms of geographic distribution, eight respondents were based in Hai Duong province, five in Hanoi, and four in Hung Yen. Regarding occupation, nine respondents identified as residents without agricultural or industrial activities, three as farmers or rice growers, and one as a factory or industrial worker. The remaining four respondents indicated other occupations, including a café worker, a staff member of the Bac Hung Hai Irrigation Company, a government official, and an office worker. To contextualise the survey findings, the demographic characteristics of the respondents are summarised in Figure 11.18.

Daily experience

The majority of respondents obtain water from a public pipeline (n = 12), of whom six rely exclusively on this source. Six respondents reported using rainwater collection, and six indicated using surface water, of which five draw from public surface water sources, two of whom use this as their only source, and one from a private surface water source. Two respondents use a well as part of their water supply. Four respondents indicated other water sources: three purchase water exclusively from a commercial clean water company, and one reported using water originating from the Song Da river.

The primary reason cited for choosing a particular water source was accessibility, mentioned by nine respondents, followed by cleanliness, mentioned by seven respondents, all of whom obtain water exclusively from a public pipeline or a commercial clean water company. Habit was mentioned by three respondents as a reason for their choice.

Regarding water use, respondents mostly use water for domestic purposes such as cooking, cleaning, and laundry (n = 15). Notably, 11 respondents also indicated using water for crop irrigation. These findings are visualised in Figure 11.19.

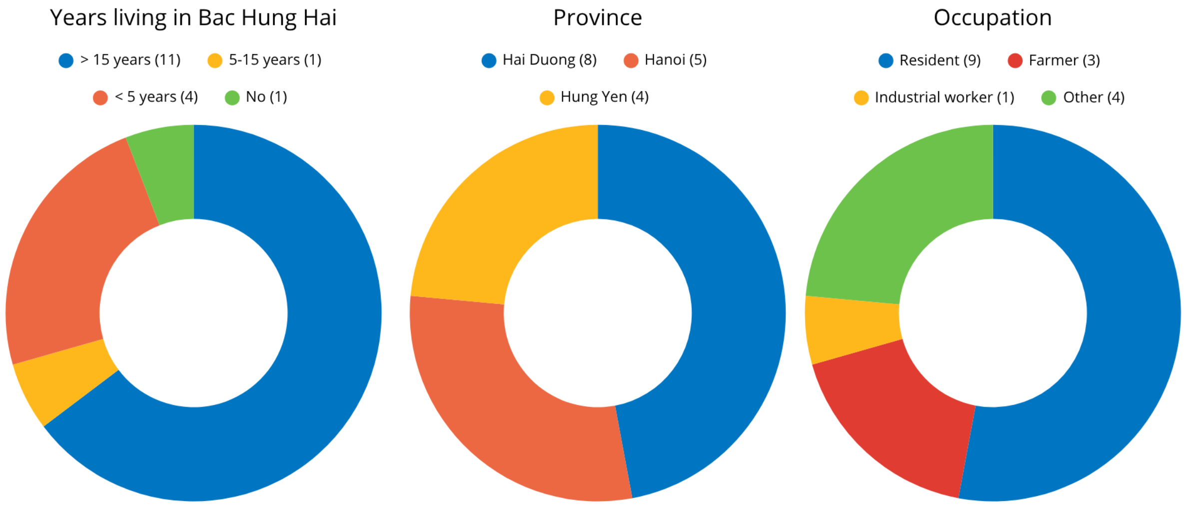


Figure 11.18: General characteristics of the respondents in Bac Hung Hai.

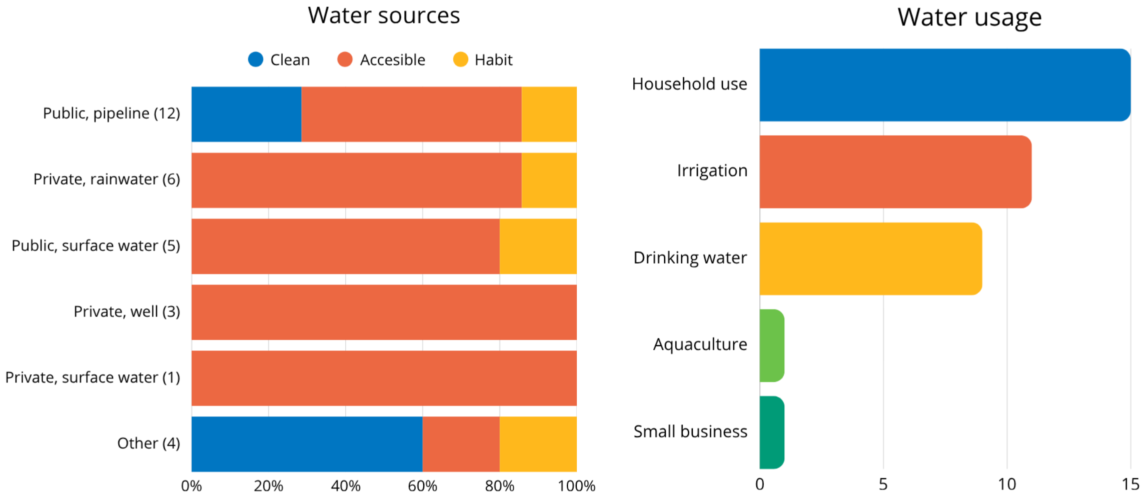


Figure 11.19: Water sources and use of the respondents in BHH.

Figure 11.20 presents the water quality characteristics as reported by the respondents. Water was described as completely clear by six respondents, all of whom rely exclusively on a public pipeline or a commercial clean water company as their water source. Among respondents using multiple water sources, combinations of quality characteristics were commonly reported. Of the six respondents who indicated that water quality varies significantly by season, five also reported using rainwater collection and five reported using surface water. The single respondent who described their water as saline or brackish relied on a well located in Hung Yen province.

When asked about changes in water quality and availability over the past ten years, the majority of respondents reported a deterioration in both (Figure 11.21). In terms of water quality, respondents described changes such as increased pollution during the dry season and surface water becoming darker. In terms of water supply, they mentioned having to switch to tap water and being seasonally dependent as well. Although a trend in decrease of quality and supply was mentioned by most respondents, some respondents relying only on water from pipelines mentioned an increase in quality and supply. They mentioned that the tap water is clean after treatment, and that the supply is getting increasingly better. Regarding water supply stability, respondents rated it at an average of 3.88 out of 5, where 1 indicates frequent shortages, and 5 indicates water always being available.

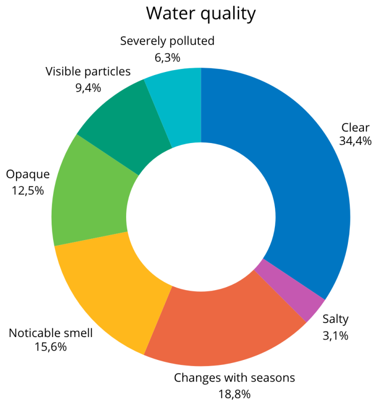


Figure 11.20: Water quality described by respondents in BHH.

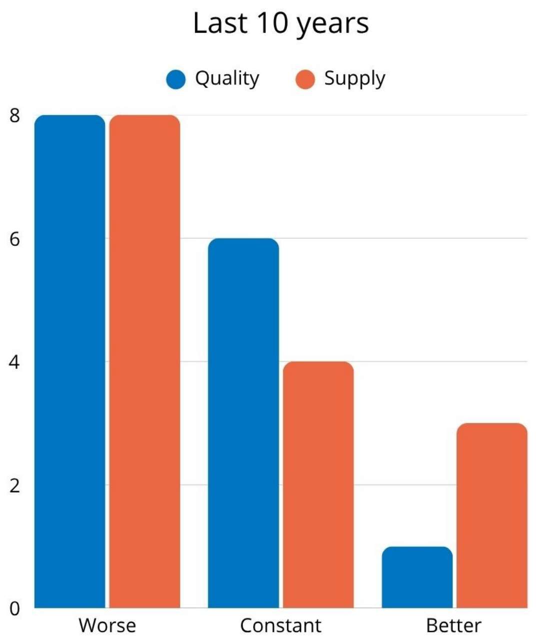


Figure 11.21: Change in water quality and supply in the last 10 years in Bac Hung Hai.

Regarding wastewater treatment, the majority of respondents indicated that they do not treat their wastewater prior to discharge (Figure 11.22). Nine reported applying no treatment at all. Five respondents use a septic tank, in which solid particles settle at the bottom and the remaining water is discharged back into the system. Two respondents make use of a drainage system, and one respondent has installed a personal filter.

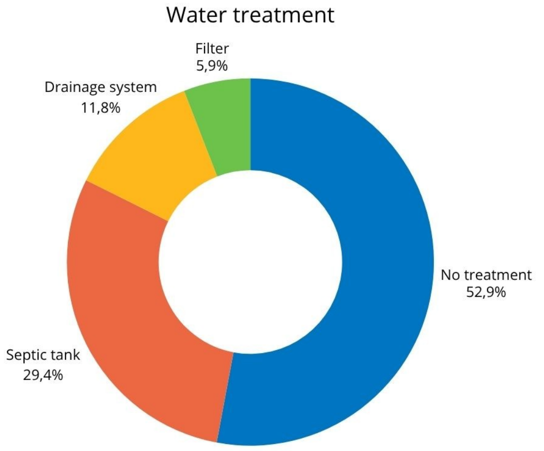


Figure 11.22: Ways in which respondents in Bac Hung Hai treat their wastewater.

Respondents who identified as farmers were asked additional questions regarding their agricultural practices. Of the three farmers, two indicated using pesticides. Despite this, all three expressed concern about the potential consequences of pesticide use on water quality in the area.

Perceived problems and solutions

When asked about the severity of water-related problems in the area, respondents gave an average score of 2.76 out of 5, where 1 indicates no problems and 5 indicates severe problems. The most frequently mentioned problem was water pollution, primarily due to industrial and factory discharge and the absence of a centralised wastewater treatment facility. Additional problems mentioned include saltwater intrusion and a monopoly on water distribution. When asked how the water situation had affected their personal life or work, several respondents reported a reduced quality of life or an effect on their health. Three respondents indicated that they had considered or already decided to stop farming as a result of the water problems. Proposed solutions included waiting for the water to become safe again, abandoning their land, or switching to perennial crops. Furthermore, two respondents indicated that water-related problems had led them to consider changing occupation and relocating to Hanoi.

Respondents generally attributed water problems to a combination of causes, with industrial factories (n = 15), domestic wastewater (n = 14), and agricultural activities (n = 14) cited most frequently (Figure 11.23). Similarly, when asked which parties should be involved in finding a solution, respondents indicated that this would require a combination of parties. People and communities were mentioned nine times, of which six times in combination with the central government. The provincial government was mentioned eight times, of which six times in combination with large-scale water users.

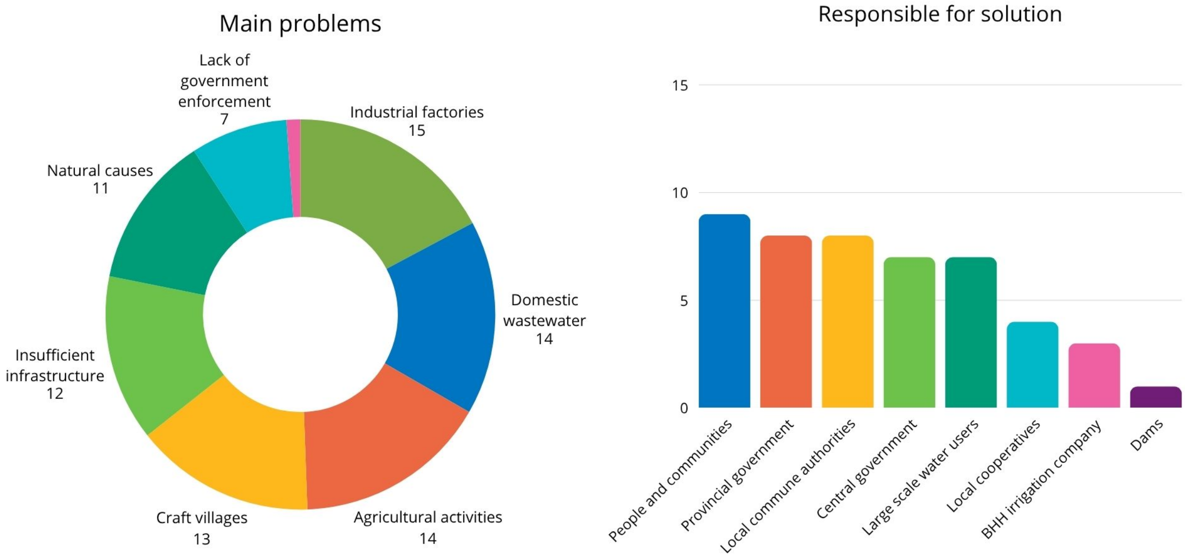


Figure 11.23: Main causes and organisations that should be part of the solution, as perceived by respondents in Bac Hung Hai.

11.3.3.2. HUNRE students

Another survey was done with English students at HUNRE, to obtain more quantitative results of the survey, with some students living or orginating in the Bac Hung Hai area. Because not all answers were related to the BHH area, results might be shown differently.

General characteristics

A total of 37 students took the survey, of which five students live in Bac Hung Hai (four for more than 15 years, one for less than 5 years). The other students are living in Hanoi province. All the participants are students, but some may have interpreted the questions as their family business, causing different results in occupation (Figure 11.24).

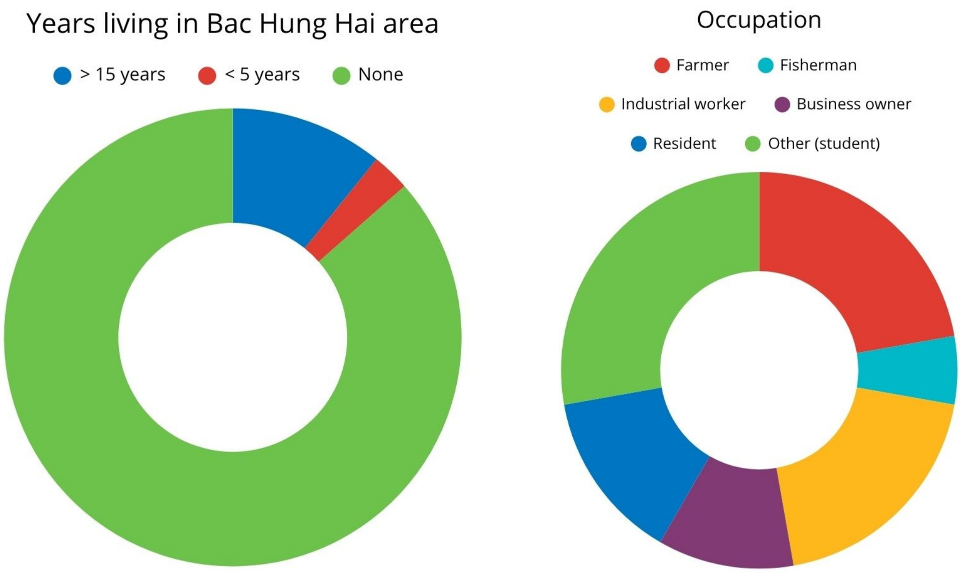


Figure 11.24: General characteristics of the HUNRE students.

Daily experience

From the results in different clusters, one can identify that public pipelines are the main water source according to the students (Figure 11.25). For the working class (which consists of 50% of farmers and fishermen), more than 80% of the water comes from public sources. While the residents show more use of private sources, such as private wells. Public pipes are primarily chosen due to their accessibility, affordability, and cleanliness. In contrast, when public pipes are not used, proximity becomes a more important factor, while cleanliness is mentioned less frequently. Private sources are mainly selected for their close proximity and ease of access. Percentages between Bac Hung Hai and Hanoi are roughly the same.

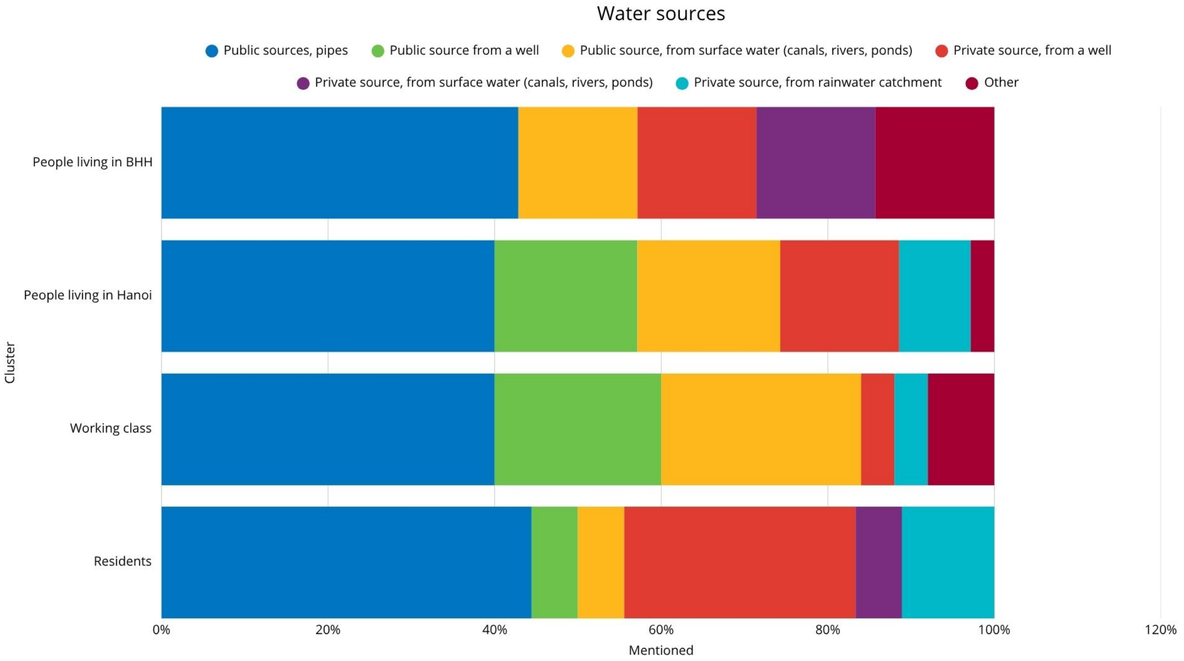


Figure 11.25: Percentual visualisation of people's water source. Divided in different clusters: People living in BHH, Hanoi; The working class and residents/students

Following this, respondents were asked how their water source has developed over the past ten years in terms of both quality and supply (Figure 11.26). These results include all responses and do not distinguish between the Bac Hung Hai area and other regions. Although only five responses originated from the Bac Hung Hai area, three of the six respondents who reported a worsening in water quality were from this region, while the remaining two indicated no change.

Looking further into the quality of the water, Figures 11.27 and 11.28 show comments of respondents on their water quality. Answers filtered in public pipes only (the most used source) and in combination with other sources. The figure clearly shows that the public source is mostly clean; when including other sources as well, the quality of observations worsens.

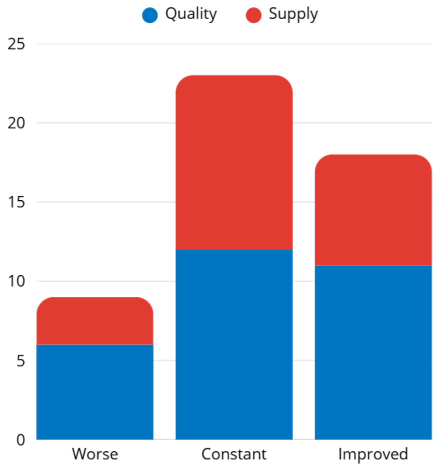


Figure 11.26: The mentioning of improvement or worsening of water supply and quality over the last 5 years

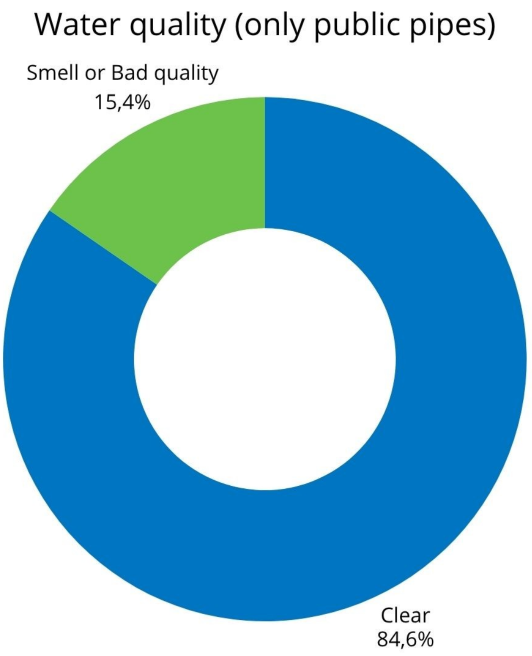


Figure 11.27: Quality of water looking at answers only mentioning using pipes.

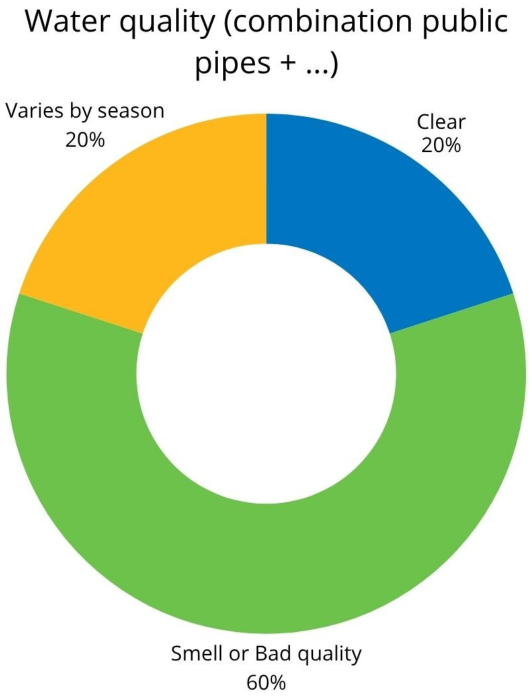


Figure 11.28: Quality of water looking at answers only mentioning using pipes in combination with other sources.

Figure 11.29 shows how people get rid of their waste water. To get an insight in comparison with the Bac Hung Hai area, these answers only include people who do not live in the area. The wastewater most likely has a big impact on water quality problems, seeing that about 20% of the answers dump waste in the surface water without treating. The drainage answers are uncertain since the people answering the survey don't know what happens with their drainage system. People who drain waste water into surface water: students (2), business owner (1), factory worker (1), farmer (1).

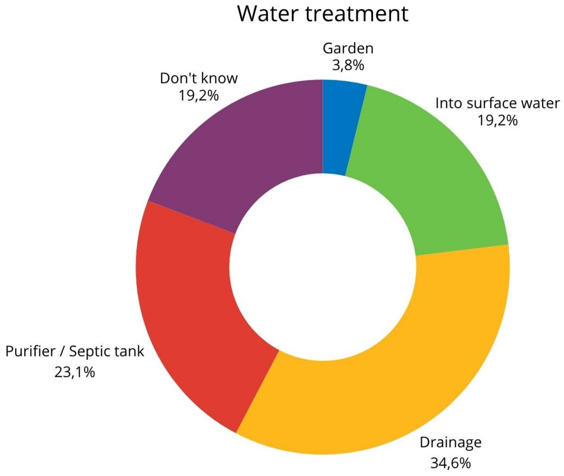


Figure 11.29: How people get rid of their wastewater. Only considering people not living in Bac Hung Hai area

Perceived problems and solutions

The overall changing land use in Bac Hung Hai and also in Vietnam is explained earlier. To find out reasons for changes in land use, the survey asked if people considered or actually changed their (work) activities. Bac Hung Hai mentioned a lot more change in work activities and actually stopping farming. From these answers 60% mentioned water pollution as a driver and 40% water availability.

The effects on people's life mostly considered health problems and everyday life activities (shower, cooking, etc.). A large part also mentioned no problems at all in their life.

Most of the answers for who should contribute to solutions in the Bac Hung Hai area mentioned "Provincial Government" or "Residents and communities. Figure 11.30 shows with what type of organisations these solutions should be paired with or none. Mostly, the answers determine a collaboration between a bigger and a smaller party.

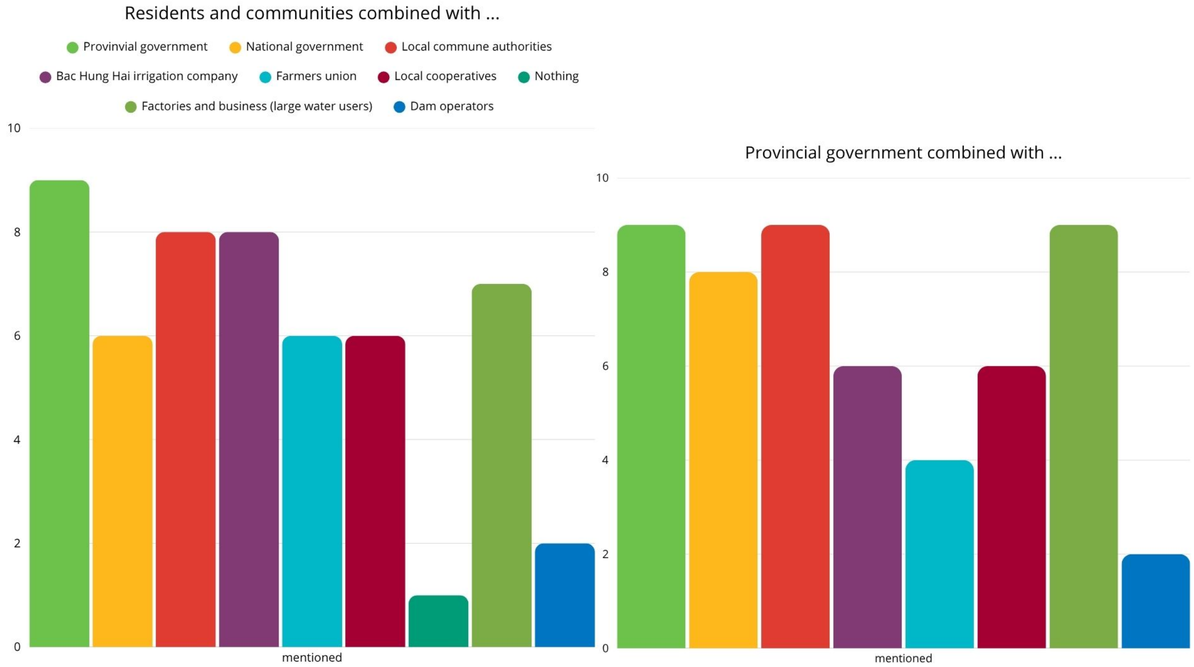


Figure 11.30: Visualisation of who should be part of the solution. Graphs are split into answers combined with "Residents and communities" and "Provincial government"

11.3.4. Water balance

The water balance gives an overview of the different fluxes throughout the seasons. The management influences these fluxes to ensure enough water storage within the system. To ensure enough water is available for irrigation, industry, and domestic use throughout the year.

Seasonal patterns

The water balance reveals clear seasonal patterns in the main fluxes of the BHH irrigation system. During the dry season, evaporation is relatively high while precipitation is low (Figure 11.31). Despite these conditions, the modelled delta storage remains positive throughout most of the dry months.

Outlet behaviour

Outlet discharge shows a strong seasonal pattern, with reduced or zero flow at several outlets during parts of the dry season (Figure 11.32). The average monthly discharge at each outlet over the period 2020–2026 is shown in Figure 11.32.

Inlet trend

A decreasing trend in inlet discharge is observed at the Xuan Quan inlet (Figure 11.33). Without pump operation, the trend shows a negative slope of -0.1052 m^3/s ($p = 0.066$), which is not statistically significant at the 5% level. When pump capacity is included, the trend becomes less pronounced (slope = -0.0487 m^3/s, $p = 0.419$), indicating that there is no statistical evidence of a trend under these conditions.

At the downstream inlet locations (Cau Cat, Cau Xe, and An Tho), a statistically significant decreasing trend is observed (slope = -0.0195 m^3/s, $p = 0.001$) (Figure 11.34). Although absolute discharge volumes at these locations are smaller compared to the upstream inlet, the consistent negative trend indicates a reduction in downstream intake over time.

Delta storage - precipitation correlation

A strong relationship is observed between precipitation and modelled delta storage (Figure 11.35). Periods of high precipitation correspond to increased storage levels. The correlation between precipitation and delta storage is high (Pearson $r = 0.87$, $p < 0.001$).

Water demand

Table 11.7 shows the water demand within Bac Hung Hai. This is calculated with the same method as Nghia (2016) but with updated quantities.

Category	**Water demand**	**Unit**
Domestic	4.20	m^3/s
Industrial	6.46	m^3/s
Agriculture	54.76	m^3/s
Aquaculture	3.52	m^3/s
Livestock	4.64	m^3/s
Environmental	7.36	m^3/s
Total	80.94	m^3/s
	99.03	mm

Table 11.7: Water demand per sector (adapted from (CityPopulation.de, n.d.; Food and Agriculture Organization of the United Nations, n.d.; General Statistics Office of Vietnam, 2024b; Vietnam Ministry of Construction, 2006)).

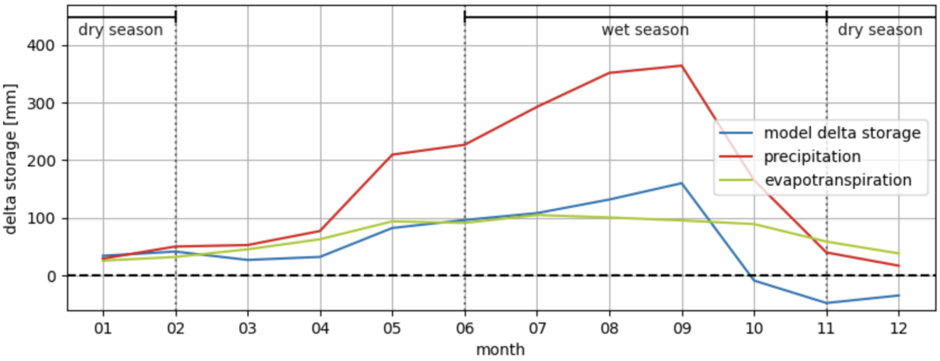


Figure 11.31: Average year over the period 2020–2026, including modelled delta storage. Satellite data were used for precipitation and evapotranspiration.

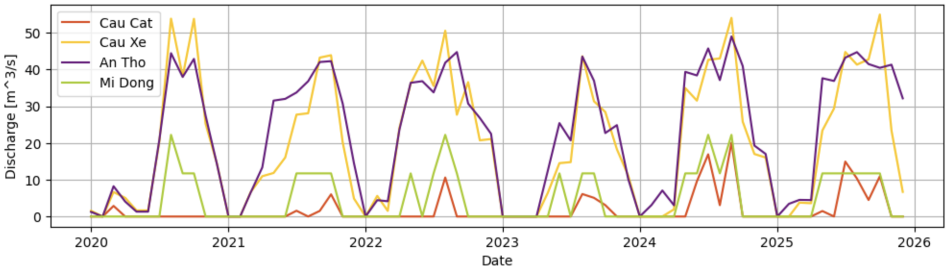
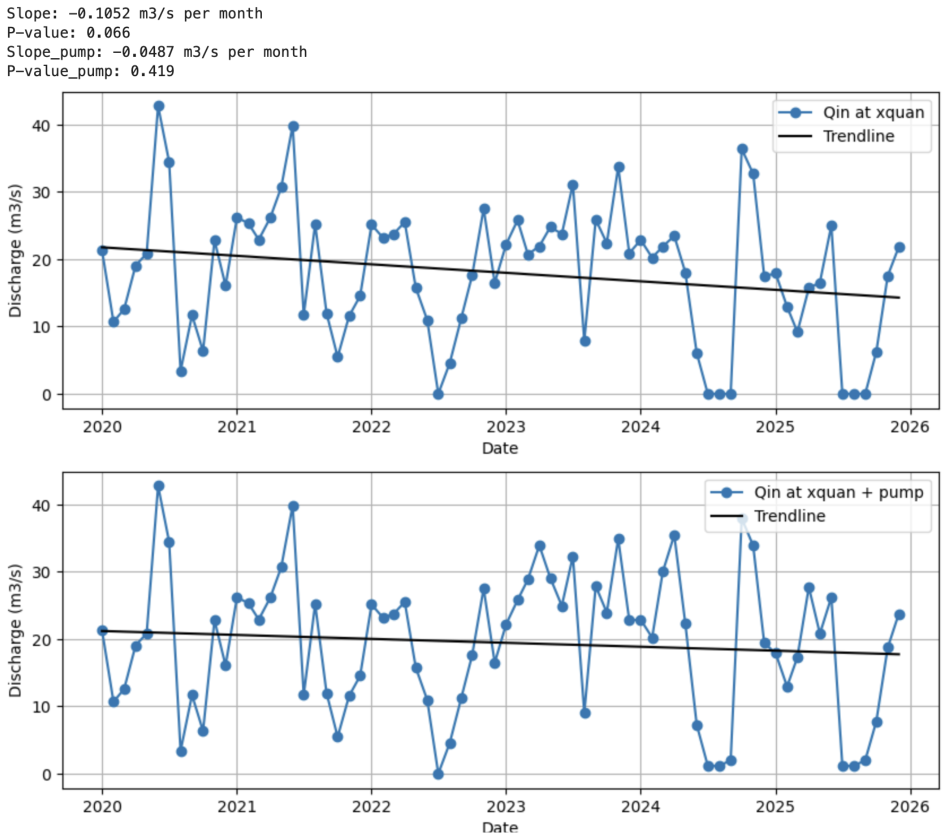
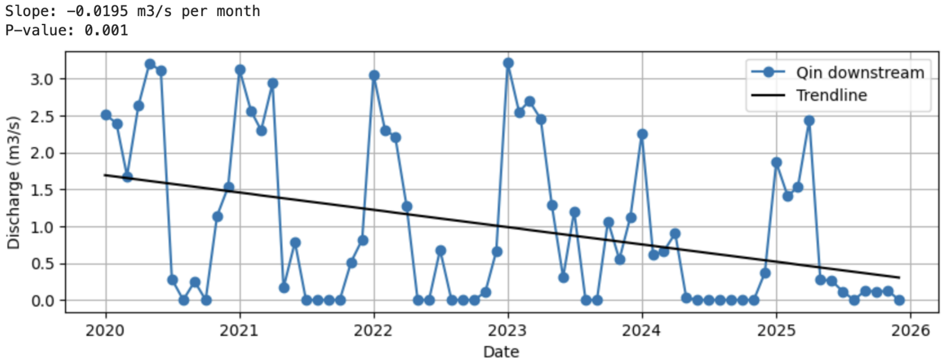


Figure 11.32: Discharge at outlet locations (m^3/s) at different river locks and the Mi Dong pump from 2020–2026.



```
Slope: -0.1052 m3/s per month
P-value: 0.066
Slope_pump: -0.0487 m3/s per month
P-value_pump: 0.419
```

Figure 11.33: Inlet discharge at Xuan Quan with and without pump capacity. Linear regression lines are shown for both cases.



```
Slope: -0.0195 m3/s per month
P-value: 0.001
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Figure 11.34: Inlet discharge at downstream locks (Cau Cat, Cau Xe, and An Tho) with linear regression.

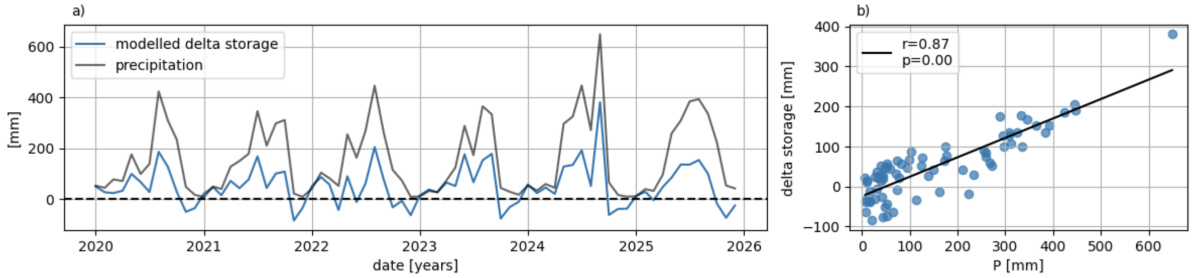


Figure 11.35: a) Absolute values of precipitation and modelled delta storage. b) Correlation between precipitation and delta storage (Pearson r = 0.87, p < 0.001).

11.3.5. System dynamics model

The system dynamic results consist of two main parts. First, the line plots of the model outcomes for the different scenarios. The chosen plots that are shown here are the same as the metrics as stated in the XLRM framework presented in the System Dynamics methods section in figure 11.9 It is important to note that the SD model is a very early version that is made with coefficients rather than real-world values. This means that it functions more as a proof of concept than a real model. This means that the results need to be seen in the larger picture of a proof of concept rather than stand-alone results that can be used for real-world application.

Regional Capital

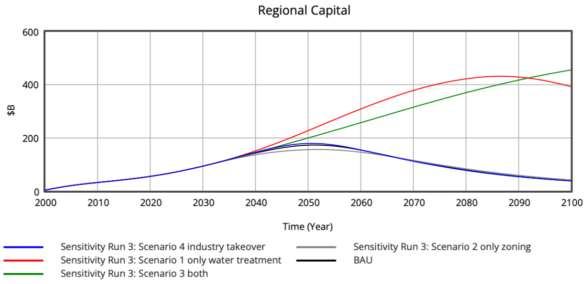


Figure 11.36: Regional capital over all 4 scenarios

Regional capital represents the value accumulated in the region over time. The graph shows two distinct types of behaviour. In the first, capital peaks around 2050 and then declines, which is the trajectory followed by the BAU, the zoning-only, and the industry-takeover scenarios. In the second, capital continues to accumulate steadily throughout the simulation period, as seen in Scenario 1 (only water treatment, red line) and Scenario 3 (combined, green line). Even in Scenario 1, capital growth eventually levels off and begins to decline around 2085, while Scenario 3 keeps accumulating capital until the end of the simulation. This indicates that water treatment is the most impactful policy: by limiting ecological degradation, it raises the ceiling at which the system would otherwise collapse, allowing capital accumulation to continue for longer and reach higher levels.

Water Quality

The graph clearly shows that once Scenarios 1 and 3 take effect in 2030, water quality begins to recover, even if only slightly. All other scenarios stay on the same downward trajectory, with water quality continuing to decline throughout the simulation. Zoning appears to have little to no effect on water quality, as the zoning-only scenario closely tracks the BAU.

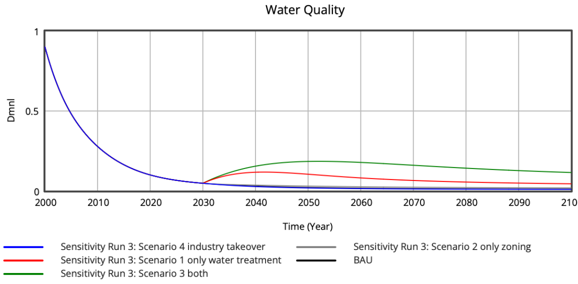


Figure 11.37: Water demand plot for different scenarios

Ecological health

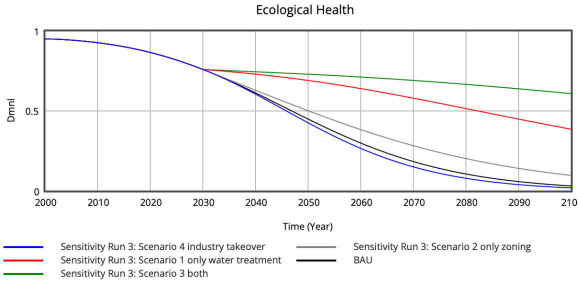


Figure 11.38: Ecological health plot for different scenarios

A similar pattern is visible for ecological health. The decline is much slower and shallower in Scenarios 1 and 3, again confirming that water treatment is the most effective policy and has the largest impact on the system's outcome. It is worth noting that the green and red lines still decline gradually throughout the simulation, indicating that water quality remains insufficient to fully halt ecological degradation, even though the situation is markedly better than in the other scenarios.

Water demand

The total water demand of the region decreases over time, which is logical given that agriculture has a higher water requirement per km² than either industrial or residential land use. As land is converted from agriculture to other uses, the overall water demand of the system therefore declines.

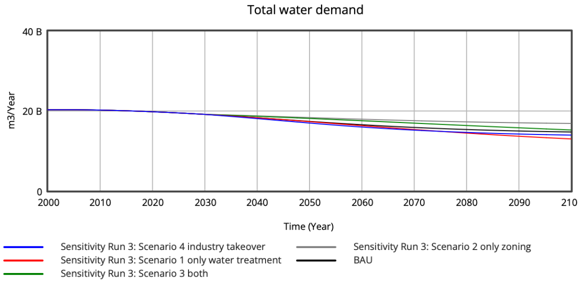


Figure 11.39: Water demand plot for different scenarios

Sensitivity Analysis

The sensitivity analysis examines how the performance metrics behave under variation in the model's input parameters. The different colours of the bands represent the confidence interval of the model output. The aim of the sensitivity analysis is to assess how trustworthy a single model run is and to determine whether small changes in input values lead to substantially different outcomes.

All scenarios use the same colour scheme for the confidence interval plots:

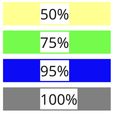


Figure 11.40: Sensitivity Plot confidence interval legend

Before any policy scenarios are plotted, a benchmark is needed to serve as the baseline for further analysis. This benchmark is provided by the Business as Usual (BAU) scenario, in which all policy levers are switched off, and the system is allowed to evolve under current trends without intervention. The BAU represents the natural flow that the system would follow if no action were taken.

By comparing the model behaviour under different policy settings to the BAU, it becomes possible to assess whether the policy levers have a significant effect on the system.

In this report, the scenario settings are mainly used to test the influence of the policy levers rather than to predict specific outcomes. A more sophisticated model calibrated with real-world data could be used to generate rough predictions of future system trajectories, but since the current model is not tuned to that level of precision, there is no need for empirically based lever settings.

The BAU scenario serves as a benchmark against which subsequent scenarios are compared. By contrasting the model behaviour under different policy settings with the BAU baseline, it is possible to assess whether the policy levers have a significant effect on the system.

Scenario 0: Business As Usual

For the BAU all policy levers are switched off.

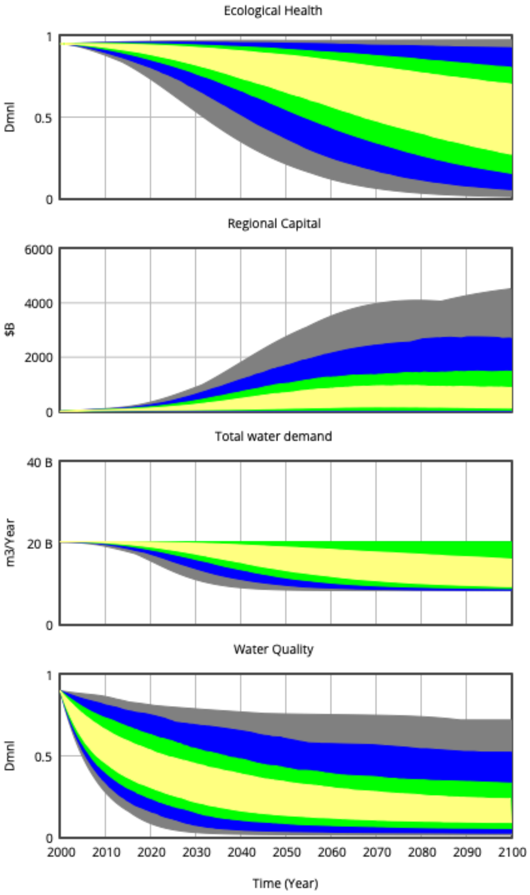


Figure 11.41: SD model output Business as usual

Lever settings	
Domestic water treatment	Off
Industry water treatment	Off
Industrial land zoning	Off
Domestic land zoning	Off

Table 11.8: Lever settings for Business As Usual Scenario

The output shows a steady decline in ecological health throughout the simulation period, eventually approaching zero. Water quality drops sharply in the first decades and stabilises at very low values.

The BAU shows what the consequences are of unconstrained development: short-term economic growth is achieved at the cost of long-term ecological collapse.

Scenario 1: Only water treatment

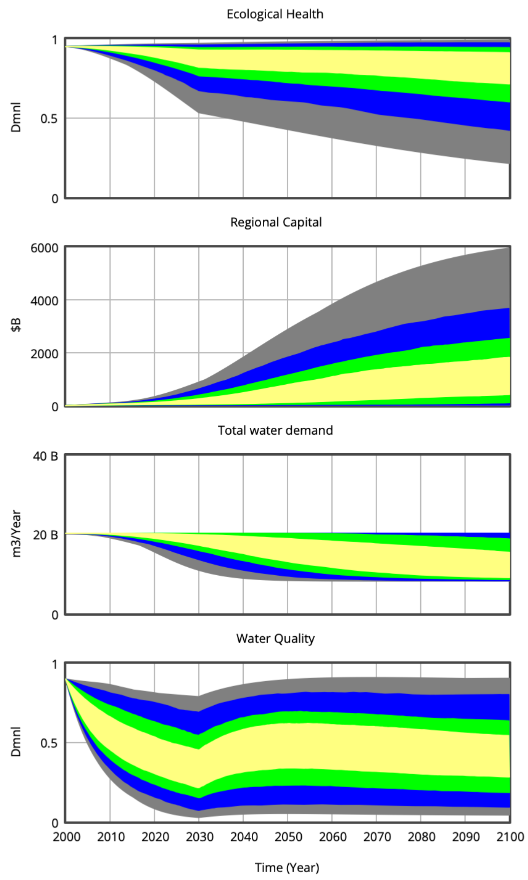


Figure 11.42: SD model output for scenario 1

Lever settings	
Domestic water treatment	70%
Industry water treatment	80%
Industrial land zoning	Off
Domestic land zoning	Off

Table 11.9: Lever settings for scenario 1

In the water-treatment-only scenario, we can see a clear impact on the system output. Water quality shows a hockey-stick curve, recovering noticeably after the policy kicks in, and this effect carries through to ecological health. The ecological decline becomes much slower, although it does not fully stabilise. Regional capital reaches a much higher ceiling than in the BAU since the system avoids collapse and can keep growing for longer. Water demand, on the other hand, appears largely unchanged compared to the other scenarios.

Scenario 2: Only land zoning

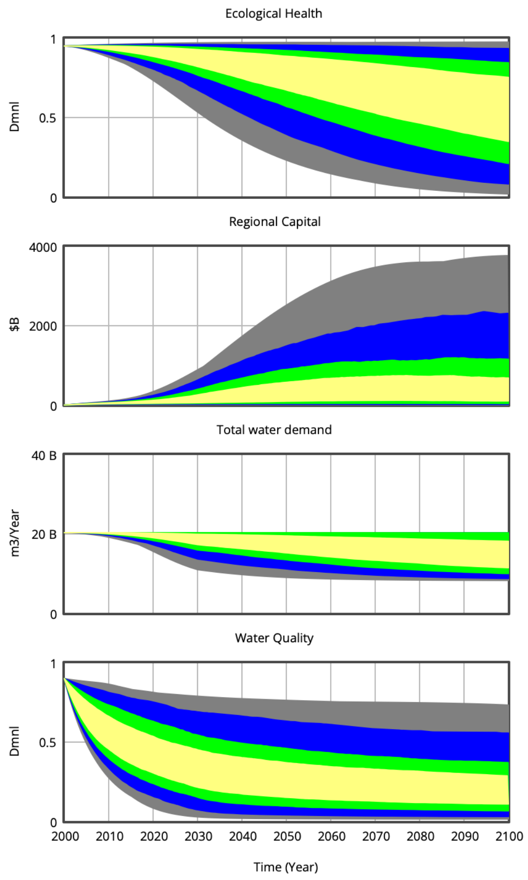


Figure 11.43: SD model output for scenario 2

Lever settings	
Domestic water treatment	Off
Industry water treatment	Off
Industrial land zoning	60%
Domestic land zoning	50%

Table 11.10: Lever settings for scenario 2

In the zoning-only scenario, water treatment is switched off and only land-use restrictions are imposed. The improvement compared to the BAU is marginal: water quality remains low throughout the simulation and ecological health continues to decline towards values close to zero. Regional capital is also lower (around 3,000–4,000 $B), since restricting land conversion limits industrial expansion. Zoning alone therefore, reduces economic output without delivering meaningful environmental benefits.

Scenario 3: Both Zoning and Water Treatment

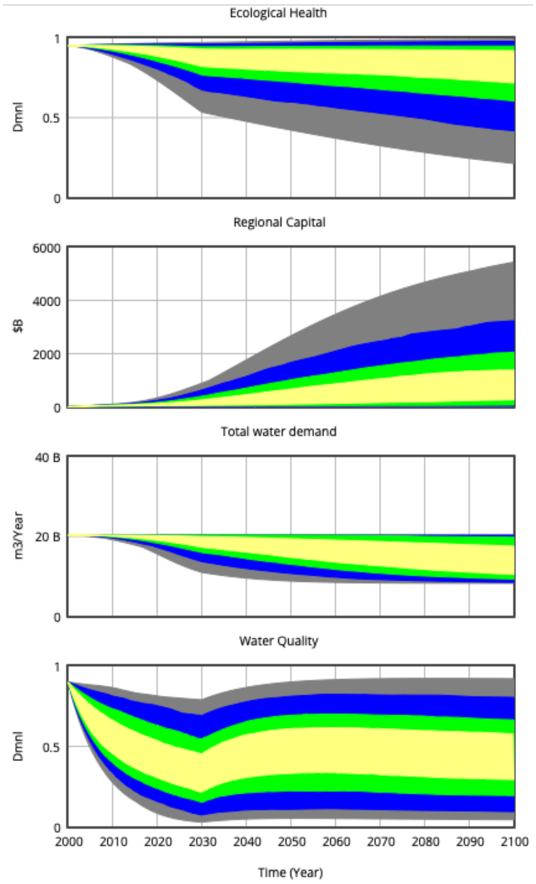


Figure 11.44: SD model output scenario only water treatment policies

Lever settings	
Domestic water treatment	70%
Industry water treatment	80%
Industrial land zoning	50%
Domestic land zoning	40%

Table 11.11: Lever settings for scenario 3

Combining both levers produces results that are very similar to the treatment-only scenario. Water quality and ecological health recover to comparable levels, but regional capital is slightly lower (around 5,500 $B) due to the additional zoning constraints. The marginal contribution of zoning on top of water treatment is therefore small.

Scenario 4: Growth acceleration

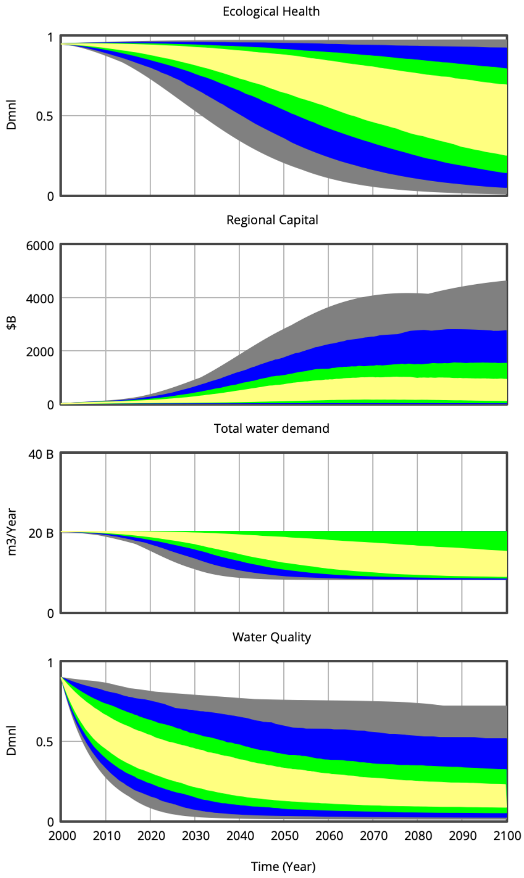


Figure 11.45: SD model output for scenario 4: growth acceleration without treatment.

Lever settings	
Domestic water treatment	Off
Industry water treatment	Off
Industrial land zoning	-30%
Domestic land zoning	-20%

Table 11.12: Lever settings for scenario 4

In this scenario, industrial development is actively encouraged, and no water treatment or zoning constraints are applied. The output closely resembles the BAU: ecological health declines steadily towards near-zero values, water quality drops sharply in the first decades and stabilises at very low levels, and regional capital follows a similar growth trajectory. The fact that aggressively expanding industry produces results so close to the BAU shows that the system is already operating close to its degradation ceiling under unconstrained conditions. In other words, leaving water treatment switched off is in itself one of the most damaging policy choices, since the system collapses regardless of whether industrial growth is moderate or accelerated. This further reinforces the conclusion that water treatment, rather than zoning or growth control, is the decisive lever for protecting the BHH system.

Insights

The results indicate that water treatment is by far the most effective policy lever for protecting the BHH system. Scenarios that include treatment achieve substantially better water quality and ecological health than the BAU, while also maintaining strong regional capital growth.

The amount of pollution determines how fast the system collapses, meaning that decreasing the pollution is most important for a sustainable region. Even if it only extends the lifespan rather than makes the system sustainable.

Zoning, in contrast, produces only minor improvements over the BAU and comes at the cost of reduced economic output. Within the structure of this model, investment in water treatment infrastructure therefore appears to be the most promising policy direction, while zoning on its own is insufficient to safeguard the system.

11.4. Discussion

In this chapter, the results are interpreted in relation to the CLD. The findings of this study confirm that water quality is indeed a key issue in the Bac Hung Hai system. Observations from the field visit indicate that ongoing urbanisation and industrialisation contribute to a deterioration of water quality. In addition, survey results suggest that farmers in the Bac Hung Hai area are changing occupations, which aligns with the feedback between declining water quality and reduced agricultural activity in the CLD. However, the influence of groundwater extraction on water quality, as proposed in the CLD, could not be confirmed based on the applied methods. This suggests that this mechanism may play a smaller role within the system than initially assumed, or that its effects were not captured within the scope of this study.

In the following subsections, the findings are discussed for each of the key relationships between sectors. This is followed by a reflection on the limitations associated with each method.

11.4.1. Environment & Water

Low river discharge at outlet locks

As seen in the results of the water balance, sometimes the outlet discharge is zero or almost zero. Besides this, the survey showed that people experience different water qualities throughout the seasons. This is because operators want to ensure sufficient water is available within the irrigation system. In dry periods therefore the outlet through the rivers is minimised since the inflow (through the rivers and precipitation) is small. This is due to the seasonal characteristics of the system, as explained in the literature. This really slow flow will result in a decrease in the water quality within the system. Furthermore, zero discharge makes it impossible to flush the system to increase the water quality. It is currently used as a method to try to meet the water quality standards. Therefore, it is possible that there is a sufficient quantity of water available within the system, while the quality is not sufficient. Inhabitants can still experience a water shortage. This could be a reason why inhabitants explained during the survey that they use several water sources. To ensure they will not experience water scarcity. Discharge through rivers could be an indicator of water availability. If the discharge is large enough, it means that there is enough water available for storage (otherwise the locks would be closed) and the quality is more likely to be sufficient. Therefore, this is a better indicator for the available water within the system than the storage change. Since this indicator also takes water quality into consideration.

Water pollution upstream

Next to that, the results showed that a lack of water treatment facilities upstream results in a large pollution source at the beginning of the system. The survey showed that large groups of respondents not living in Bac Hung Hai, do not treat their water. If their living area is upstream, this will result in a gathering of contaminated water at the beginning of the system. Such a gathering location was visited during the field visit. At this site, it was visible that the polluted water entering Bac Hung Hai has a different composition from the fresh water. This polluted water results in a separation line at the beginning of the system and a congestion of the polluted water. Since there is a very slow flow, the soil in these locations will be largely contaminated. The consequences of this contaminated soil will remain in the system for a very long time. When wastewater treatment facilities resolve this pollution source, the soil will still pollute the water passing this point. In addition, the water balance showed that agriculture is the largest water consumer in the system, and will therefore be strongly affected by this polluted water. Since the water quality will be strongly influenced by the quality of the soil, soil quality could be a potential indicator for water pollution. The soil contains more information about the long-term consequences than the water itself. However, this relation needs more research to confirm whether this indicator is useful.

Sensitivity to flooding

The results show a strong correlation between precipitation and a large delta storage. If the delta storage in combination with the previous storage is too large, flooding can occur. Currently, an area is sacrificed to protect another area during floods. The storage that Bac Hung Hai can buffer decreases due to illegal developments close to the riverbanks. Furthermore, climate change is expected to increase the frequency of peak precipitation events. Due to these events, the outlet points downstream are not able to discharge enough water. This results in an increase in expected flood damage. Currently, more pump capacity is being built to increase the drainage capacity. When the illegal development continues, the demand for drainage capacity keeps increasing. Next to that climate change will also increase the need for pumps. This will all cause an increase in the energy demand. The drainage capacity could be an indicator of vulnerability to flooding. Furthermore, the precipitation predictions could be an indicator to show the likelihood of flooding events.

11.4.2. Food & Water

The survey results indicate that water-related problems are already affecting agricultural activity in the area. Three respondents had considered or decided to stop farming due to water quality issues. Notably, 11 people indicated using water for irrigating their crops, while only three out of these answers were actual farmers. Meaning, a large number of people also have crops for domestic use only. Contributing to the importance of water quality in the area even more.

The actor analysis adds a governance dimension to this relationship. The communication structure within the Bac Hung Hai system is hierarchical, meaning that a farmer's water quality concern must pass through multiple administrative layers before reaching the Bac Hung Hai Irrigation Company. The company has limited capacity to act on complaints of pollution due to the absence of wastewater infrastructure.

The water balance results add a further dimension to this vulnerability. The declining free-flow intake at both the upstream and downstream inlet points suggests that water availability for irrigation may decrease in the future. Furthermore, peak precipitation events and large increases in storage indicate a growing risk of flooding, which can cause damage to crops and agricultural land.

11.4.3. Energy & Water

As visible in the results of the water balance, the free flow inlet has decreased the past year. This observation has been confirmed by operators during the field visit.

Upstream at Xquan inlet: The operators say this is likely a result of the lowered riverbed in the Red River. As explained in the literature, this is caused by sand mining and the reservoir-dam systems that cause sand trapping. Both a result of an increasing population growth, urbanisation, and industrialisation, which cause an increase in the construction sand demand and energy demand. Both are expected to keep increasing in the future, and therefore the found declining trend in the results is expected to continue in the future.

Downstream inlets: The operators explained during the field visit that saltwater is observed more frequently at the downstream inlet points. Forcing them to close the locks, resulting in less inlet. As found in the literature, this increase in saltwater intrusion is caused by river bed lowering and amplified by climate change. The river bed lowering, caused by sand mining and sediment trapping, results in an increase in tidal amplification. This is amplified by a rising sea level. Therefore, it is also expected that in the future the downstream locks cannot open due to salt water.

To ensure a sufficient water inlet, an increased pump capacity is needed. Currently, extra pump capacity is being built at the Xquan inlet; in the future, this problem will only worsen, therefore it is expected that more pumps will be necessary. These pumps use electricity, which therefore will create a higher energy demand. Resulting in a trade-off between energy and water.

An indicator for the amount of electricity needed could be a waterbed change, to monitor the change that causes the lowering water levels. As long as the waterbed decreases, more pump capacity will be needed in the future.

11.4.4. Cultural context

Survey respondents consistently indicated that solutions to water problems should involve a collaboration between local stakeholders and larger governmental or institutional actors. However, the actor analysis revealed that the current governance structure is strictly hierarchical, with actors at different levels having no direct communication with one another. Local organisations and districts cannot engage directly with the Bac Hung Hai Irrigation Company. This mismatch between the collaboration favoured by residents and the structure of the water management system creates a barrier to effective water management. Information and requests must pass through multiple levels before reaching the relevant authority, reducing both the speed and effectiveness of responses to water-related problems. The number of communication layers between a water user and the decision-maker could serve as an indicator of governance efficiency. A reduction in the number of levels required for communication could be an improvement in water management functioning.

11.4.5. Research limitations

Survey

The survey of this study is subject to several limitations. First, the number of participants was relatively small, which limits the generalizability of the findings. In addition, there is an uncertainty regarding whether all respondents fully understood the survey questions. For example, differences between concepts such as water quality and water supply may not have been clear to all participants. This issue was further worsened by language barriers, as some respondents, especially students, had limited knowledge of English. Consequently, their responses may not accurately reflect their true perceptions. For this reason, they were only considered qualitatively as a comparison with the Bac Hung Hai responses. Therefore, no firm conclusions can be drawn from this subgroup, although they may indicate directions for future research. Furthermore, as respondents could indicate multiple water sources, it was not possible to directly link specific problems to individual sources. This limits the interpretability of the survey results.

Water balance

The water balance model contains several simplifications that affect the reliability of its outputs. An output of approximately 45 mm per month is missing, suggesting that the outflow is currently underestimated. As a result, the system appears to overflow. Lock operations are approximated due to the complexity of the Excel sheet, which leads to occasional underestimation of in- and outflow at the downstream locks. Finally, pumping data was unavailable, resulting in assumptions being made about pump contributions. During peak events, this may result in an underestimation of outlet discharge. These limitations mean that the water balance results should be interpreted as indicative of system behaviour rather than precise quantitative estimates.

System dynamics model

The system dynamics model has several limitations that should be considered when interpreting its output.

First, the BHH system is treated as an independent system: inflows of clean water, outflows of polluted water, and the influence of the surrounding land on the system are not represented. Because the model does not draw on input from a water balance, its results should be regarded as indicative rather than quantitatively precise. Further model development could establish this connection and thereby improve the usability of the output. Nevertheless, the current model still fulfils its purpose of illustrating the effects of sustained pollution on the system.

Secondly, the impacts of pollution sources on the WQI ratio are represented through coefficients that act as a surrogate for more intricate system dynamics. These coefficients, together with the lookup tables used to determine the strength of different effects, are based on educated estimates and have been tuned to produce realistic timing rather than calibrated against real-world measurements. As a result, they strongly influence the model's output. The coupling between GDP and ecological quality is likewise fixed at a predetermined level rather than derived from data.

Thirdly, the model is built as a proof of concept for later research to prove the functionality in a WEFE nexus context. This means that the model should not wholly be judged on its performance but also on its feasibility for future projects.

Finally, the model includes several structural simplifications. Land-use conversions are one-way and final: residential areas cannot revert to industrial use, nor can industrial areas revert to residential. There is no feedback from the system to population health or demographics, despite the fact that such effects would be expected in reality. The model also contains no link between residential and industrial development, even though people generally need to live near where they work.

12

Conclusion

This study aimed to answer the following research question: *What methods and indicators can be used to assess the WEFE Nexus in the Thac Ba reservoir–dam system and the Bac Hung Hai irrigation system?*, with the broader objective of contributing to the development of generalizable methods and indicators for the Red River–Thai Binh basin.

For the Thac Ba reservoir–dam system, the combined application of a water balance and scenario analysis proved effective in identifying key indicators related to water availability and food security. Precipitation and discharge were found to be critical indicators for assessing excessive water quantity, while the Water Stress Index (WSI) and subsurface storage were identified as relevant indicators for food security.

Although the stakeholder analysis did not directly result in indicators, it provided important insights into the social dimension of the system. It helped identify vulnerable stakeholder groups that should be monitored to prevent disproportionate impacts. This highlights the importance of adding qualitative approaches when assessing the WEFE Nexus.

In the Bac Hung Hai irrigation system case, a combination of a field visit, social surveys, actor analysis, water balance modelling, and a system dynamics model was used to identify relevant WEFE Nexus indicators. The field visit and actor analysis primarily contributed to identifying communication-related challenges. These methods led to the definition of the indicator: the number of communication barriers, highlighting difficulties in coordination between stakeholders.

Indicators related to water quality were derived from the water balance analysis in combination with the field visit and the system dynamics model. The indicator soil quality followed from the field visit. Furthermore, the outlet discharge through rivers results from the water balance method. In addition the system dynamics model showed the importance of the indicator of the percentage of treated wastewater relative to total water flow. All three methods contributed to different indicators that monitor several aspects of the water quality. This shows the importance of applying multiple methods, if only one methods was used only one of the indicators would have been found and the challenges would be monitored one dimensional. This also suggests that there are additional methods that could provide an more extensive monitor system.

In addition, the reduction in inlet capacity was linked to the level of the riverbed. While flooding sensitivity was assessed using drainage capacity and precipitation forecasts. These indicators followed from the water balance and have been confirmed by the field visit. Together, these indicators capture key pressures on both water availability and system resilience.

The social survey did not directly result in additional indicators, as the answers were less reliable. As a result, its contribution to the analysis was limited in this study. However, this does not imply that social surveys are not valuable, but rather that their effectiveness depends strongly on data quality.

This study demonstrates that a combination of qualitative and quantitative methods is required to effectively assess the Water–Energy–Food–Environment (WEFE) Nexus in complex systems. The results show a significant difference between key challenges identified in the literature and those derived from the applied methods in the case studies. This highlights the importance of carefully considering the context, as the specific characteristics of a system and its cultural setting can lead to substantially different outcomes. Moreover, it suggests that directly transferring methods and indicators without critical adaptation risks losing important contextual information, potentially leading to incomplete or misleading assessments. This underscores the challenges associated with the broader objective of developing generalizable methods and indicators for the Red River–Thai Binh basin.

13

Recommendations

This chapter presents recommendations structured in three levels: first, methodological improvements for future case studies at similar sites; second, unexplored links within the CLD that warrant further investigation; and third, directions towards a basin-wide WEFE Nexus assessment for the entire Red River–Thai Binh basin. Together, these sections provide a roadmap for future research groups.

13.1. Methodological improvements

The methods applied in this study provide a solid foundation for future research in similar contexts. However, several improvements are recommended when applying these approaches to other dams or irrigation systems in the region.

13.1.1. Thac Ba

Water balance and scenario analysis

The monthly timestep used in this study is insufficient to capture extreme discharge peaks and short-duration flood events. Future studies should use daily input data to better resolve these dynamics, particularly during periods of intense rainfall when peak discharges are most consequential for dam safety and downstream flooding risk.

A second limitation concerns the influence of Chinese upstream dams. At least four hydropower reservoirs operate upstream of the Thac Ba catchment on the Chinese side of the border, yet their operations are not incorporated in the water balance. Including these reservoirs, either through coordination data or by representing them as a regulated inflow boundary, would substantially improve the accuracy of simulated reservoir inflows. Especially during dry periods when their buffering effect is most pronounced.

Several key model parameters, including the maximum groundwater storage and precipitation partitioning factor, are currently based on literature-derived assumptions rather than field measurements. Future studies should calibrate these parameters against observed data or supplement them with field campaigns. In particular, the model consistently overestimates reservoir storage, as noted in the validation results; refining the groundwater storage parameters is the most likely avenue for reducing this bias.

Finally, the estimation of future evapotranspiration in the scenario analysis introduces additional uncertainty because it is not derived from physically consistent model-based projections. A more robust approach would be to use climate model output that provides consistent temperature and humidity projections, or to estimate evapotranspiration as a residual term in a constrained water balance, thereby avoiding the compounding of separate projection uncertainties.

Stakeholder analysis

The stakeholder analysis in this study was based primarily on secondary sources such as academic literature, news articles, and company reports due to the absence of fieldwork. While this provided a useful overview of formal actors and governance structures, it likely does not include informal institutions, local-level perspectives, and recent developments that are not yet captured in published sources. Future studies should complement document analysis with in-person interviews or structured surveys targeting local communities, ecotourism operators, and downstream residents. Such primary data would also allow for validation of the power–interest positions assigned in the current analysis, which were necessarily based on interpretation of secondary sources alone.

13.1.2. Bac Hung Hai

Water balance

The discharge estimation method used in this study combines lock operation logbooks with observed water levels and a fixed fractional coefficient to represent the proportion of time each lock is open. Two improvements are recommended. First, the exact opening and closing times recorded in the logbook should be used directly, with discharge derived from the corresponding water level differences at those specific moments, rather than from a daily average fraction. Second, hourly water level recordings, rather than the current six-hour interval data, would improve temporal resolution if available from system operators.

Storage within the system is currently estimated from satellite-derived water surface observations. On site storage measurements, if obtainable from system operators, would reduce the dependence on remote sensing data and improve the reliability of the estimated water balance.

Finally, the current model does not explicitly represent flooding, baseflow, or groundwater recharge. Incorporating a delayed baseflow component would better capture the lag between precipitation events and system response. Quantifying groundwater recharge would also establish a more direct link between the water balance and food security outcomes, as it enables estimation of soil moisture availability for crop uptake, a connection that the current model cannot make.

Survey

Several methodological improvements are recommended for future survey implementation. Distribution via QR code created a barrier to participation and resulted in a low response rate; in-person distribution is advised in the future to increase the number of usable responses. For richer qualitative insight, structured interviews are preferable over open-ended survey questions, as the outcome conducted only brief and difficult-to-interpret responses in the current study. It is also important to assess the knowledge level of respondents, for example, by including a short screening question. This, so that the reliability of individual responses can be weighted accordingly during analysis. Finally, questions regarding water sources should be restricted to a single answer, as multiple-response options complicated the identification of meaningful associations between variables.

System dynamics model

The modelling shows that it is possible to integrate socio-economic features into the broader context of the WEFE Nexus. By making the links between system features, policy levers, and outcomes explicit, the model helps to identify which variables behave as meaningful WEFE indicators for the region. Variables that respond strongly to changes in pollution, land use, or treatment policies are more useful as indicators than those that remain stable across scenarios, since they capture the dynamics that ultimately determine the state of the system. In this way, the modelling provides a structured way of distilling a complex set of interactions into a smaller set of indicators that can inform both analysis and policy.

A key limitation is that the system dynamics model currently operates independently from the water balance. Establishing a connection between the two models. So that simulated water availability and pollution loads inform each other. This would substantially improve the realism and policy relevance of both. Future research should therefore apply this integration. In addition, the model does not represent health or demographic feedbacks, despite the fact that sustained poor water quality would be expected to affect population health and, in turn, labour productivity and economic output. Incorporating such feedbacks is recommended for subsequent model iterations.

13.2. Missing links in the CLD

13.2.1. Thac Ba

The CLD developed in this study captures the main feedback loops between hydropower operations, climate extremes, flooding, agricultural output, and local livelihoods. Several links identified during the analysis were not fully investigated and require further research.

The relationship between upstream dam operations, the Chinese reservoirs, and sediment dynamics in the Thac Ba reservoir remains unquantified. Hydropower dams are known to trap significant sediment loads, reducing reservoir storage capacity over time and altering downstream geomorphology; quantifying this for the Thac Ba system would improve both the water balance and the long-term sustainability assessment.

The link between ecotourism and reservoir management has not been formally investigated. The attractiveness of the reservoir as a tourism destination is sensitive to water levels, water quality, and landscape conditions, all of which are influenced by dam operations. Establishing this relationship through for example, visitor data, revenue records or stakeholder interviews would allow ecotourism to be included as a formal performance component in future nexus analyses.

The stakeholder analysis revealed that the local population, including ethnic minority communities, lacks formal representation in water management decisions, yet is directly exposed to the consequences of dam operations. The link between perceived dam failure risk and migration behaviour has not been explored but is relevant for understanding population dynamics and the R1 feedback loop in the CLD. This could be investigated through community surveys or analysis of historical resettlement patterns following flood events.

Land use change, particularly deforestation in the upper catchment, affects runoff generation, sediment yields, and landslide frequency. While climate change is included as a driver of hydrological extremes in the current analysis, land use change scenarios were not considered. Future research should incorporate these scenarios to distinguish the relative contributions of land use and climate change to changing reservoir inflows and hazard frequencies.

Typhoon Yagi (2024) struck the Chay catchment during the study period and represents a well-documented extreme event that severely tested the dam's operational limits. Future research should use Yagi as a historical stress-test case to validate model behaviour under extreme conditions and to evaluate whether current operational rules and spillway capacity are adequate under the intensified storm frequencies projected by climate scenarios. This kind of event-based validation would substantially strengthen confidence in model outputs beyond what monthly-scale calibration alone can provide.

Finally, the relationship between growing energy demand and hydropower security deserves more detailed investigation. As Vietnam's overall electricity demand increases, the economic and operational pressure on existing hydropower infrastructure intensifies. Analysing this dynamic at the basin scale, including the role of Thac Ba within the broader basin characteristics, would contextualise the site-level findings within the regional energy transition.

13.2.2. Bac Hung Hai

Several important dynamics in the Bac Hung Hai system could not be fully addressed within the scope of this study. The link between water storage dynamics and agricultural water demand was not directly quantified. Incorporating a Water Scarcity Index (WSI) into the water balance, analogous to the approach used for Thac Ba, would provide a more direct connection between modelled water availability and food security outcomes.

The consequences of sea level rise and changing Red River water levels on salinity intrusion were not included in the scenario analysis. Given that salinity currently exceeds permissible intake thresholds at multiple locations, and that both sea level rise and upstream water abstraction are expected to worsen intrusion, this represents a significant gap. Future work should develop scenario analyses that link projected sea level rise and upstream discharge changes to salinity dynamics at the intake structures.

The relationship between riverbed lowering, driven by sand mining and altered sediment supply from upstream dams and energy infrastructure has not been explored. Declining bed levels reduce the hydraulic head available at low-head hydropower installations and compromise the structural integrity of hydraulic infrastructure. Quantifying this relationship would strengthen the energy component of the nexus analysis.

The influence of population growth and economic development on system pressures, through changing water demand; shifting land use; and altered migration patterns, was addressed in broad terms through the system dynamics model but not disaggregated spatially. More detailed scenario analyses examining how different development trajectories affect the balance between water supply and demand would improve the practical relevance of the findings.

13.3. Towards a basin-wide WEFE Nexus assessment

The two case studies presented in this report examine subsystems within the much larger Red River–Thai Binh basin. While they were analysed independently, they are in fact hydrologically connected: the Chay catchment upstream of Thac Ba drains into the Red River, which is the primary water source for the Bac Hung Hai irrigation system downstream. This means that operational decisions at Thac Ba, particularly the timing and volume of flood releases, propagate downstream and directly affect intake conditions at Bac Hung Hai. A next research group should therefore perform an integration of these two subsystems.

A practical starting point would be to use the discharge outputs from the Thac Ba water balance model as a boundary condition for the Bac Hung Hai water balance, creating a coupled upstream-downstream model. This would allow the downstream consequences of different Thac Ba management scenarios. For instance, increased wet-season releases under future climate conditions: to be evaluated in terms of their effect on irrigation water availability, salinity intrusion risk, and flood exposure in the delta. Conversely, drought-driven reductions in Thac Ba outflow could be linked to reduced Red River levels and declining intake capacity at Xuan Quan, a dynamic that is currently treated as an external given in the Bac Hung Hai analysis. Beyond the two case studies, extending this coupled model to the full basin would require incorporating the remaining major reservoirs (Son La, Hoa Binh, Tuyen Quang) and eventually the Chinese upstream infrastructure, building towards the integrated multi-reservoir framework described below. So for extrapolation include more dams upstream through the same methods as Thac Ba.

A further structural challenge at the basin scale is transboundary governance. The Chinese upstream reservoirs exert substantial influence over inflow volumes and timing into the Vietnamese part of the basin, yet no coordinated operational framework currently exists between the two countries for the Red River. The Mekong River Commission offers a relevant institutional model for transboundary water governance in the region; investigating whether an analogous mechanism exists or is under development for the Red River, and what data-sharing arrangements might be achievable, is an important step that future research should address alongside the technical modelling work.

The following thematic directions are proposed to support the development of a full basin-wide WEFE Nexus framework.

Water governance and flow allocation *(W, E, F)*. A central question at the basin scale is whether sufficient downstream water availability can be maintained under the cumulative effects of all upstream dams. This requires a multi-reservoir water balance that accounts for the full cascade of reservoirs from the Chinese border to the delta, and that is capable of evaluating how different allocation strategies affect water availability across sectors and seasons. Improved discharge and storage data from EVN and the Ministry of Agriculture and Environment would be essential inputs for such a model.

Energy demand and hydropower capacity *(E, W)*. Vietnam's rapidly growing electricity demand, combined with plans to expand hydropower capacity, raises questions about the long-term sustainability of the existing infrastructure. Future research should investigate whether projected demand can be met as population grows, and what role the existing hydropower capacity, including Thac Ba, can realistically play relative to alternative energy strategies such as solar and wind.

Sediment, morphology, and land loss *(W, E, F)*. The chain from reduced sediment supply (due to upstream trapping by dams and sand mining) through altered discharge regimes to coastal erosion and land loss in the delta is well-documented in the literature but has not been quantified for the Red River–Thai Binh system as a whole. A basin-scale sediment budget, coupled to morphological modelling at the delta, would fill this gap and support coastal management planning.

Food security and water extremes *(F, W)*. At the basin scale, food security outcomes are shaped by the interaction between population growth, land use change, and water availability under a changing climate. Spatial analysis of land use change, combined with crop water demand modelling and hydrological scenario analysis, would allow for a systematic assessment of food security risk across the basin under different development and climate pathways.

Environmental quality and biodiversity *(E_{nv}, W, F)*. The current study addresses ecological health primarily through the lens of water quality in Bac Hung Hai. A basin-wide assessment should incorporate biodiversity monitoring data, pollution gradients from upstream to coast, and the cumulative effects of dam operations on river ecology. Evaluating the state of natural areas and tracking pollution levels across the basin would provide a more comprehensive picture of environmental nexus trade-offs.

Integrated nexus index *(W, E, F, E_{nv})*. Ultimately, the goal of a basin-wide analysis should be to develop a composite WEFE Nexus index that allows the performance of the basin to be tracked across all four dimensions simultaneously. Such an index should build on the indicators identified in the literature review and the two case studies, be grounded in observed and modelled data, and be structured to support policy evaluation under uncertainty.

A

Appendix A: Tables & Figures from literature

A.1. Figures from Chapter 1 Contextualisation

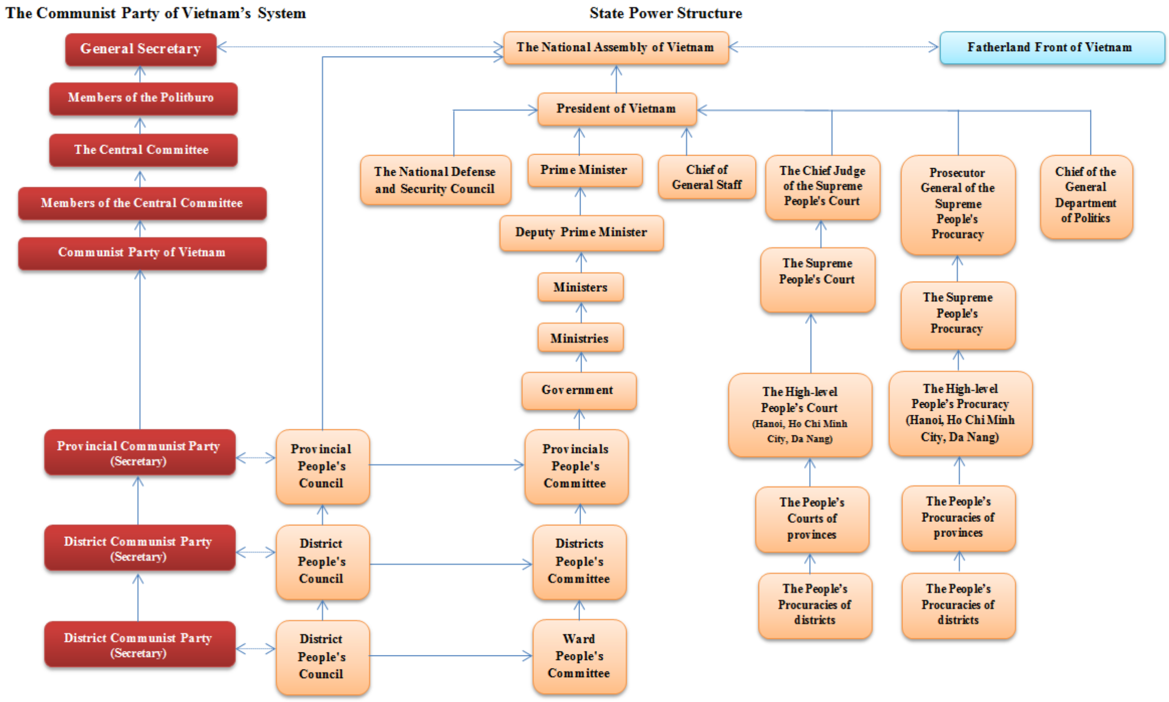


Figure A.1: Vietnam governance structure (Wikimedia Commons contributors, 2026)

A.2. Figures from Chapter 2 WEFE nexus literature

A.2.1. Methodologies

Method	Studies	Method	Studies
Environmental management			
Scenario analysis	25	Footprinting	13
Life cycle assessment	8	Stakeholder engagement	2
Decision support	2	Benefit analysis	2
Economic			
Input-output analysis	14	Cost-benefit analysis	1
Trade-off analysis	10	Social accounting matrix	1
Economic modeling	6	Value chain analysis	2
Supply chain analysis	3		
Indicators			
Indicators / metrics / indices	18		
Statistics			
Principal component analysis	1	Regression statistics	3
Trend analysis	2		
Social science			
Institutional analysis	4	Questionnaires, surveys or interviews	8
Historical analysis	3	Agent-based modeling	1
Delphi technique	2	Critical discourse analysis	2
Ontology engineering	1	Stakeholder analysis	3
Participatory workshops / focus groups	8	Policy analysis	4
Integrated modeling			
Integrated assessment models	6	CLEWS model	2
Hydro-economic modeling	3		
Systems analysis			
Multi-sectoral systems analysis	2	Material flows analysis	3
Systems informatics and analytics	1	Causal loop diagrams	2
Mathematical / engineering modeling	2	Resource flows analysis	3
Network analysis	1		
Geospatial			
Spatial analysis	11	Remote sensing	2
Hydrologic modeling			
Hydrologic modeling	6	Water management models	3
Energy modeling			
Energy models	2		
Food systems			
Caloric-demand analysis	2		

Table A.1: Overview of methods used in WEFE Nexus studies and the number of studies applying each method.

A.2.2. Indicator table

Table A.2: Proposed WEFE Nexus Indicators (Schlemm et al., 2024)

Domain	Indicators
Water	River flow, lake levels, nutrient pollution, sediment transport, water demand, water access
Energy	Hydropower production, energy demand, energy access
Food	Crop yield, fisheries yield, livestock, irrigation water, food demand, food access
Environment	Aquatic biodiversity, eutrophication, land degradation

A.2.3. Correlation matrix

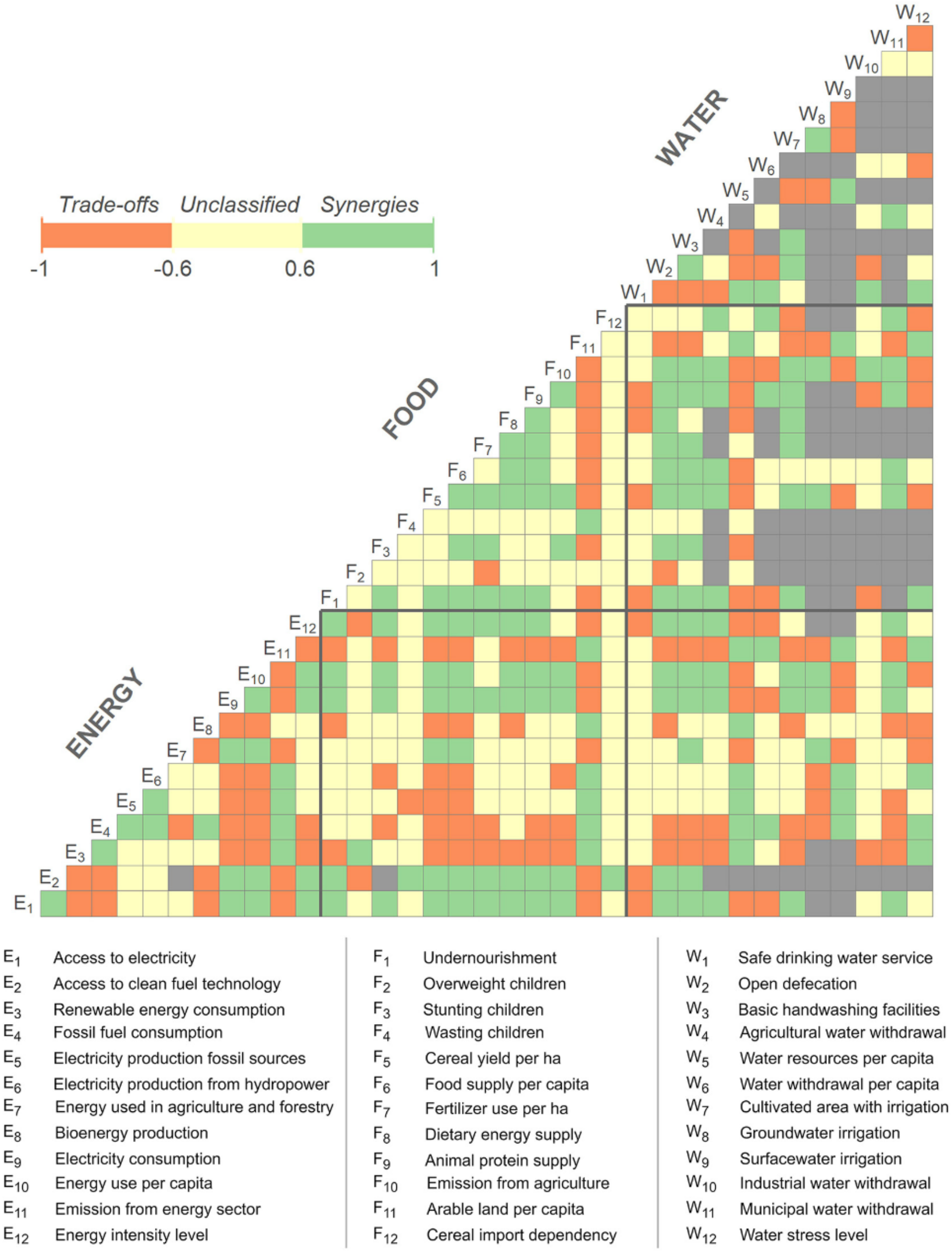
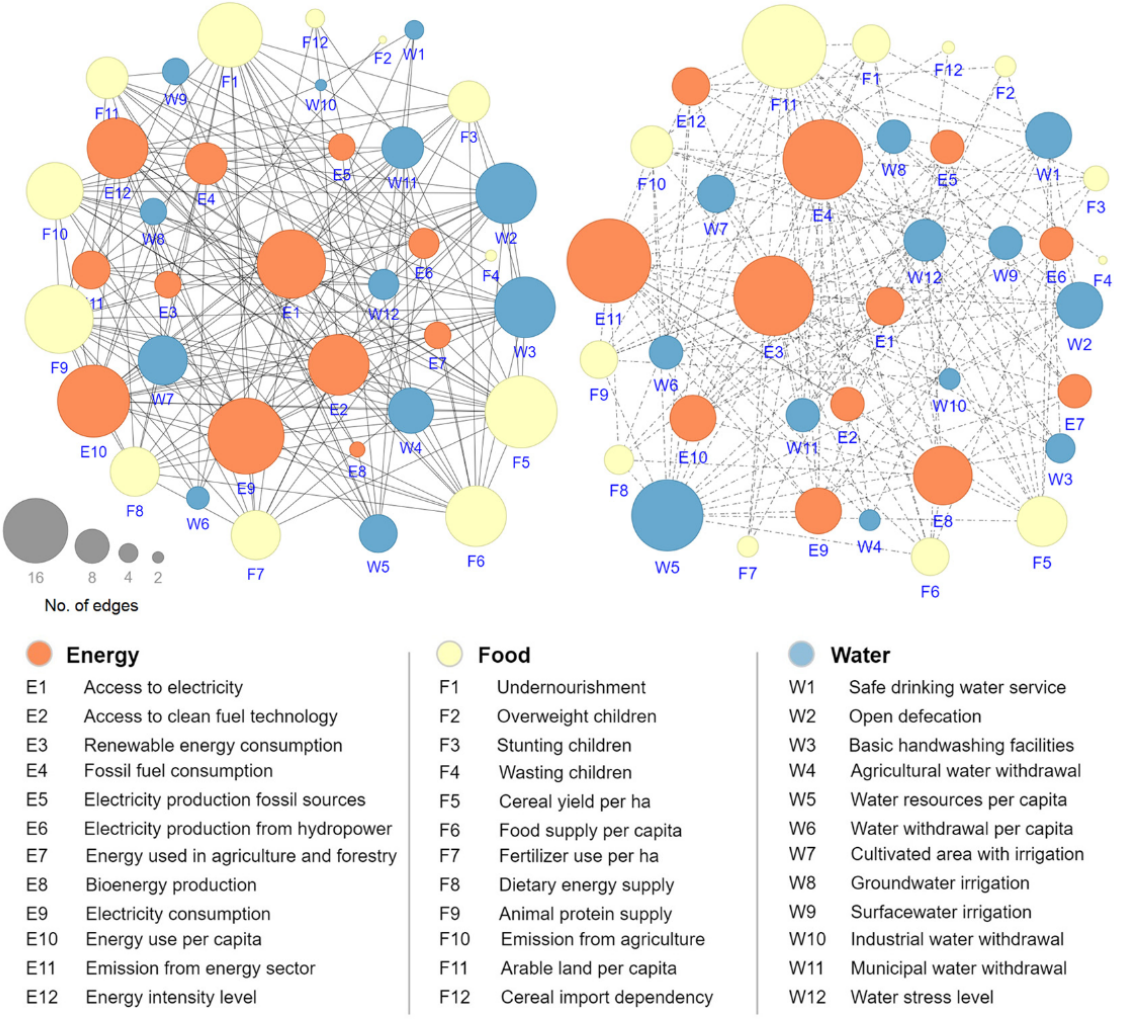


Figure A.2: Observed interactions between the water, energy, and food (WEF) sectors in South Asia – synergies (green), trade-offs (orange), and unclassified (yellow). The grey colour depicts insufficient data. The codes in the diagonal represent the indicators. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article. ((Putra et al., 2020)

A.2.4. Node network of WEFE indicators



● Energy		● Food		● Water	
E1	Access to electricity	F1	Undernourishment	W1	Safe drinking water service
E2	Access to clean fuel technology	F2	Overweight children	W2	Open defecation
E3	Renewable energy consumption	F3	Stunting children	W3	Basic handwashing facilities
E4	Fossil fuel consumption	F4	Wasting children	W4	Agricultural water withdrawal
E5	Electricity production fossil sources	F5	Cereal yield per ha	W5	Water resources per capita
E6	Electricity production from hydropower	F6	Food supply per capita	W6	Water withdrawal per capita
E7	Energy used in agriculture and forestry	F7	Fertilizer use per ha	W7	Cultivated area with irrigation
E8	Bioenergy production	F8	Dietary energy supply	W8	Groundwater irrigation
E9	Electricity consumption	F9	Animal protein supply	W9	Surfacewater irrigation
E10	Energy use per capita	F10	Emission from agriculture	W10	Industrial water withdrawal
E11	Emission from energy sector	F11	Arable land per capita	W11	Municipal water withdrawal
E12	Energy intensity level	F12	Cereal import dependency	W12	Water stress level

Figure A.3: Networks of the synergies (left side) and trade-offs (right side) based on interactions among the water, energy, and food sectors for South Asia. Bigger nodes have more edges and larger influences in the networks compare to smaller ones. Putra et al. (2020)

A.2.5. Indicator tables

Water sector

Table A.3: Evaluation index system of the water sector Song et al. (2023)

ID	Index	Unit
W1	Level of Water Stress	%
W2	Water Use Efficiency	USD/m^3
W3	Percentage of Wastewater Safely Treated	%
W4	Proportion of Population Using Safely Managed Drinking Water Services	%
W5	Total Fresh Water Withdrawal	10^3 m^3/yr
W6	Fresh Water Withdrawal Per Capita	10^3 m^3/yr
W7	Agricultural Water Use Efficiency	%
W8	Industrial Water Efficiency	%
W9	Municipal Water Efficiency	%
W10	Level of Agricultural Water Stress	USD/m^3
W11	Level of Industrial Water Stress	USD/m^3
W12	Level of Municipal Water Stress	USD/m^3

Energy sector

Table A.4: Evaluation index system of the energy sector (Song et al., 2023)

ID	Index	Unit
EN1	Total Primary Energy Consumption per Dollar of GDP	10^3 Btu/USD
EN2	Energy Sufficiency	%
EN3	Percentage of Investments in Fixed Assets in the Energy Sector	%
EN4	Total Primary Energy Production	10^{15} Btu
EN5	Total Primary Energy Consumption	10^{15} Btu
EN6	Natural Coal Production	10^3 tons
EN7	Consumption of Natural Coal	10^3 tons
EN8	Oil Production	10^3 tons
EN9	Consumption of Oil	10^3 tons
EN10	Natural Gas Production	mln m^3
EN11	Consumption of Natural Gas	mln m^3
EN12	Electricity Generation	TWh
EN13	Gross Electricity Consumption	10^6 Kw.h
EN14	Biomass Energy Consumption	10^6 tons

Food sector

Table A.5: Evaluation index system of the food sector (Song et al., 2023)

ID	Index	Unit
F1	Food Production Index	—
F2	Fertilizer Consumption	kg/ha
F3	Prevalence of Undernourishment	%
F4	Agricultural Products of Republic of Uzbekistan	10^9 soums
F5	Arable Land	10^3 ha
F6	Total Area Equipped for Irrigation	10^3 ha
F7	Cereals and Legumes, Total	10^3 tons
F8	Cotton Production	10^3 tons
F9	Wheat	10^3 tons
F10	Corn for Grain	10^3 tons
F11	Rice	10^3 tons
F12	Potatoes	10^3 tons
F13	Fruits and Vegetables	10^3 tons

Ecology sector

Table A.6: Evaluation index system of the ecology sector (Song et al., 2023)

ID	Index	Unit
EO1	Ecological Deficit	Gha
EO2	Ecological Footprint	Gha
EO3	Biocapacity	Gha
EO4	CO_2 Emissions Per Unit of GDP	kg
EO5	Population Carrying Capacity	per/km^2
EO6	Forest Area as a Percentage of Total Land Area	%
EO7	Urbanization Rate	%
EO8	Area of the South Aral Sea	10^3 km^2
EO9	Water Level in the South Aral Sea	m
EO10	Water Volume of the South Aral Sea	km^3
EO11	Dust Event Severity	Enh. Dust Index
EO12	Dust Event Frequency	—
EO13	Salinization	10^4 km^2

A.2.6. WEF Nexus Tools

Table A.7: Selected most used and available WEF nexus tools from Taguta et al. (2022)

WEF nexus tool	Short description
WEF Nexus Discovery Map	A map-based pool/database of catalogued and classified WEF nexus information from otherwise geographically and topically diverse independent and academic communities worldwide.

NeFEW	A data analysis toolbox for synthesizing available global data to enable estimating country-specific estimates of water resources required to produce different types of food and energy.
SD-WFE	A spatiotemporal disaggregated WEF nexus model that assesses water and food supply security considering ecosystem provisioning services. The model contains modules for population, water, agriculture, and energy.
WEF Nexus Index	A web-based WEF nexus global visualization map comprising an index that is a composite indicator derived from integrating WEF resource sectors' indicators.
SIM4NEXUS	A WEF system dynamic integrated model and serious games for investigating potential plausible cross-nexus implications and synergies under different climate change and socioeconomic pathway scenarios due to policy interventions for 12 multi-scale case studies ranging from regional to global.
Nexus Game	An integrated "hardware" simulation game addressing the interrelated challenges of WEF production to meet demand.
Pardee RAND WEF Security Index	An online interactive WEF nexus security index with an unweighted geometric mean of three sub-indices, each for the three WEF sectors.
CLEWs	A module-based approach to quantitatively and simultaneously assess/explore land, energy and water resource systems as closely linked resources (and climate) within a modelling framework that integrates detailed models from different tools.
WEAP – LEAP	An integrated research planning, analyses and decision-making of the closely interlinked energy and water systems. Allows exchanging parameters and outputs, such as hydropower generated or cooling water requirements, water supply characteristics for projecting energy demand, hydropower modeling and consistent weekly time-step calculations.
ANEMI	An integrated assessment model of global change that emphasizes the role of water resources. The model uses feedback processes among its subsystems and system dynamics simulation principles to analyze changes in the Earth system.
MuSIASEM	An integrated diagnostic and simulation tool that characterizes the metabolic pattern/flows of energy, food and water and their interlinkages about socio-economic and ecological variables simultaneously.

A.3. Tables from Chapter 6, Food

Statistical values on Food (General Statistics Office of Vietnam, 2024a)

To utilize values from the statistical report, the area of each province within the Red River Basin (RRB) first had to be determined. Since not all provinces are entirely located within the basin boundaries, a spatial analysis was performed in QGIS. Provincial boundaries were clipped to the RRB extent, after which the area of each clipped province was calculated. The proportion of each province located within the basin was then derived by comparing the clipped area with the total provincial area. Values from the statistical report were subsequently multiplied by this proportional factor to obtain a first-order approximation of food-related areas and associated values within the Red River Basin.

Province	Area within RRB (km^2)	Total Area (km^2)	Percentage RRB (%)
Bac Giang	3891.829	3903.984	99.69
Bac Kan	3236.270	4745.666	68.19
Bac Ninh	801.345	801.345	100.00
Cao Bang	1905.827	6195.541	30.76
Đien Biên	7496.869	11147.765	67.25
Hà Giang	7871.630	7871.630	100.00
Hà Nam	935.706	935.706	100.00
Hà Noi	3303.219	3303.218	100.00
Hai Duong	1726.828	1726.828	100.00
Hai Phòng	975.739	976.231	99.95
Hòa Bình	2830.180	4236.011	66.81
Hung Yên	895.167	895.167	100.00
Lai Châu	5780.174	5780.173	100.00
Lang Son	2057.980	7616.631	27.02
Lào Cai	7836.954	7836.955	100.00
Nam Đinh	1533.385	1537.549	99.73
Ninh Bình	1164.427	1268.310	91.81
Phú Tho	3425.403	3425.403	100.00
Quang Ninh	1371.872	5283.611	25.96
Son La	9475.414	14315.798	66.19
Thái Bình	1577.334	1577.702	99.98
Thái Nguyên	3348.937	3448.303	97.12
Thanh Hóa	19.273	10868.078	0.18
Tuyên Quang	6111.103	6111.095	100.00
Vĩnh Phúc	1359.041	1359.041	100.00
Yên Bái	6663.125	6663.132	100.00

Table A.8: Area of Vietnamese provinces within the Red River Basin (RRB).

The values for Oranges and Bud Tea were given in production, kilograms of product. To estimate back to hectares, for Oranges about 25 hectares is needed to produce 10^6 kg (*Oogst en opbrengsten van sinaasappelbomen | Wikifarmer*, 2026). Bud Tea requires about 125 hectares to produce 10^6 kg (T. T. Nguyen & Anh, 2019).

Stage	**50%**		**95%**	
	Demand	**Flow rate (Feb)**	**Demand**	**Flow rate (Feb)**
Current (2024)	6.48 billion m^3/y	841.9 m^3/s	6.88 billion m^3/y	892.4 m^3/s
2030: RCP 4.5	5.87 billion m^3/y	720.3 m^3/s	6.23 billion m^3/y	765.5 m^3/s
2030: RCP 8.5	5.93 billion m^3/y	725.5 m^3/s	6.30 billion m^3/y	927 m^3/s

Table A.11: Projected water demand and corresponding February flow rates under different scenarios.

Province	Cereals (10^3 ha)	Rice (10^3 ha)	Spring Rice (10^3 ha)	Winter Rice (10^3 ha)	Maize (10^3 ha)	Sweet Potatoes (ha)	Cassava (ha)	Sugar Cane (ha)	Peanut (ha)	Bud Tea (ha)	Oranges (ha)
Bac Giang	105.27	94.50	46.16	48.35	10.77	3529.98	990.91	147.54	7475.65	0	692.84
Bac Kan	24.69	15.21	5.73	9.55	9.48	287.78	202.54	64.10	395.53	579.65	0
Bac Ninh	58.50	57.50	28.90	28.60	1.00	166	0	9	459	0	0
Cao Bang	21.84	9.32	1.14	8.18	12.49	244.55	1222.15	878.54	489.10	0	0
Đien Biên	53.46	36.72	6.59	30.13	16.75	242.77	11320.86	56.49	704.11	0	0
Hà Giang	92.30	37.60	9.30	28.30	54.70	1707	5302	536	9047	11262.50	1105.00
Hà Nam	60.80	56.00	27.80	28.20	4.80	388	0	2	461	0	0
Hà Noi	165.00	152.90	81.00	71.90	12.10	1306.00	525.00	8.00	2063.00	2075.00	0
Hai Duong	110.70	107.30	53.90	53.40	3.40	769	0	41	840	0	0
Hai Phòng	56.87	55.87	27.29	28.59	0.90	704.64	0	33.98	147.93	0	0
Hòa Bình	46.17	25.59	11.02	14.57	20.58	2328.41	5077.07	4275.32	2590.98	0	1570.09
Hung Yên	52.10	49.00	24.60	24.30	3.10	216	0	1	529	0	707.50
Lai Châu	50.50	31.40	6.80	24.60	19.10	174.00	8634.00	194.00	974.00	8300.00	0
Lang Son	18.35	12.92	4.19	8.75	5.40	367.47	243.72	41.88	699.00	0	0
Lào Cai	67.00	34.20	9.90	24.30	32.80	604.00	6983.00	271.00	1528.00	5850.00	0
Nam Đinh	143.51	140.62	70.11	70.61	2.79	768.91	0	46.87	4482.83	0	0
Ninh Bình	68.95	65.00	36.36	28.64	3.95	594.92	0	356.22	1864.65	0	0
Phú Tho	74.70	58.00	35.40	22.60	16.70	680	5548	50	2620	22487.50	0
Quang Ninh	11.14	9.55	3.87	5.69	1.58	727.79	0	77.12	458.28	0	0
Son La	79.96	30.78	8.67	14.50	49.24	167.46	29239.44	6708.87	724.10	4409.81	208.49
Thái Bình	158.06	148.37	74.18	74.28	9.60	3089.28	0	42.99	2618.39	0	0
Thái Nguyên	79.73	65.26	28.07	37.20	14.57	2186.14	968.27	78.67	2647.45	33226.64	0
Thanh Hóa	0.47	0.40	0.20	0.20	0.07	8.83	25.46	25.96	14.48	0	0.60
Tuyên Quang	59.70	41.30	18.50	22.80	18.50	1627.00	1548.00	2560.00	4380.01	8850.01	1780.00
Vĩnh Phúc	61.30	52.30	28.90	23.40	9.00	1699	0	2	2039	0	0
Yên Bái	71.20	42.50	19.40	23.00	28.80	3189.99	8015.99	247.00	1965.00	8599.99	392.50

Table A.9: Estimated crop areas within the Red River Basin (RRB) for 2024. Values are obtained by multiplying provincial agricultural statistics from the General Statistics Office with the proportional fraction of each province located within the basin.

Type of crop	**Cereals**	**Rice**	**Spring Rice**	**Winter Rice**	**Maize**	**Sweet Potatoes**	**Cassava**	**Sugar Cane**	**Peanut**	**Bud Tea**	**Oranges**
Total area 2024 (10^3 ha)	1792.27	1430.11	667.97	754.62	362.16	27.77	85.85	16.76	52.22	105.64	6.46

Table A.10: Total cultivated area of major crops in 2024.

Province	Buffalo (10^3 heads)	Cattle (10^3 heads)	Pigs (10^3 heads)	Poultry (10^3 heads)
Bac Giang	23.83	90.22	682.57	194058.91
Bac Kan	17.25	9.62	94.86	1483.22
Bac Ninh	4.10	19.00	254.70	6259.00
Cao Bang	31.93	31.07	92.10	956.06
Dien Bien	96.03	70.48	208.07	3338.96
Ha Giang	138.50	135.00	582.90	6240.00
Ha Nam	3.60	33.20	349.90	8971.00
Ha Noi	28.80	120.40	1279.80	37383.01
Hai Duong	5.50	14.00	358.30	15949.00
Hai Phong	4.20	6.30	146.43	8460.73
Hoa Binh	69.08	59.46	321.77	5665.02
Hung Yen	4.70	29.70	459.70	9393.00
Lai Chau	92.00	28.30	216.60	1834.00
Lang Son	14.59	7.40	46.64	1288.83
Lao Cai	87.00	21.20	346.90	5730.00
Nam Dinh	7.78	29.02	585.61	10219.25
Ninh Binh	11.57	31.31	212.81	6355.04
Phu Tho	49.50	85.60	672.10	15669.00
Quang Ninh	5.92	5.92	64.57	1425.46
Son La	71.02	257.14	408.91	5456.58
Thai Binh	7.20	52.39	589.56	14401.64
Thai Nguyen	33.89	40.11	352.05	15753.58
Thanh Hoa	0.20	0.36	1.75	49.33
Tuyen Quang	85.90	40.10	568.60	7451.01
Vinh Phuc	13.00	78.90	487.40	12026.00
Yen Bai	92.70	39.90	529.10	7424.99
Total	999.79	1336.09	9913.70	403242.65

Table A.12: Estimated livestock numbers within the Red River Basin (RRB) for 2024. Values represent the proportional share of provincial livestock statistics located within the basin.

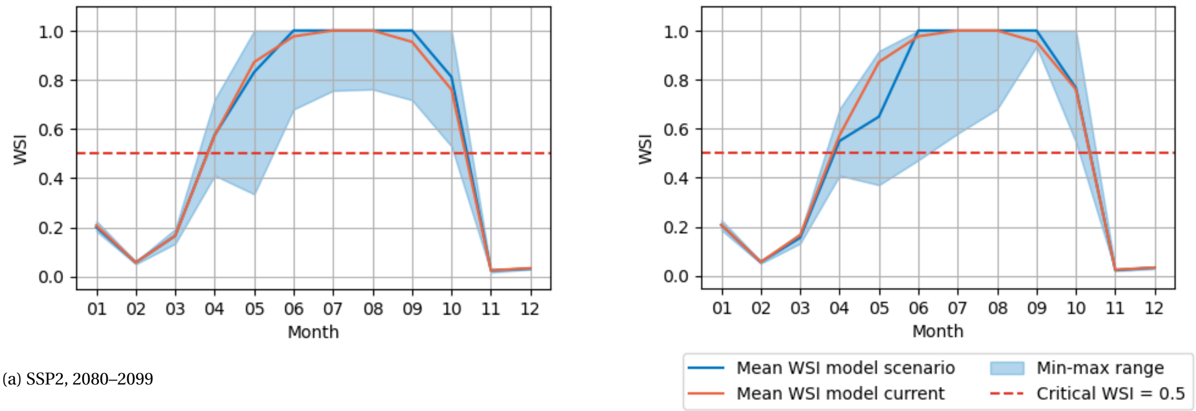
Province	Aquaculture (10^3 ha)
Bac Giang	9.17
Bac Kan	0.89
Bac Ninh	4.50
Cao Bang	0.09
Dien Bien	1.82
Ha Giang	2.40
Ha Nam	5.60
Ha Noi	20.80
Hai Duong	12.60
Hai Phong	11.09
Hoa Binh	1.60
Hung Yen	4.90
Lai Chau	0.90
Lang Son	0.32
Lao Cai	2.60
Nam Dinh	14.46
Ninh Binh	13.86
Phu Tho	11.20
Quang Ninh	7.48
Son La	1.99
Thai Binh	16.10
Thai Nguyen	5.15
Thanh Hoa	0.04
Tuyen Quang	3.30
Vinh Phuc	6.00
Yen Bai	2.60
Total	161.45

Table A.13: Estimated aquaculture water surface within the Red River Basin (RRB) for 2024. Values represent the proportional share of provincial aquaculture statistics located within the basin.

B

Appendix B: Additional Results

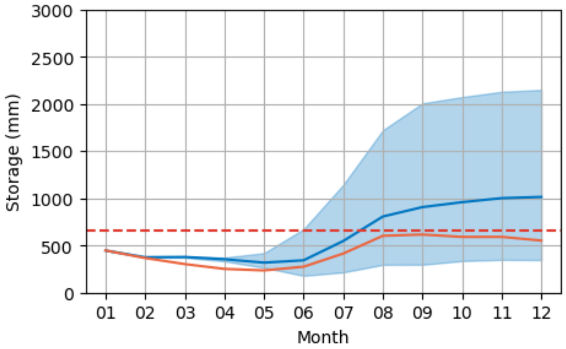
B.1. Thac Ba, scenario analysis



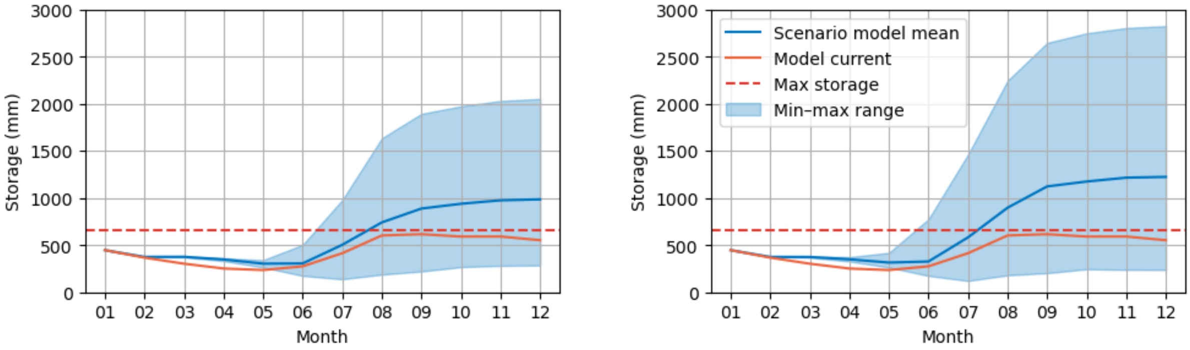
(a) SSP2, 2080–2099

(b) SSP5, 2040–2059

Figure B.1: Water Stress Index (WSI) under different climate scenarios and time periods.



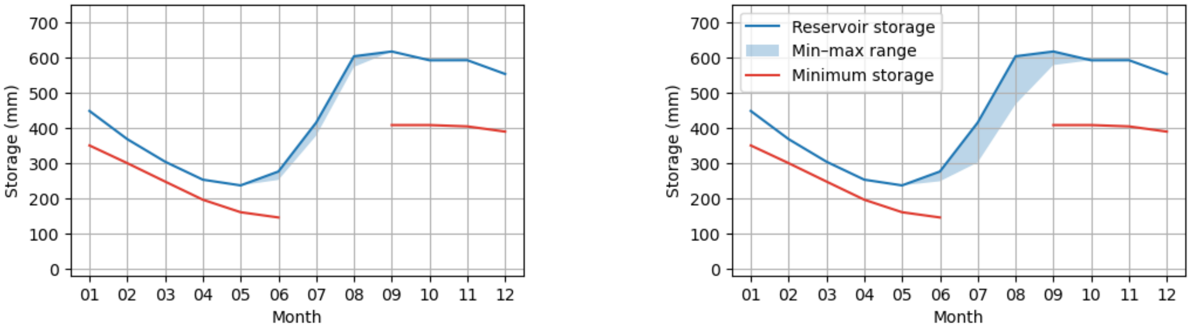
(a) SSP2, 2080–2099



(b) SSP5, 2040–2059

(c) SSP5, 2080–2099

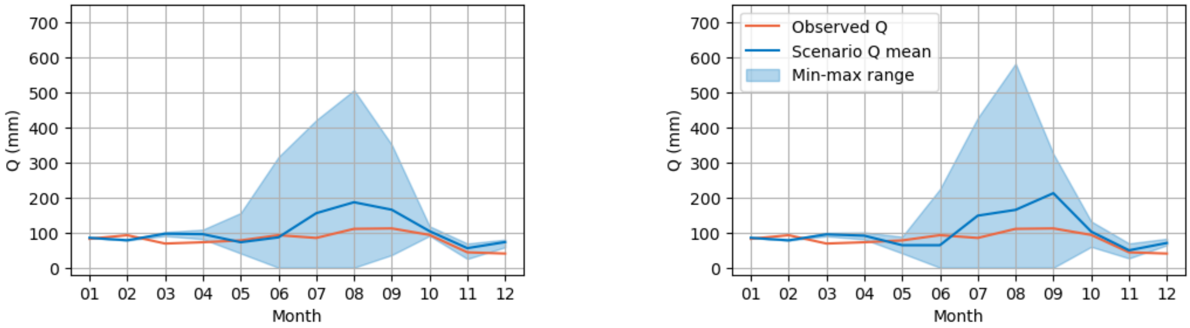
Figure B.2: Monthly Reservoir Storage



(a) SSP2, 2080–2099

(b) SSP5, 2040–2059

Figure B.3: Modelled storage for scenarios



(a) SSP2, 2080–2099

(b) SSP5, 2040–2059

Figure B.4: Modelled discharge for scenarios

B.2. System Dynamics: Model Overview

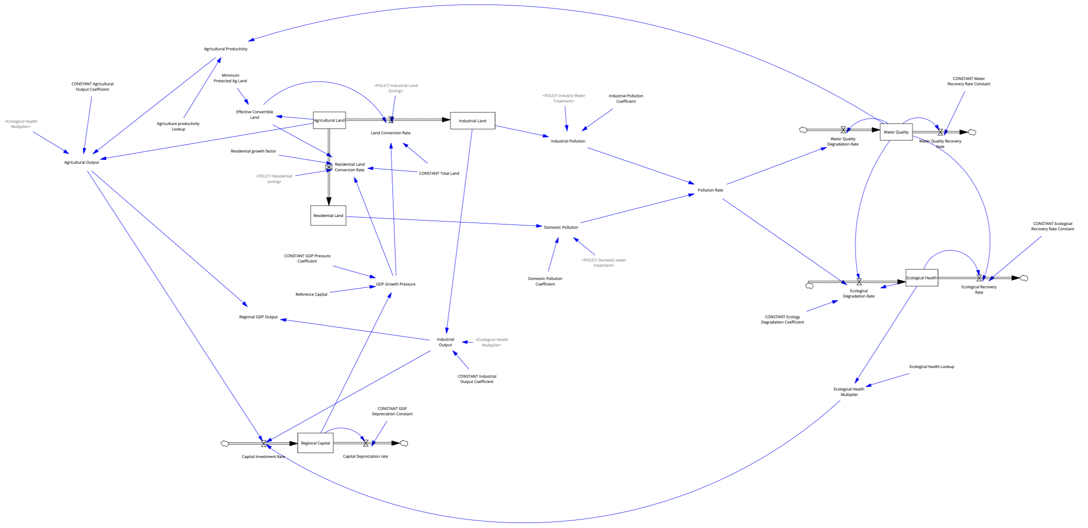


Figure B.5: Overview of System Dynamics model

B.3. Recommendations overview table

Recommendation	Case study	WEFE pillar(s)	Priority
Use daily input data for water balance	Thac Ba	W	High
Include Chinese upstream dams in inflow boundary	Thac Ba	W, E	High
Calibrate groundwater storage parameters against field data	Thac Ba	W, F	High
Use climate-model evapotranspiration projections	Thac Ba	W	Medium
Complement stakeholder analysis with primary fieldwork	Thac Ba	all	Medium
Use exact lock opening times for discharge estimation	Bac Hung Hai	W	High
Obtain on-site storage measurements	Bac Hung Hai	W	Medium
Add baseflow and groundwater recharge to water balance	Bac Hung Hai	W, F	High
Improve survey distribution and design	Bac Hung Hai	all	Medium
Couple system dynamics model with water balance	Bac Hung Hai	W, F, E_{nv}	High
Add health and demographic feedbacks to SD model	Bac Hung Hai	all	Medium
Quantify sediment trapping by upstream dams	Thac Ba	W, E	Medium
Investigate ecotourism–reservoir management link	Thac Ba	E_{nv}, F	Low
Investigate dam-failure-risk and migration link	Thac Ba	F, all	Low
Include land-use change scenarios	Thac Ba	W, F, E_{nv}	Medium
Use Typhoon Yagi as a historical stress-test	Thac Ba	W, E	High
Add Water Scarcity Index to BHH water balance	Bac Hung Hai	W, F	High
Develop sea level rise / salinity intrusion scenarios	Bac Hung Hai	W, F	High
Quantify riverbed lowering effect on infrastructure	Bac Hung Hai	E, W	Medium
Couple Thac Ba and Bac Hung Hai water balances	Both	W, F	High
Investigate transboundary governance frameworks	Basin-wide	all	Medium
Develop integrated WEFE Nexus index	Basin-wide	all	Long-term

Table B.1: Overview of recommendations, grouped by case study and WEFE pillar. Priorities reflect a combination of impact on the analysis and feasibility for a next research group. W = Water, E = Energy, F = Food, E_{nv} = Environment.

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