Sustaining the Flow:

Modelling Water Reuse Strategies in Dutch Water Sector

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Sustaining the Flow

Modelling Water Reuse Strategies in Dutch Water Sector

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Preface

I always remember how my father used to talk about the great river that once flowed past our home, winding its way through our town when he was a child. I would imagine how beautiful it must have been, a vibrant lifeline weaving through the land. But by the time I was old enough to see it for myself, it was gone. As I grew up, I kept hearing similar stories—about rivers drying up, lakes shrinking, and water becoming scarcer in my beloved home country. It made me realize how deeply human activities impact our environment, especially our water resources.

For a long time, I believed that water problems were confined to arid regions, places with little rainfall or limited access to water. But then, to my surprise, I learned that even a country like the Netherlands, which appears to be rich in water, faces significant challenges. This realization marked the beginning of my journey into this field. Later, throughout my master studies, I found myself wondering: could the knowledge I was gaining help me make even the slightest difference? That question became the foundation of this study. This work would not have been possible without the support and guidance of many people, to whom I owe my deepest gratitude.

First, I would like to thank Dr. Servaas Storm. Your expertise and knowledge, combined with the time and dedication you invest in your students, have been a great source of support throughout this journey.

I am also deeply grateful to Dr. Lisa Scholten. This work could not have taken shape without your expertise in water-related issues. Your insights and guidance have been invaluable.

A heartfelt thank you to Amir, my dear husband, Through the ups and downs of this thesis, we have faced many challenges and grew together. And again and again, you have shown me that no matter what, you will always stand by my side, offering your unwavering support and love.

To my father, those sixteen years with you filled me with so much love and self-assurance that they continue to fuel me through life.

To my mother and brothers, your acceptance and support mean the world to me, reminding me that I always have a place where I belong.

To my wonderful friends, each of you has had a profound impact on both my personal and academic journey. The thought of going through life without you is unimaginable.

Finally, I send my love to my grandfather, whom I lost this past year. He was one of the most inspiring people I have ever met, and his memory will always guide me.

For all the challenges and lessons this journey has brought, I carry forward a deep sense of gratitude and purpose, hoping that this work will contribute, even in a small way, to a better future for our water resources.

Reihaneh Momeni
Delft, February 2025

Summary

The increasing challenge of water scarcity, driven by climate change, population growth, and economic expansion, has placed immense pressure on existing water resources. Traditional water management strategies, built on a linear model of extraction, consumption, and disposal, are no longer sufficient to meet future demands. The growing mismatch between water availability and human consumption necessitates a shift towards a circular water economy, where reuse and resource recovery play a pivotal role. Water reuse presents an opportunity to close resource loops, reduce reliance on freshwater, and enhance water security. However, despite its potential, water reuse remains underutilized due to economic, technical, and social barriers.

Like many sociotechnical transitions, the adoption of water reuse faces structural challenges. While technological advancements have made water reclamation feasible, economic considerations and social acceptance remain key hurdles. Reuse water is often perceived as an economic burden rather than a cost-effective alternative, limiting investment in reuse infrastructure. A review of existing literature indicates that extensive research has been conducted on the economic aspects of water reuse, focusing on different aspects of water reuse integration and its impact on water systems, which are inherently complex, shaped by diverse stakeholders, regional dependencies, and complex interactions. Understanding these dynamics is crucial for designing effective policy instruments that promote water reuse while balancing economic feasibility and sustainability.

Inspired by these streams of literature, this study aims to address the following research question:

Main Research Question

"How can policies and water reuse strategies, tailored to the local characteristics of water systems, be designed to make water reuse an economically viable alternative to freshwater?"

The literature review revealed that economic parameters related to water reuse are seldom tailored to single aspects instead of a general framework, limiting their practical applicability. To bridge this gap, this study develops a framework that quantifies the interactions within water systems and integrates them into a model capable of analyzing the impact of different policies and strategies. To achieve this, the Netherlands—a country widely perceived as having abundant water resources but increasingly facing serious water shortages—is selected as the case study.i

To answer the research question, this study examines the historical and structural dynamics of the Dutch water system and translates them into a dynamic partial equilibrium model. This framework enables the simulation of water reuse policies and the evaluation of their impacts across key stakeholders, including environmental considerations. Policy effectiveness is assessed through key performance indicators, including total freshwater savings, reuse efficiency, price of water, and consumer total water costs.

The study evaluates multiple scenarios, including a business-as-usual approach as a benchmark and two key policy interventions: centralized reuse and decentralized reuse. The results highlight the potential of centralized reuse, which, when implemented at a large scale (over 30% of total water demand), can significantly reduce consumer costs and become financially competitive with conventional urban water supplies. However, achieving this level of implementation requires massive infrastructure investments, amounting to multi-billion euros, alongside strong public and political support—a major barrier to widespread adoption. At lower adoption levels (less than 10% of total demand), its impact is negligible, making large-scale commitment essential for effectiveness.

Decentralized reuse, in contrast, does not naturally present a financial advantage on its own but can become economically viable when combined with supportive policies, such as wastewater treatment cost reductions, tax incentives, or subsidies. Unlike centralized reuse, decentralized systems offer greater

flexibility, making them well-suited for localized applications where ultra-pure water is not required, such as industrial cooling, irrigation, and sanitation. Additionally, decentralized reuse can be customized to consumer needs, making it a practical solution for targeted water reuse applications. While it may not deliver the same cost savings as centralized systems, it provides an opportunity to diversify water sources, reduce pressure on freshwater supplies, and increase overall system resilience.

This study highlights how water reuse can be effectively integrated into water systems and under what conditions it can become a competitive alternative to freshwater. By quantifying the economic and policy dynamics of water reuse, it provides a foundation for designing more effective, evidence-based strategies that contribute to a sustainable and resilient water future.

Contents

List of Figures

List of Tables

Part I

Introduction

1 Introduction

Water, an essential element for human survival and a vital contributor to various sectors of the economy, faces challenges due to its irregular distribution in space and time, compounded by the pressures of human activities and economic development. The acceleration of urbanization and the expansion of municipal water supply and sanitation systems further contribute to the escalating demand. Moreover, climate change scenarios project spatial and temporal variations in water cycle dynamics, intensifying the disparities between water supply and demand. (UNESCO, 2017)

Water for irrigation and food production emerges as a significant stressor on freshwater resources, with agriculture responsible for over 70% of global freshwater withdrawals and up to 90% in rapidly growing economies.(UNESCO, 2017) Projections related to biofuel production indicate that achieving the EU target of 10% biofuel-powered road transport by 2020 would translate to at least 20% of global water usage for agriculture by 2030. (Voulvoulis, 2018) Industry, accounting for a substantial share of water consumption (ranging from 10% in Asia to 57% in Europe), adds to the complexity of the global water crisis (World Economic Forum, 2023). The World Economic Forum Global Risk Report highlights water (availability/scarcity/management) as a top global risk, projecting a 40% shortfall in global water supply by 2030 if fundamental changes in water management practices are not implemented. (World Economic Forum, 2023)

Beyond being a vital resource for human survival and economic development, water plays a fundamental role in sustaining ecosystem services crucial for the Earth's functionality. However, human activities such as accessing, developing, transporting, and utilizing water resources leave an impact that can degrade the services provided by the rivers, lakes, wetlands, or groundwater aquifers supplying the water. (Chicharo, 2015) Water scarcity becomes a key stressor in numerous river ecosystems, exacerbating the detrimental effects of other stressors by increasing pollutant concentrations and ecological impacts.

As freshwater supplies dwindle and economic development spurs increased water demand, technologies like desalination and water reuse are recognized as promising solutions to bridge the gap between water availability and demand(International Water Association, 2015). However, the broader implementation of desalination raises concerns due to the release of brine containing chemical residues, negatively impacting coastal ecosystems. Additionally, while desalination addresses water scarcity in stressed areas, the associated wastewater management poses challenges and costs (International Water Association, 2015). Neglecting wastewater as a significant social and environmental problem jeopardizes efforts towards achieving the 2030 Agenda for Sustainable Development (United Nations, 2017).

The ability to reuse water, whether for augmenting supplies or managing nutrients in treated effluent, offers several positive benefits, motivating the implementation of reuse programs (U.S. Environmental Protection Agency, 2015). These benefits include improved agricultural production, reduced energy consumption associated with water production, treatment, and distribution, and noteworthy environmental benefits such as decreased nutrient loads in receiving waters due to the reuse of treated wastewater

(Fatta-Kassinos, 2016).

While water reuse is currently implemented in many countries, its potential remains under exploited in numerous areas, and the proportion of water reuse in total wastewater generation is still relatively small. However, this is changing, with global water reuse capacity estimated to have increased. (Voulvoulis, 2018)

A transition to a Circular Economy could further accelerate this rise, marking a paradigm shift akin to a third industrial revolution. This emerging worldview, supported by the internet age facilitating unique idea exchange, sees states leveraging their financial and regulatory capacities to kick-start a circular economy, fostering significant synergies for the widespread adoption of water reuse. This concept arises in response to the drawbacks of the conventional 'take-make-consume and dispose' model of growth, signaling a shift towards sustainable development. (Voulvoulis, 2018)

In recent years, significant research has explored the potential of water reuse and recycling. Technical studies have focused on identifying technologies that can recover valuable by-products alongside treated water, such as nutrients, chemicals, and bioenergy resources, including phosphorus and nitrogen fertilizers, biogas, and biofuel from various wastewater streams. Social research has examined public acceptance of high-quality treated water and its by-products, highlighting real-world challenges and barriers. Economic analyses have concentrated on the water economy and the feasibility of a circular economy model, particularly given the availability of inexpensive water resources(Voulvoulis, 2018). However, water reuse adoption remains limited, partly due to an insufficient understanding of the future impacts on water systems and the role of water reuse within them.

1.1. Research Objective

The objective of this study is to provide insights into the impact of water reuse strategies on water system . Through simulating various water reuse policies across multiple scenarios, it explores how different strategies could impact water demand, resource availability, and economic conditions over time. The model captures complex interactions within the water sector, enabling an analysis of how shifts in reuse practices might support sustainability goals and contribute to a circular economy.

1.2. Research Scope

Several key decisions define the scope of this study, the most important of which are:

- the focus on reusing collectible wastewater
- the focus on economic aspects of water reuse
- using dynamic partial equilibrium in order to analyze the impact of water policies and strategies for adopting water reuse
- the focus on the Netherlands as a case study

These scoping decisions are further elaborated upon in the following chapter.

1.3. Structure of the Study

This study is organized into four distinct parts. The first part, comprising Chapters 1 to 3, introduces the general context and problem of the study. Chapter 1 offers an introduction to the subject matter, outlining the scope and significance of the issue. Chapter 2 provides a comprehensive review of the relevant literature, focusing on key areas such as the water cycle, water reuse and recycling practices, the economics of water reuse, and the economic modeling techniques used in water reuse research. Based on the gaps identified in the literature, the main research question is formulated. In Chapter 3, the sub-research questions necessary to address the main research question are identified, and the research approach for answering these questions is outlined, establishing the methodology and analytical framework to be used throughout the study.

The second part of the study is dedicated to presenting the methods and tools used to answer the research questions. Chapter 4 provides an analytical examination of the Dutch water system, exploring the interactions between various agents and stakeholders within this system. Chapter 5 introduces the mathematical conceptualization of the Dutch water system, which forms the foundation for determining the key parameters in the economic modeling of water reuse. This chapter also discusses the financial aspects of water reuse technologies, drawing on data from previous studies to inform the economic model. Chapter 6 details the formalization and implementation of the model, outlining the specific methodologies used to simulate the effects of water reuse strategies. Finally, Chapter 7 organizes the research problem in a way that effectively addresses the sub-research questions, providing the structure for the analysis in the later stages of the study.

The third part of the study presents the results of the simulation outcomes. Chapter 8 validates the general behavior of the model by analyzing the future trajectory of the Dutch water system without the implementation of water reuse strategies, establishing a baseline for comparison. In Chapter 9 and 10, the simulation outcomes for various water reuse strategies and scenarios are presented, illustrating the effects of different approaches on the water system and broader economic and environmental factors.

The study concludes with a discussion section in the fourth part. Chapter 11 explores the limitations of the study, providing a critical assessment of the research design, methods, and findings. . In Chapter 12, the main and sub-research questions are revisited, summarizing the key insights and conclusions of the study. Recommendations for policymakers and the technology sector are provided, and potential avenues for further research are identified, highlighting areas where additional investigation could contribute to a deeper understanding of water reuse and its implications for sustainable water management.

2 Literature Review

In this chapter, various strands of literature on water reuse are thoroughly reviewed and synthesized to uncover the knowledge gaps on which this study is based. Section 2.1 provides a foundational overview of the urban water cycle, including how water reuse and recycling fit into the broader system. Section 2.2 introduces the core concepts of water reuse and recycling, defining key terms and ideas critical for this study. Section 2.3 expands on different perspectives of water reuse, covering environmental, social, and technological dimensions that highlight its importance and relevance to the current study. In Section 2.4, the economic aspects of water reuse are examined in depth. Section 2.5 then reviews various modeling approaches used to evaluate the economic impacts of water reuse, comparing methodologies from prior studies. Section 2.6 explains the necessity of a case study and presents the Netherlands as our choice. Finally, Section 2.7 synthesizes the insights from previous sections, pinpointing specific knowledge gaps that inform the research questions and objectives driving this study.

The next section will discuss the concept of circular economy as a potential solution to the water crisis.

2.1. Urban Water Cycle

The continuous expansion of urban areas around the world is deeply interconnected with the rapid growth in economic activity, population, and urban infrastructure. Currently, urban centers accommodate more than half of the global population, with over 500 cities surpassing one million residents. As urban populations continue to rise, the importance of securing and managing water resources becomes increasingly critical.(Marsalek, 2008)(Pinto et al., 2022)

One of the foundational concepts in hydrology and water resource management is the hydrologic cycle, also known as the water cycle.(figure 2.1) This cycle has been theorized and studied since ancient times, evolving into a widely recognized model that describes the movement and storage of water across various parts of the Earth. While definitions can vary slightly, the hydrologic cycle is generally understood as a conceptual model that explains how water is stored and circulated between the biosphere (the living organisms), atmosphere (the air layer around the planet), lithosphere (the Earth's crust), and hydrosphere (the combined water bodies). Water resides in multiple storage locations such as the atmosphere, oceans, lakes, rivers, streams, soils, glaciers, snowfields, and groundwater aquifers. The transfer of water among these storage areas is driven by processes that include evapotranspiration, condensation, precipitation, infiltration, percolation, snowmelt, and runoff—collectively known as the components of the water cycle. These processes ensure that water is continuously moving and transforming, supporting ecosystems, human activities, and climate regulation. (Marsalek, 2008)

As urban areas grow and develop, they bring with them the forces of urbanization, industrialization, and increased population densities, all of which exert considerable pressure on natural landscapes. This pressure extends to the hydrological responses of watersheds, as these natural systems adapt to accommodate higher demands and altered landscapes. Although human activities reshape many environmental elements, including the paths water takes and the sources from which it is drawn, the fundamental structure of the hydrological cycle remains largely intact within urban settings. However,

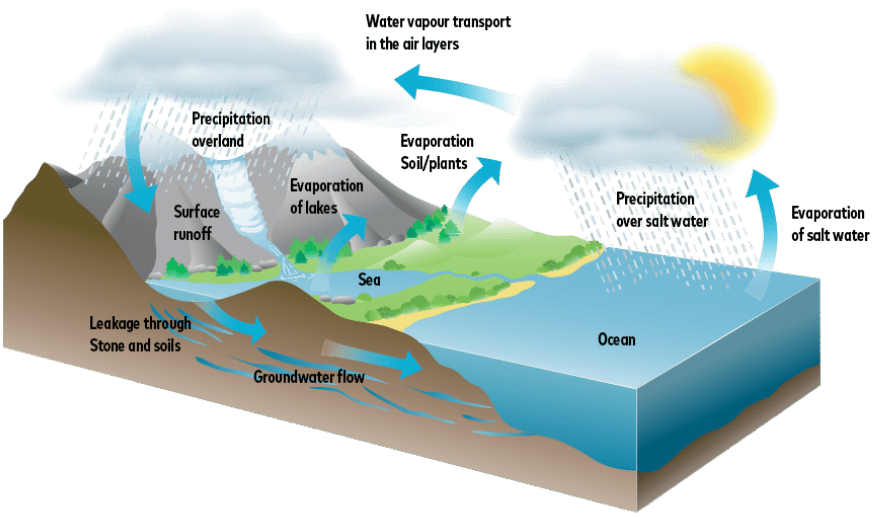


Figure 2.1: A simplified visual representation of the natural hydrologic cycle, illustrating key processes such as precipitation, evaporation, infiltration, and runoff as water moves between the atmosphere, land, and water bodies.(Apure, 2023)

urbanization brings about substantial modifications to the hydrologic cycle, fundamentally reshaping it in response to urban demands for water services. These services encompass essential functions such as water supply, drainage, wastewater collection, and the management of receiving waters for various beneficial uses. (Peña-Guzmán et al., 2017)

The intensification of human activities in urban settings introduces additional complexities to the hydrologic cycle, resulting in what is often referred to as the "urban water cycle" (UWC).(figure 2.2) The UWC is an adapted version of the traditional water cycle, altered by human intervention to meet the needs of urban areas. Unlike the natural hydrologic cycle, which operates based on natural processes, the UWC incorporates infrastructure and engineered solutions to manage the altered flow patterns, control pollutants, and recycle water to support urban populations.(Ahammed et al., 2017) Urban infrastructure, including water treatment plants, sewage systems, and drainage networks, plays a crucial role in sustaining water availability, quality, and accessibility within cities.(Wei et al., 2018)

This urban water cycle, or UWC, differs significantly from its natural counterpart due to the myriad anthropogenic influences. Water in urban areas is not only drawn for consumption but also channeled through various systems that treat and reuse it, manage stormwater, and control pollution, creating a more complex network of pathways and processes. For instance, while natural precipitation would typically be absorbed into the soil or flow into rivers, in urban areas, impervious surfaces such as roads and buildings prevent absorption, leading to increased runoff. This runoff must then be managed through stormwater systems to prevent flooding and minimize contamination of water bodies. Furthermore, wastewater generated by urban populations requires collection and treatment before it can be safely discharged or repurposed, adding additional layers to the urban water cycle.(Peña-Guzmán et al., 2017)

2.1.1. Type of water in water sector

Within the water cycle, different categories of water are identified based on their sources, uses, and levels of pollution. These categories include blue, green, grey, and black water, each playing a unique role in both natural ecosystems and human water usage. (Falkenmark & Rockström, 2006)

- **Blue water** refers to the freshwater stored in rivers, lakes, aquifers, and surface water reservoirs. This is the most commonly used water source for human activities such as drinking, irrigation, and industrial use. Blue water supports about 30% of global food production, especially in regions where irrigation is critical for crop growth. It also sustains aquatic ecosystems, contributing to biodiversity in freshwater habitats. Given its essential role in supporting both human needs and the environment, blue water is often the most stressed and over-exploited resource, particularly in

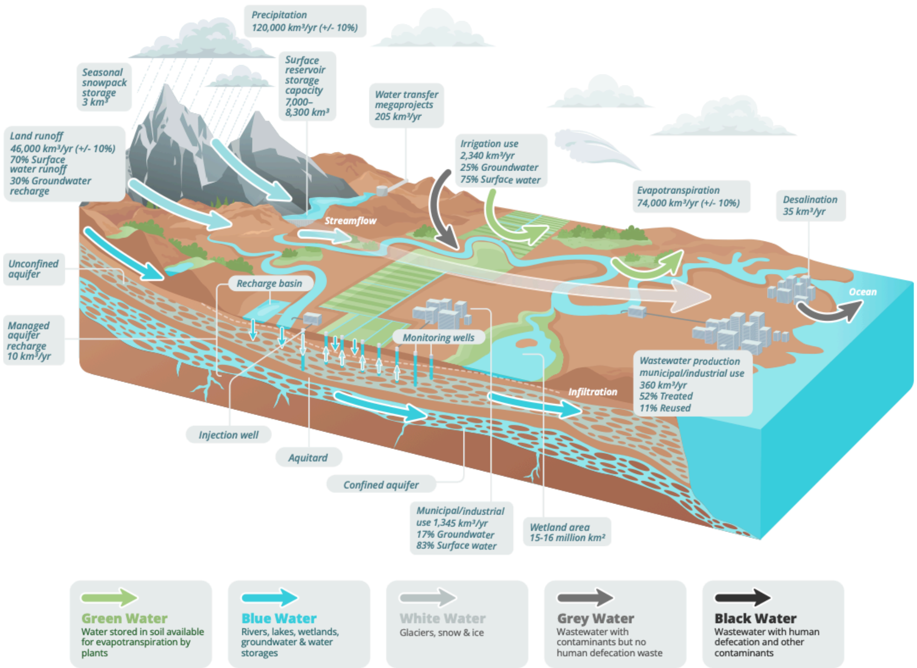


Figure 2.2: A simplified visual representation of the urban water cycle, highlighting key components and pathways influenced by natural processes and urban infrastructure(Global Commission on the Economics of Water, 2023)

arid and semi-arid regions where water scarcity is a growing concern.(Falkenmark & Rockström, 2006)

- **Green water** is the water stored in the soil, mainly in the form of soil moisture, which is accessed by plants through evaporation and transpiration. This type of water is crucial for rainfed agriculture, where crops rely on natural rainfall rather than irrigation. Green water powers ecosystems, enabling plants and trees to thrive and sustain wildlife. Unlike blue water, which is withdrawn and transported for human use, green water is primarily a natural, cyclical resource that remains in place within ecosystems. However, the management of green water is essential to prevent soil degradation, especially as deforestation and land use changes reduce its availability for plant growth.(Falkenmark & Rockström, 2006)
- **Grey water** is used water that has been polluted by human activities but has not yet reached the stage of contamination requiring full treatment. It typically comes from household or industrial sources, such as wastewater from washing dishes, laundry, and bathing. Though it may contain pollutants like detergents or food particles, grey water can often be treated and reused for non-potable purposes, such as irrigation or flushing toilets.(Falkenmark & Rockström, 2006)
- **Black water** refers to water contaminated with human waste, typically from toilets, and contains pathogens and harmful chemicals. Because of the high contamination levels, black water requires extensive treatment before it can be safely returned to the environment or reused. Effective treatment and management of black water are crucial for maintaining public health and protecting water sources from contamination.(Falkenmark & Rockström, 2006)

In the urban water cycle, a portion of wastewater flows through the urban wastewater system, while the remainder continues through the natural water cycle.

Definition

The wastewater that is collected and can potentially be treated and reused before being released back into the environment is referred to as **collected wastewater**. This type of wastewater is generally captured before it reaches natural water bodies and can include, greywater,blackwater, industrial effluent and stormwater.

Scoping Decision

this study focuses specifically on the reuse and recycling of **collected wastewater**.

To effectively manage and mitigate the impact of human activities on the water cycle, while ensuring the availability of sufficient, high-quality water for human consumption, governments implement a range of environmental policies. These policies are crucial in regulating water usage, protecting water resources, and fostering sustainable practices. In the following section, we will explore the European policies specifically focused on the urban water cycle.

2.1.2. European Policies in Water Sector

The European Commission has introduced several water management directives over the years, starting with the 1980 Drinking Water Directive (Directive 80/68EEC), which set standards for toxic chemicals and substances that pose health risks in drinking water. This was followed by various directives addressing the chemical and ecological status of European waters, such as the Nitrates Directive (1991), Urban Wastewater Treatment Directive (1991), Plant Protection Products Directive (1991), Integrated Pollution Prevention and Control Directive (1996), Biocides Directive (1998), the New Drinking Water Directive (1998), and the Groundwater Directive (2006). Although these directives marked progress in specific areas, they did not adequately address the multiple stressors impacting water bodies.(European Commission, 1980)(European Commission, 2002)(European Commission, 2007)(European Commission, 2012)(European Commission, 2017)

The issue of fragmented responses persisted in EU policies until the introduction of the Water Framework Directive (WFD) in 2000 (Directive 2000/60/EC). The WFD was a pioneering approach to water management, offering a comprehensive framework that simultaneously tackles multiple environmental, social, and economic stressors. It encompasses water quality, quantity, and aquatic habitat, addressing both the chemical and ecological status of water. Waters are classified based on their qualitative and quantitative status, with categories such as poor, moderate, good, and high quality.

The WFD is structured into three management cycles: the first cycle concluded in 2015, the second cycle ended 2021, and the third cycle will conclude in 2027. Its implementation requires Member States to identify river basins, characterize the baseline status of these basins, assess pressures and water uses, and inter-calibrate national systems for ecological status assessment. Additionally, Member States must identify and implement cost-effective measures to meet the WFD's environmental objectives, publish River Basin Management Plans (RBMPs), and adopt sustainable water pricing policies.(Tsani et al., 2020)

Each RBMP outlines specific Programmes of Measures (PoMs), which incorporate technical, non-technical, and economic tools to control pollution, meet environmental standards, and enhance public awareness and capacity. The WFD's Articles 5 and 9 mandate the recovery of the full economic cost of water services, emphasizing the socio-economic importance of achieving both good environmental and chemical status for water bodies. This includes the financial cost (operating, maintenance, administration, and investment costs), the resource cost (the opportunity cost of water use), and the environmental cost (costs associated with water degradation). To ensure total water cost recovery, all water uses must be identified and linked to the respective economic agents and sectors, including households, industry, and agriculture. Financial costs are typically easier to quantify, particularly through infrastructure costs and maintenance expenditures.(Tsani et al., 2020)

The new proposal to directive 91/271/EEC in the wastewater sector introduces significant changes aimed at improving wastewater treatment and management across the European Union (EU). Notably, the new rules expand coverage to include smaller towns, addressing an important gap in previous legislation.(European Commission, Directorate-General for Environment, 2022) Under the 1991 EU regulations, approximately 43% of all urban agglomerations in the EU, which have fewer than 2,000 population equivalents (PEs), were exempt from wastewater collection and treatment requirements. However, this exemption resulted in significant pollution of water bodies. Under the new directive, towns with a population of 1,000 or more will be required to follow wastewater treatment rules by 2035. (European Commission, Directorate-General for Environment, 2022)

A major aspect of the new directive is the requirement for EU countries to reduce nitrogen and phosphorus levels in wastewater. By 2039, wastewater treatment plants serving populations of 150,000 PE or more must remove these nutrients to protect water quality. Furthermore, by 2045, the directive mandates the removal of micro-pollutants, such as pharmaceuticals and personal care products, which have become a growing concern in wastewater management.(European Commission, Directorate-General for Environment, 2022)

Over 90% of micro-pollutants found in wastewater are attributed to pharmaceuticals and cosmetics. The new directive requires producers and importers in these sectors to implement treatment processes to remove toxic substances, based on the "polluter pays" principle. This extended producer responsibility ensures that industries contributing to wastewater contamination are held accountable for their environmental impact.(European Commission, Directorate-General for Environment, 2022)

The wastewater sector is also tasked with reducing its greenhouse gas emissions, which currently account for around 0.85% of all EU emissions. One of the key goals is energy neutrality by 2045, meaning urban wastewater treatment plants should generate the energy they consume. The energy can be produced on-site or sourced externally, with up to 35% of the required energy allowed to be purchased.(European Commission, Directorate-General for Environment, 2022)

In line with the circular economy principles, the new rules promote the recovery and reuse of resources. For example, phosphorus extracted from wastewater sludge will be recovered and repurposed to produce fertilizers for agricultural use, thereby minimizing waste and enhancing resource efficiency.

2.2. Water Reuse: a Circular Approach

Within the urban water cycle, a variety of factors contribute to the growing pressures on water resources, making a water crisis increasingly inevitable.(Global Commission on the Economics of Water, 2023)

- **Population Growth**: The global population, projected to reach 9.7 billion by 2050, is primarily increasing in regions like sub-Saharan Africa and South Asia. This growth intensifies demands for water, food, and energy, with agriculture and livestock production putting a heavy strain on water resources. With rising water withdrawals, estimated to increase 20-30% by 2050, aquifers are being depleted, especially in nations like India, China, the U.S., and Pakistan. Many rivers are also impacted by excessive water extraction, leading to deterioration.
- **Economic Development**: Water is essential for multiple sectors, including energy production and the mineral industries, linking it to GDP growth. While economic gains may reduce poverty and improve access to water, they often degrade natural capital, especially impacting marginalized communities. Pollution, driven by industry and urban waste, is a persistent issue, with affluent groups consuming more water per capita and contributing more to environmental degradation than lower-income populations.
- **Urbanization**: Currently, over half of the global population lives in urban areas, with projections indicating a rise to 68% by 2050. Urbanization drives higher water demand, as urban citizens generally have greater access to water services, sanitation, and waste treatment systems. Informal settlements, however, often lack adequate water services, exacerbating public health and environmental challenges. High-density urban areas increase greywater production, reduce groundwater recharge, and increase runoff, contributing to pollution that affects surrounding ecosystems.
- **Climate Change**: Shifts in climate contribute to intensified water-related challenges, from extreme weather events and rising sea levels to alterations in snow cover and freshwater availability. Climate-related impacts reduce groundwater recharge, impair water quality, and disrupt food security. Such impacts are spatially varied, with some regions like South America and North Africa projected to experience unprecedented droughts by 2050, further intensifying water scarcity.
- **Technology and Innovation**: Technological advancements present opportunities and challenges. For instance, improved irrigation techniques can boost crop yields but may reduce river and aquifer recharge. Water access and management technologies, particularly in low-income regions, help enhance health outcomes and reduce time spent on water collection.

These forces collectively place significant strain on water systems, resulting in challenges related to supply, distribution, and management. The rapid growth of urban areas, coupled with inefficient water use and increasing demand, intensifies the issue, underscoring the critical need for improved water sustainability and resource management.

The concept of the circular economy introduces a fresh perspective on the relationships between markets, customers, and natural resources, advocating for sustainable and resource-efficient policies and practices. This innovative business model helps economic growth while minimizing the extraction of virgin resources. Across various states and corporations, there is a significant shift from linear to circular production and consumption models. The growing body of evidence highlights the imperative for policies and regulations to support this transition, steering economies away from polluting trajectories toward cleaner, more sustainable paths. Embracing a circular economy not only encourages more efficient water use but also provides robust incentives for innovation, enhancing an economy's capacity to address the increasing imbalance between water supply and demand. (Kearney, 2017)

Figure 2.3: Flows of water (closing the loop) and by products in circular economy approach(Delgado et al., 2021)

2.2.1. Closing the Loop: Wastewater

To fully integrate wastewater into the water cycle, it must be treated and reintroduced as a valuable resource, allowing it to circulate sustainably within the system. Wastewater treatment plays a vital role in this transformation, enabling society to manage water resources more responsibly. The primary objectives of treatment are to remove pollutants, large particles, toxic substances, and pathogens to ensure that the treated water—known as effluent—can either safely return to the environment or be repurposed for various applications, such as agricultural irrigation, industrial cooling, and even certain non-potable urban uses.(Silva, 2023)

This shift toward viewing wastewater as a resource, rather than merely a waste product, reflects a fundamental change in water management strategy. Historically, wastewater was seen as a liability and a health hazard, with treatment processes aimed primarily at safe disposal. However, with growing recognition of water scarcity in regions such as arid and semi-arid areas, there has been an increased need to recycle wastewater to support domestic, industrial, and agricultural demands. In these water-stressed regions, wastewater recycling has become a crucial practice, helping to ensure water availability and resilience against shortages.(Singh et al., 2023)

Aligned with circular economy principles, wastewater treatment now emphasizes the recovery of materials and energy, transforming wastewater into a sustainable asset rather than a discarded byproduct. The circular economy promotes minimizing waste, regenerating resources, and using materials efficiently to reduce reliance on natural reserves. As such, significant research has focused on advancing technologies that enable wastewater to be treated, recycled, and safely reused. By recovering nutrients, generating energy, and extracting chemicals, treated wastewater can support various sectors. For example, nutrients like nitrogen and phosphorus can be extracted from wastewater and repurposed as fertilizers, and organic matter can be used to produce energy for powering treatment facilities.(Jodar-Abellan et al., 2019)

While these advancements contribute to sustainability and environmental protection, they do not entirely resolve the increasing demand for water resources driven by population growth, economic expansion, and urbanization. Despite progress in wastewater treatment and resource recovery, the need for clean, accessible water continues to rise, fueled by higher standards of living and industrial growth.(Silva, 2023)

Wastewater reuse goes beyond traditional recovery by allowing treated wastewater to serve directly as a source of water for various applications, alongside material and energy recovery. This approach not only aligns with the circular economy by reducing the demand for fresh water but also maximizes the utility of wastewater, broadening its role in a sustainable water management system.(Van der Bruggen, 2021)

The concept of wastewater reuse dates back millennia; in 3000 BCE, the Minoan civilization in Crete used wastewater for agricultural irrigation. Today, wastewater reuse is common across many regions. In the European Union, it is estimated that up to 40% of wastewater could be reused. However, to enable wastewater reuse, additional treatment steps are often necessary to ensure safety and meet the required water quality standards, primarily by removing pathogenic microorganisms and chemical contaminants.(Silva, 2023)

Each recovery technology has unique characteristics, and often a combination of multiple treatment processes is necessary to meet the desired water quality. Selecting the appropriate methods involves evaluating several factors, including the initial quality of the wastewater, the required quality for its intended reuse, economic costs, and environmental impacts.(Silva, 2023)

Given the potential of water reuse as a solution to the water crisis and as a step toward a sustainable future, this study will focus primarily on exploring water reuse strategies alongside other approaches.(Silva, 2023)

> Scoping Decision
>
> this study will focus primarily on exploring **water reuse** strategies.

In the next section, we will explore the various aspects and considerations of water reuse, examining its role as a solution for sustainable water management in a resource-constrained world.

2.3. Topics on Water Reuse

Water reuse involves a variety of factors that influence the adoption and effectiveness of its practices. These factors can generally be categorized into three main areas: technological, social, and economic aspects.(Florides et al., 2024) Each of these categories plays a crucial role in shaping the implementation and success of water reuse systems. The following section discusses these aspects in detail.

2.3.1. Technological Aspect of Water Reuse

Reuse technologies for water recovery can be broadly divided into conventional and extensive categories. Conventional technologies are known for their high energy demands and compact space requirements. Among these, membrane processes, especially reverse osmosis (RO), are some of the most widely used methods for water recycling. RO, as part of membrane technology, is highly effective in removing contaminants such as bacteria, viruses, dissolved salts, and organic compounds, ensuring recycled water meets stringent quality standards for safe reuse. This process is adaptable, allowing for flexibility based on specific water quality requirements, with various membrane types and configurations to achieve the desired quality standards. Although membrane processes involve a higher initial investment, they can offer long-term savings by reducing the need for fresh water and wastewater disposal. With ongoing advancements, the cost of membrane technology has been steadily decreasing, enhancing its economic feasibility.(Khanzada et al., 2024)

Current research in wastewater management introduces two key concepts: minimum liquid discharge (MLD) and zero liquid discharge (ZLD). The MLD approach involves less energy-intensive processes compared to ZLD but still achieves a high rate of water recycling, with efficiencies reaching up to 80–95%. In contrast, ZLD complements MLD with energy-intensive technologies such as thermal thickening, evaporation, and crystallization, which can process wastewater with a high concentration of contaminants and reach efficiency rates close to 100%.(Panagopoulos & Haralambous, 2020)

Other conventional recovery technologies include physicochemical systems (e.g., coagulation-flocculation), ultrafiltration, rotating biological contactors, and disinfection methods such as UV radiation and chlorine dioxide.(Florides et al., 2024)

On the other hand, extensive technologies rely on natural processes, which require larger land areas but have low energy demands and minimal operation and maintenance requirements. Examples include stabilization ponds, constructed wetlands, and infiltration–filtration systems, where treatment occurs at a natural rate. (Florides et al., 2024)

Each recovery technology has unique attributes, and often, combining multiple technologies is recommended to achieve optimal quality and performance. Selecting the appropriate technology should consider the wastewater's quantity and quality, the required final quality for its intended use, economic costs, and environmental impacts. The European Directive (2010/75/EU) outlines the term Best Available Technique (BAT), which emphasizes choosing the most suitable water recovery technology for the intended purpose, ensuring environmental and economic balance.(Commission) et al., 2014)

In recent years, significant research has focused on improving the cost-effectiveness and scalability of water reuse technologies. As water scarcity becomes an increasingly pressing issue, these efforts aim to make water recycling more economically viable and widely applicable. A major area of research has been the development of more efficient and affordable treatment technologies that can handle varying water qualities, thus expanding the potential for water reuse in different contexts. The goal is to lower operational and capital costs while ensuring high-quality treated water that meets the necessary standards for its intended use.(Florides et al., 2024)

In addition to advancements in treatment technologies, substantial progress has been made in measurement tools, particularly in the real-time monitoring of water and wastewater contamination. Traditional water management systems have relied on natural buffers, such as wetlands and ecosystems, to mitigate contaminants and maintain water quality. However, with the bypassing of these natural buffers in the water reuse approach, there is a heightened need for more precise and continuous monitoring to ensure that the recycled water meets safety standards and does not pose health risks. Real-time monitoring technologies, such as sensors and automated systems, enable the detection of contaminants and pathogens, helping to optimize treatment processes and ensure the safety of reused water.(Florides et al., 2024)

Another important area of technological research has been the recovery of critical and valuable materials from wastewater. Water reuse technologies not only aim to recycle water but also to recover valuable resources, such as nutrients (e.g., nitrogen and phosphorus), heavy metals, and energy. These materials can be repurposed for agricultural use, energy production, or other industrial applications, contributing to a more sustainable circular economy. (Florides et al., 2024)

2.3.2. Social Aspect of Water Reuse

Water reuse, despite its potential benefits, is not yet widely accepted by society. One of the primary reasons for this is the lack of public awareness surrounding this innovative practice, which is a key component of the circular economy model. Many consumers express concerns about the safety and quality of reused water, particularly in terms of its potential odors, color, and overall cleanliness. Additionally, there is a lack of confidence in the reliability and effectiveness of wastewater treatment plants, which further contributes to resistance to water reuse practices hesitant to adopt water reuse technologies, particularly for irrigation purposes. Their concerns often center around the variability in water quality, which may affect crop yields and soil health. There is also apprehension about the commercial value of crops irrigated with reclaimed water, as well as the potential risks associated with contaminants that could be present in the water. (Wester et al., 2016)

When it comes to drinking water, the challenge is even greater. The concept of using reclaimed or reused water for direct consumption faces even more resistance due to heightened concerns about safety, public health, and the potential for contamination. Additionally, there is often a psychological distance between the idea of using wastewater for non-potable purposes (such as irrigation or industrial uses) and the notion of reusing it for drinking. Many people associate wastewater with contamination and disease, making the idea of drinking water that has been recycled from wastewater difficult to accept, even when the water is treated to meet stringent safety standards.(Pathiranage et al., 2024)

Many studies have been conducted on the social acceptance of water reuse, as it is a critical factor in the widespread adoption of water recycling technologies. Public perception plays a significant role in determining the success or failure of water reuse initiatives. These studies typically focus on understanding the concerns, attitudes, and acceptance levels of different communities toward the use of reclaimed water for various purposes, including irrigation, industrial processes, and even drinking water.(Florides et al., 2024)

2.3.3. Economic Aspect of Water Reuse

From a circular economy perspective, water reuse presents a win-win solution by promoting the sustainable management of water resources.(Voulvoulis, 2018) However, the success of such initiatives is highly dependent on how water is valued. In many regions, water is still seen as an inexpensive or virtually free resource, which diminishes the incentive to adopt more efficient, resource-conserving practices. Although water may appear cheap, increasing water abstraction charges are a response to its growing scarcity. These charges reflect the opportunity cost of water use, encouraging decision-makers to consider the trade-offs between using water for different purposes—such as for agriculture versus urban supply or hydropower generation. Abstraction charges can differ based on factors like the type of water (surface or groundwater), availability, seasonal fluctuations, and the costs associated with alternative water sources. Ideally, these charges should be high enough to send a clear economic signal, encouraging more efficient use and better resource management.(Dige et al., 2013)

The economic feasibility of water reuse is influenced by several factors, especially when compared to other water management alternatives such as expanding conservation measures or sourcing new water supplies. The costs associated with water reuse are determined by various considerations, including the location of wastewater treatment facilities, the quality of the influent water, the specific treatment processes required to meet the desired water quality standards, and the infrastructure necessary for water transmission and pumping. Additional costs such as energy consumption, storage requirements, concentrate disposal, and permitting may also factor into the overall cost. The cost-effectiveness of water reuse systems can vary significantly depending on local conditions and the intended use of the reclaimed water, whether for non-potable or potable purposes.(Voulvoulis, 2018)

Ultimately, the practicality and cost-effectiveness of water reuse depend on a comprehensive analysis that looks beyond direct costs to include broader economic, environmental, and societal considerations. This should also account for the ”cost of inaction”—the consequences of not pursuing water reuse and failing to implement alternative water management strategies.(Council et al., 2012)

In any given scenario, different strategies for water reuse can influence cost-effectiveness, regardless of the specific technology or infrastructure involved. Moreover, the economic aspects of water reuse have a direct impact on the social and technological dimensions of its implementation.

Understanding these interconnected economic factors is crucial for developing a balanced and effective approach to water reuse. Therefore, this study will focus on economic aspect of water reuse strategies.

> Scoping Decision
>
> this study will focus primarily on exploring the **Economic** aspect of water reuse strategies

2.4. Economy of Water Reuse

Water reuse technologies offer a promising solution for addressing global water scarcity, a challenge that affects both developed and developing regions. Despite this promise, the adoption of water reuse practices remains limited, with critical players such as water utilities—ranging from large, centralized wastewater treatment plants to decentralized systems designed for households—being instrumental in this process. These utilities operate within a complex urban water system, where multiple stakeholders, including urban water consumers, local communities, environmental agencies, and regulatory bodies, each exert influence on the acceptance and success of water reuse initiatives. Thus, understanding how water reuse technologies interact with existing urban water infrastructure and affect various stakeholders is essential for promoting the smooth and effective integration of reuse practices into water management frameworks.(Cagno et al., 2022)

Recent studies and economic analysis of water reuse technologies is central to advancing these systems. Research frequently examines the scalability of reuse systems by evaluating both capital expenditures (CAPEX) and operational expenditures (OPEX), which vary according to the quality of water produced and the technology employed.(Keller et al., 2022) Additionally, market analysis has identified potential revenue streams from byproducts of water reuse processes, such as reclaimed nutrients or treated water for industrial purposes. This analysis highlights the profitability of these byproducts, which could play a crucial role in improving the financial feasibility of reuse projects. For instance, Orsini et al.(Orsini & Rossi, 2023) evaluated the financial benefits of implementing SMARTechs—technologies that enable wastewater utilities to create marketable byproducts. Using a financial model based on Italian water tariff structures, Their study assessed scenarios with and without markets for these byproducts, applying financial metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), and payback period. Results indicated that the inclusion of byproducts improved financial outcomes across all scenarios, leading to recommendations for regulatory changes to encourage market growth. However, the model also revealed limitations in assessing the long-term economic impact of these technologies.

Cost-benefit and cost-effectiveness analyses also play a vital role by assessing how water reuse aligns with environmental and social sustainability goals, providing a nuanced understanding of the broader implications of reuse practices. For example, Chhipi-Shrestha et al. (2019) (Chhipi-Shrestha & Shrestha, 2019) employed a multicriteria decision analysis (MCDA) combined with game theory to evaluate sustainable water reuse options in Penticton, British Columbia. This study incorporated diverse stakeholder perspectives, examining environmental, economic, and social factors through techniques such as Life Cycle Cost (LCC) analysis, energy and carbon footprint estimations, and public acceptability surveys. The authors introduced a Water Reuse Sustainability Index (WRSI) within the MCDA framework, which aids in selecting the most viable water reuse options. This approach highlights how integrating various criteria can support informed decision-making; however, the model's lack of financial assessment underscores the need for further research into the economic viability of these approaches.

Policy analysis is another crucial component, with studies investigating the effects of regulatory frameworks on stakeholders, including the environment, private companies, and consumers. For instance, D'Orazio and Ruggeri (2019) (D'Orazio & Ruggeri, 2019) utilized an agent-based computational model to explore the role of financial incentives in environmental innovation. This research underscored the importance of both public and commercial investments—especially for small and medium enterprises (SMEs)—in advancing the adoption of green technologies. By modeling interactions among consumer preferences, firm innovation, and financial constraints, the study found that public investments in environmental projects can significantly enhance the diffusion of green technologies, driving GDP growth. They suggest that public investment banks play a critical role in bridging the "green financial gap," a necessary step toward sustainable development and climate resilience.

Cagno et al. (2022) (Cagno et al., 2022) adopted a partial equilibrium model to simulate how various regulatory and operational scenarios affect water reuse adoption. Their research explored the economic integration of water reuse within existing water systems, examining the impacts of different configurations—such as variations in utility ownership, loop topology, and effluent quality. By modeling diverse scenarios, they illustrated how regulatory policies could influence costs, demand, revenues, and profit margins, resulting in different economic outcomes for stakeholders. The study concluded that effective policy interventions are essential to ensure the long-term economic viability of water reuse systems, highlighting the importance of regulatory support in stabilizing utility operations within a reuse context.

Economic and policy analyses of water reuse technologies underscore the complex, interwoven impacts of these practices on environmental, social, and economic factors. This body of research provides essential insights into the drivers and barriers to the scalability of water reuse systems, emphasizing the importance of a holistic approach when evaluating reuse technologies and associated policies. The findings collectively suggest that economic, social, and policy dimensions are deeply interconnected, each influencing the potential for successful water reuse implementation. This highlights the need for a comprehensive perspective that accounts for economic, technological, and societal factors to promote sustainable water management practices. Therefore, this study focuses on analyzing the impact of policies and strategies for adopting water reuse.

Scoping Decision

this study focuses on analyzing the **impact of policies and strategies** for adopting water reuse.

2.5. Modeling Approaches for Policy and Strategy Analysis in Water Reuse

Analyzing the impacts of policies and strategies in water reuse requires robust modeling frameworks capable of capturing complex system dynamics and stakeholder interactions. Several modeling approaches are available, each with strengths and limitations that make them suitable for different aspects of policy analysis.

Dynamic Partial Equilibrium (DPE) models, provide a framework for capturing the interactions among multiple economic sectors and stakeholders in response to policy changes. By simulating economic agents (e.g., consumers, water utilities, and governments) and their decision-making processes within interlinked markets, DPE models can evaluate how changes in one part of the economy (e.g., introducing water reuse technology) affect other parts (e.g., labor markets, industrial output, and environmental quality). DPE models are particularly effective at analyzing policy scenarios over time, capturing dynamic changes in variables such as prices, resource allocation, and production levels across sectors.(Fang et al., 2016)

One of the strengths of DPE modeling is its ability to provide a macroeconomic perspective, assessing not only direct impacts on water usage and conservation but also indirect effects on related sectors, government revenue, and consumer welfare. (Luckmann et al., 2014) Moreover, DPE models enable the integration of environmental factors, such as the effects of water reuse policies on natural resource sustainability and pollution levels, thereby supporting a holistic assessment of policies.(Fang et al., 2016)

In addition, water reuse policies often have long-term environmental and economic impacts, which DPE models can track over time. The model's dynamic nature allows for an assessment of how the adoption of water reuse technologies might evolve under various economic scenarios, such as changes in resource prices or policy incentives, while accounting for feedback effects within and between sectors.

This study employs Dynamic Partial Equilibrium modeling as it aligns well with the goal of evaluating the economic feasibility and sustainability of water reuse policies across different sectors. DPE is an appropriate choice for several reasons. Water reuse initiatives often involve economic trade-offs between sectors, such as agriculture, industry, and urban users, where resource allocation changes influence productivity, resource availability, and consumer behavior across the economy. DPE allows for capturing these interdependencies in a cohesive, integrated manner, providing a comprehensive view of the potential shifts in economic equilibrium resulting from policy interventions.(Luckmann et al., 2014)

By utilizing a DPE approach, this study can provide policymakers with a data-driven understanding of how water reuse policies affect the economy at large, while also considering sector-specific outcomes and sustainability goals. The ability of DPE models to integrate economic, environmental, and policy variables into a single, cohesive framework makes them a powerful tool for guiding strategic decision-making in the water sector. This approach ensures that water reuse policies are evaluated not only for their feasibility but also for their potential to support long-term economic resilience and environmental sustainability.

Scoping Decision

this study uses **dynamic partial equilibrium** in order to analyzing the impact of policies and strategies for adopting water reuse.

2.6. Case Study: Water Reuse in Netherlands

While theoretical modeling and general policy analysis offer valuable insights into water reuse, they often overlook critical region-specific factors, including geography, climate, economic conditions, and existing water management infrastructure. A case study enables a closer examination of how these unique factors influence the effectiveness and limitations of water reuse policies, providing targeted, evidence-based recommendations that can inform both local and broader water management strategies. By focusing on a particular region, this research can analyze water reuse policies within a clear framework, yielding actionable insights that are closely aligned with the specific characteristics and challenges of the chosen context. Conducting a case study is thus a crucial element of this research, as it situates policy analysis within a real-world environment where the impacts, dynamics, and effectiveness of water reuse policies can be examined comprehensively.

Although often perceived as a water-abundant country, the Netherlands faces distinct water management challenges, including water scarcity and quality issues driven by seasonal variability, high population density, and pollution from agriculture and industry. Climate change is exacerbating these challenges by increasing drought risks and altering precipitation patterns, which intensifies dependence on groundwater resources and raises concerns about sustainable water use. In this context, water reuse presents a promising approach to addressing water shortages while supporting environmental sustainability.

The urgency of these challenges became evident on August 3, 2022, when the Dutch government declared a ”de facto water shortage (level 2),” escalating from a prior ”threat of water shortage (level 1).” This declaration prompted the delegation of water distribution management to a national commission, the Management Team Water Scarcity, tasked with closely monitoring water scarcity developments and reacting swiftly if additional measures are needed. While current efforts primarily focus on preventive actions, the situation underscores the severity of water scarcity in the Netherlands.(Toreti et al., 2022)

Europe as a whole has been experiencing severe-to-extreme drought since early 2022, with forecasts pointing to continued drier-than-normal conditions in the months ahead. In the Netherlands, the impacts of these droughts have been pronounced, particularly in the form of severely low flow in the Rhine River. This has disrupted commercial navigation, threatened dike stability in the western peatland areas, and caused related issues such as water distribution difficulties and seawater intrusion throughout the country’s strongly interconnected water system. Although these problems remain manageable, they highlight the fragility of the Dutch water management system under increasing stress.(Toreti et al., 2022)

On April 24, 2024, Deltares presented the new Delta Scenarios for the Netherlands, offering four potential trajectories to guide water and spatial planning policy until the end of the century. All four scenarios point to significantly more challenging agendas for water management. Freshwater shortages during summer are expected to intensify, issues with excess water from rainfall will become more frequent, and floods will have greater impacts. These compounding bottlenecks—including water shortages, excess water, and flood risk management—will increasingly affect the entire country.(Rijkswaterstaat, 2024)

Additionally, the demand for drinking water in the Netherlands is projected to grow until at least 2030. However, this rising demand is already straining supply due to climate change and pollution, with some regions already experiencing shortages. If proactive measures are not implemented, widespread drinking water shortages could occur across the Netherlands by 2030. According to the RIVM, a mix of solutions is needed to prevent a structural shortage of drinking water. The Dutch government must take a leading role now to address obstacles and develop comprehensive strategies to ensure a sustainable and reliable drinking water supply for the future.(RIVM, 2024)

The Netherlands also benefits from a highly advanced and integrated water management system, featuring strong regulatory frameworks and a long-standing commitment to innovative water policy. This well-regulated and collaborative environment allows for an in-depth examination of water reuse strategies within a mature infrastructure that includes diverse stakeholders, such as government agencies, water utilities, industrial sectors, agriculture, and the public. The Netherlands' well-established regulatory framework provides an ideal setting for assessing the practical application of water reuse policies and exploring how various strategies interact with existing water rights, regulations, and levels of public acceptance. Additionally, the Dutch commitment to the circular economy—an approach focused on closing resource loops and minimizing waste—aligns well with the objectives of water reuse. Studying water reuse in this progressive policy landscape presents a unique opportunity to analyze how circular economy principles can enhance sustainable water management practices.

Moreover, recent studies indicate high public acceptance of water reuse in the Netherlands, with around 75% of the population supporting water reuse practices, even for drinking water. This favorable public attitude minimizes the social barriers typically encountered in water reuse projects. Furthermore, the Netherlands has a robust history of water technology innovation and is home to many specialized research institutions dedicated to water sector advancements, which helps address technical barriers to reuse. Given these factors, this study places a particular emphasis on the economic aspects of water reuse policies and strategies, as the Netherlands offers a supportive environment in which to investigate their economic feasibility and effectiveness. Altogether, the Netherlands' unique water management challenges, advanced regulatory system, commitment to sustainability, and strong social and institutional support make it an ideal setting for in-depth study and analysis of water reuse policies and strategies.

Scoping Decision

this study focuses on **the Netherlands** as a case study.

2.7. Knowledge Gap

Water reuse is increasingly recognized as a valuable approach to addressing water scarcity, but there remains a limited understanding of how specific policies and economic strategies can support its adoption. Much of the current research emphasizes the technical and environmental aspects of water reuse, often with less focus on the economic conditions and policy frameworks that shape its implementation. Additionally, existing studies tend to overlook the complex interactions among economic incentives, regulatory measures, and the range of stakeholders involved in water reuse systems. They also rarely consider how these policies may influence reuse practices over time, which is essential for sustainable and lasting adoption.

This study seeks to fill these gaps by investigating the impacts of different water reuse strategies within the Dutch context. By considering the Netherlands' specific economic conditions, policy landscape, and public attitudes, this research provides a structured framework for assessing how policies can be tailored to enhance sustainable water reuse initiatives. The findings offer insights into the broader effectiveness of policies, which may support the integration of water reuse into sustainable water management practices in the Netherlands and beyond.

The overarching question summarizing these knowledge gaps is:

Main Research Question

"How can policies and water reuse strategies, tailored to the local characteristics of water systems, be designed to make water reuse an economically viable alternative to freshwater?"

3

Research Methodology

This chapter introduces the research methodology used to answer the main research question of this study:

Main Research Question

"How can policies and water reuse strategies, tailored to the local characteristics of water systems, be designed to make water reuse an economically viable alternative to freshwater?"

Section 3.1 outlines the essential steps required to conduct a modeling study of a complex adaptive system. In Section 3.2, the sub-research questions necessary to address the main research question are identified.

3.1. Modeling Socio-Economic System

Wu et al. proposed that water systems should be viewed as complex socio-economic systems, as water is directly linked to global economic development, regional ecological health, and human well-being.

To develop a socio-economic model capable of analyzing water systems, the following steps have been outlined:

- **Problem formulation and actor identification**: In this step, the problem to be addressed is defined, and the actors involved in the issue are identified.
- **System identification and decomposition**: This step focuses on identifying the physical and social entities within the system, their behaviors, and how they interact.
- **Concept formalization**: Here, the concepts identified in earlier steps are transformed into a mathematical format that can be understood by a computer.
- **Model formalization**: This step involves developing the model narrative, establishing the sequence of events, and specifying the interactions between agents.
- **Software implementation**: In this step, the model is implemented using the chosen software environment.
- **Model verification**: This step ensures that the model built matches the intended design and accurately represents the system.
- **Experimentation**: Experiments are designed and conducted to provide insights into the research questions.
- **Data analysis**: The outputs from the experiments are analyzed to draw conclusions and answer the research questions.

3.2. Sub-Research Questions

Based on the main research question, the literature review, and the steps for developing a socio-economic model for a water system, the following sub-research questions are formulated:

- How can the interactions and behaviors of actors within the water system, as well as the financial aspects of water reuse, be formulated based on established policies and organizational frameworks?
- How can strategies and policies be integrated into the DPE framework and implemented within computational tools such as MATLAB?
- How can the impact of various strategies be measured using the model?
- How can different strategies be compared to one another using the model?

3.2.1. SQ1 Model Input

This study examines the impact of policies and water reuse strategies in supporting sustainable development within the water sector. To achieve this objective, it is crucial to identify the key actors and their behaviors within the current organizational framework. This research question addresses the first two steps outlined in Section 3.1: Problem Formulation and Actor Identification, as well as System Identification and Decomposition. The problem formulation has already been defined in the introduction and literature review. In the following chapters, the Dutch water system and its actors will be discussed, and the interactions between the economic cycle and the water cycle will be decomposed.

The concept formalization step is partially covered by the presentation of the model equations, which represent an initial stage toward creating a computer-understandable model, though it is not yet fully developed. The final step of concept formalization will be addressed in the subsequent research question.

3.2.2. SQ2 Model Development

This research question addresses the third, fourth, and fifth steps outlined in Section 3.1. In the concept formalization step, various concepts are translated into a machine-readable format. In the model formalization step, the sequence of actions and interactions within the model is explained. The model is then implemented using Matlab, where the structure and behavior defined in the previous steps are realized in a computational environment.

3.2.3. SQ3 Model Baseline

This research question addresses the seventh step. In this step, the behavior of the model is validated by testing whether it replicates empirically observed data and establishes a baseline for the analysis of strategies over future timelines. This validation ensures that the model accurately reflects real-world dynamics and can be used to assess the effectiveness of different strategies.

3.2.4. SQ4 Model Experimentation and Data Analysis

This research question addresses the remaining steps. The experimental design will be simulated using the developed model, and the results will be analyzed. This section provides insights for comparing different strategies and assessing their impact on socio-economic parameters, helping to evaluate the effectiveness of various water reuse strategies in the context of the model.

Part II

Methods

4
Dutch Water System

The water system in the Netherlands is structured through the involvement of multiple stakeholders, each assigned a specific role. These stakeholders are influenced by one another and contribute collectively to the functioning of the system through various interactions. In this section, an overview of the key stakeholders and their relationships within the Dutch water system will be provided, highlighting how collaboration is achieved in managing water resources. Although efforts have been made to capture the essential aspects of the system relevant to this study, certain details or perspectives have been intentionally omitted, as they fall outside the scope of the research. Focus will be placed on both the demand side and the tariff side of the water system in subsequent sections. While these aspects are interconnected, they will be discussed separately, with attention given to how they influence each other.

4.1. Stakeholders in the Dutch Water System

The Dutch water system involves a variety of stakeholders, each playing a critical role in its management and operation. The stakeholders relevant to this study will be briefly analyzed below:

The **Government (Ministry of Infrastructure and Water Management)** plays a central role in overseeing the overall structure and functioning of the country's water system. It is responsible for establishing national water policies, coordinating efforts at various administrative levels, and supervising the activities of both provinces and municipalities. Its regulatory framework ensures that water management aligns with broader environmental and public health objectives. The Department of Waterways and Public Works (Rijkswaterstaat) is an executive branch of the Ministry of Infrastructure and water management and is responsible for the management of large waters, such as the sea and rivers.(Laurens J. ZWAAN, 2023)

At the regional level, the **province** holds responsibility for translating national water policy into regional measures. They are also responsible for the creation and control of the water boards (waterschappen), to which they can issue instructions by regulatory means (Water act article 3.11). Besides, the 12 provinces are responsible for managing groundwater resources. This includes overseeing the allocation and use of groundwater to ensure its sustainable exploitation, while balancing the needs of different sectors such as agriculture, industry, and urban areas. (Laurens J. ZWAAN, 2023)

The **Municipality** is tasked with the spatial planning in their territory, local wastewater collection and transportation, urban groundwater, urban sanitation and rainwater collection. It ensures that wastewater from households, businesses, and industries is properly collected and transported to treatment facilities, contributing to public health and the cleanliness of the urban environment.(Laurens J. ZWAAN, 2023)

The **Water Boards (Waterschappen)** are key regional authorities responsible for managing water at a more localized level. The water boards have powers to make bylaws and impose taxes. They are also in charge of granting permits, for example for the abstraction of drinking water and industrial uses above 150,000 m3/year. They play a crucial role in flood protection, ensuring the safety and maintenance of dikes and levees. In addition, they are tasked with managing water quality and quantity within their regions, as well as wastewater treatment, thus contributing significantly to both environmental sustainability and public safety.(Laurens J. ZWAAN, 2023)

The **Water Supply Companies** are responsible for the provision of clean drinking water. They extract, treat, and distribute water to households, industries, and agricultural sectors, ensuring that the water supplied meets the necessary safety and quality standards.(Laurens J. ZWAAN, 2023)

Water Consumers, including households, industries, and the agricultural sector, represent the demand side of the water system. Their water needs vary in both quality and quantity depending on their activities. Although they are the end-users in the water supply chain, they are not the final component in the water cycle, as their wastewater is returned to the system for treatment and potential reuse.

Finally, **Water Resources**—comprising both groundwater and surface water—are the fundamental components of the water cycle. These resources serve as the initial source of water for supply and are also where treated wastewater is eventually returned. Sustainable management of these resources is essential to maintaining the balance of the water cycle and ensuring the long-term availability of clean water.

4.1.1. Relationships Among Stakeholders in the Dutch Water System

A crucial component of the Dutch water system is the interaction between its various stakeholders, particularly in terms of financing their activities and accessing each other's services. These relationships can be examined from two key perspectives: the flow of water and the flow of finances.

From the perspective of **water flow**, stakeholders are interconnected through the distribution and treatment of both supply water and wastewater. Water supply companies often act as intermediaries in this process, extracting water from natural sources such as groundwater and surface water for distribution. The extracted water may be delivered directly to industries and the agricultural sector, depending on the required quality, or supplied to drinking water companies that treat the water to meet higher standards. Households and some industries receive treated drinking water through these water supply companies, while other industries and the agricultural sector may also access water directly from natural sources when specific volumes or qualities are necessary for their production processes.(Government of the Netherlands, 2025a)

In terms of **wastewater**, industries and agriculture are permitted to discharge treated wastewater into natural water resources, provided they meet established environmental treatment standards. Water boards are tasked with regulating and monitoring the disposal of wastewater from these sectors. Their primary responsibility is to ensure that the discharged water complies with regulatory standards to minimize negative impacts on natural resources. Households, along with most other water consumers, are required to direct their wastewater to treatment facilities operated by water boards, typically via sewer systems maintained by municipalities . The water boards ensure that wastewater is effectively treated before being released into natural water bodies, thus protecting water quality throughout the system.(Government of the Netherlands, 2025a)

The second key dimension is the **flow of finances**. Financial interactions between stakeholders are shaped by various funding mechanisms and taxation frameworks. The government provides significant financial support to provinces, municipalities, and water boards, particularly for large-scale projects that align with national objectives related to environmental protection and infrastructure development. These funds play a vital role in sustaining and enhancing essential water services across the country. (Dutch Water Authorities, 2021)

Water consumers, including households, businesses, and industries, contribute to the financial viability of the system through a range of local and regional taxes. Municipalities levy local taxes on water consumers to support the maintenance and operation of sewer systems, while water boards collect regional taxes to fund water management and wastewater treatment activities.(Business.gov.nl, 2025) Provinces also receive regional taxes from consumers, which support their responsibilities in managing groundwater and regional water resources. Additionally, water supply companies pay taxes to the provinces for the right to extract water from natural resources, ensuring that the financial sys-

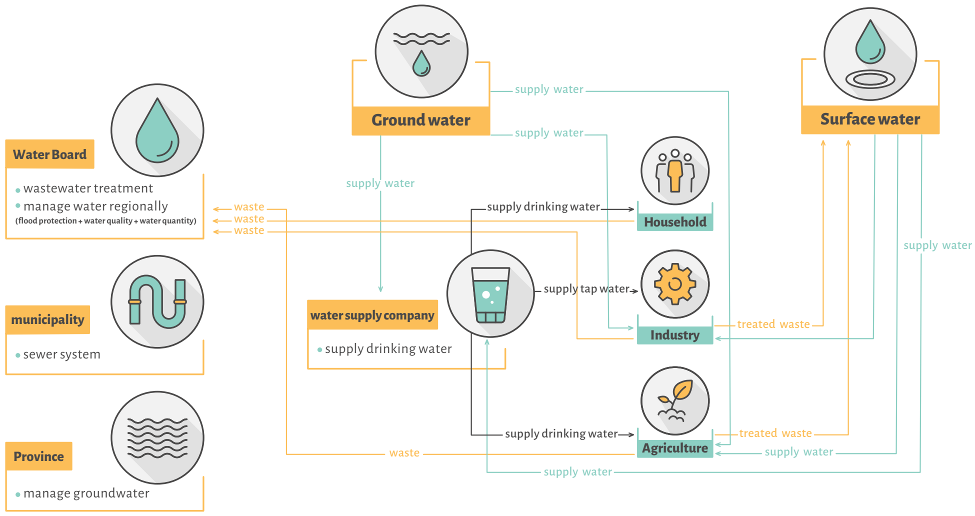


Figure 4.1: Flow of water in the Netherlands

tem supports both operational costs and environmental sustainability across the water system as a whole.(Government of the Netherlands, 2025b)

This analysis focuses on key financial and water flow interactions within the Dutch water system, as these aspects are essential for understanding stakeholder relationships and resource management in this study. Certain elements have been omitted to maintain a clear research scope and ensure feasibility. Given the complexity of water governance, a comprehensive review of all components would extend beyond the study's objectives. Instead, this research highlights the most relevant elements—those with a significant impact on financial and operational interdependencies among stakeholders and a greater influence on the analysis.

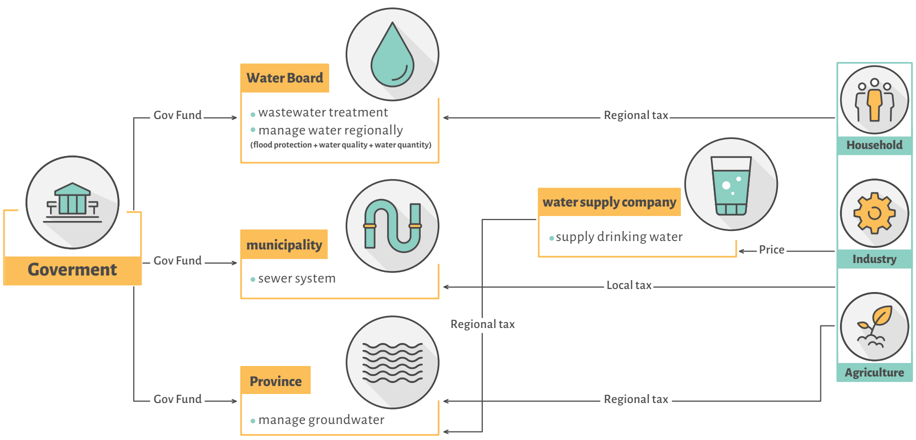


Figure 4.2: Flow of finances in water sector in the Netherlands

To effectively model and analyze relevant components of the Dutch water system for this study, it is essential to first categorize the system's different elements. Given the complexity of the system, the most logical approach is to begin by classifying the primary types of water. Once these categories are established, their respective uses can be further examined.

For this study, water has been classified into three main types: tap water, groundwater, and surface water. However, it is important to note that surface water has not been considered in the demand modeling section, as it is not subject to taxes or tariffs. As a result, surface water will not be discussed as a separate section in the analysis of demand. Instead, the focus will be on the two types of water where financial structures are more relevant—tap water and groundwater.

Within each category, the study addresses the different sectors that consume water, including household, industrial, and agricultural use of tap water and groundwater. This categorization allows for a structured examination of the water system, facilitating an analysis that aligns with the study's objectives.

In the following section, we take a closer look at the structure of the Dutch water system. The subsequent section provides a brief overview of water flow and financial aspect within the Dutch water sector, setting the stage for a comprehensive analysis in Chapter 5, where we apply our modeling approach to investigate these dynamics in detail.

4.2. Empirical Analysis of Dutch Water System

The financial framework for water use in the Netherlands encompasses a variety of pricing mechanisms, taxes, and fees that vary by water type, usage sector (household, industry, and agriculture), and region. This section categorizes the data from tap water, groundwater, surface water, and sewage, while considering their uses across households, industry, and agriculture.(Dinar et al., 2015)

4.2.1. Tap Water

In the Netherlands, tap water is sourced from both surface water and groundwater, with majority of monitored extractions coming from groundwater (63% in 2021 (CBS, 2024)). The cost of tap water is influenced by the source, as groundwater requires less treatment and is therefore less expensive to process than surface water. Ten water companies provide tap water for households and industrial use over Netherlands (figure 4.4a). Tap water rates vary across different drinking water companies, reflecting regional factors and local operating costs. The pricing structure consists of a fixed fee per connection and a variable charge based on cubic meter consumption plus water tax. Table 4.1 compare the rates for these companies for households in 2024. In general, equation 4.1 can represent water cost of each customer:

$$WB = (SC + R_{DW} * U + T_{DW} * [U|300m^3]) * (1 + VAT) \tag{4.1}$$

Where WB is water Bill of user, SC is fixed standing charge for connection, R_{DW} is variable rate for water, U is usage, T_{DW} is drinking water tax which implies on first 300 cubic meter of water usage , and VAT is the value added tax.

For business usage (industrial and agriculture) the variable rate is the same as household use, while the standing charge is set based on connection size, in most of water companies. table 4.2 compare standing charges base on tap water connection size for Dunea.

The standing charge and variable rate for tap water are primarily linked to the operational costs of providing water services. While fiscal policies do influence these rates—such as the national groundwater tax that water companies pass on to consumers—the majority of policy decisions in the water sector are shaped by taxation. The taxes included in the price of water are:

- Tax on drinking water. (Imposed on national level. € 1.13 $/m^3$ (for 2024) to a maximum of 300 m^3)
- Provincial levy. (More often included in the tariff than specified in the bill)
- Municipal or water board levy (if applicable, depending on the region)
- VAT (9%)

Water Company	Standing Charge (€/year)	Variable Rate (€/m³)	Average Rate (€/year)
Brabant Water	75.84	0.72	1.48
Dunea	78.21	1.33	2.11
Evides Waterbedrijf	85.3	1.08	1.92
Oasen	85.20	1.06	1.92
PWN	71.15	1.62	2.33
Vitens	50.50	0.95	1.46
Waternet	107.8	1.13	2.21
Waterbedrijf Groningen	73.67	0.96	1.69
WMD Drinkwater	98.6	1.00	1.99
WML	96.72	1.00	1.97
Netherlands	72.40	1.05	1.77

Table 4.1: Comparison of Water Companies household tariff in the Netherlands (Standing Charge, Variable Rate, and Average Rate)(Vewin, 2024)

Connection Capacity (m³/h)	Standing Charge (€/year)
1.5	78.21
2.5	153.50
3.5	398.87
6	812.50
10	1,594.64
15	2,723.35
40	9,939.90
60	16,975.50
150	49,139.77
250	88,874.60

Table 4.2: Comparison of standing charge vs connection capacity for Dunea (Dunea, 2024a)

In the Netherlands, water taxes now make up an average of 27.7% of the consumer price for drinking water. Most households have water meters, and the taxes are based on water usage. In rare cases where there is no meter, the taxes are calculated based on the number of inhabitants per household. (Laurens J. ZWAAN, 2023)

The provincial groundwater levy is used to cover specific provincial expenses, such as preventing and mitigating the negative impacts of water extraction and infiltration, as well as research related to groundwater policy. This levy generates about 15 million euros annually across all provinces. Some municipalities also charge concession fees for pipelines in the municipal underground.(Laurens J. ZWAAN, 2023)

The national groundwater levy was abolished at the end of 2011 (more information can be found in groundwater section) which caused a price drop of drinking water (figure 4.4), but in 2014, the drinking water tax rate was doubled. In 2019, the VAT on drinking water was increased from 6% to 9%. Provincial concession fees, a tax on subsurface pipelines, were abolished at the end of 2021. Water companies themselves are exempt from corporate taxes and do not receive structural subsidies, although they have been increasingly successful in obtaining national and European grants for innovative projects.

In 2020, taxes on drinking water totaled €516 million (€0.45/m3). Following the 2014 doubling of the tap water tax, the total tax burden returned to 2011 levels, the year before the national groundwater tax was abolished. By 2020, €45 million (€0.04/m3) of the total taxes came from cost-related taxes (provincial groundwater, pipeline royalties, and concession fees), while €471 million (€0.41/m3) came from tap water taxes and VAT. Drinking water companies pass most of the operational costs onto consumers, meaning that increases in taxes or permits do not significantly impact the financial health of these companies, as the costs are absorbed by end users. Since 2000, a national tax has been imposed on tap water to generate revenue and promote more efficient water use. Since 2015 this tax is uniformly applied across the country but only affects the first 300 m³ of water consumed per household annually,

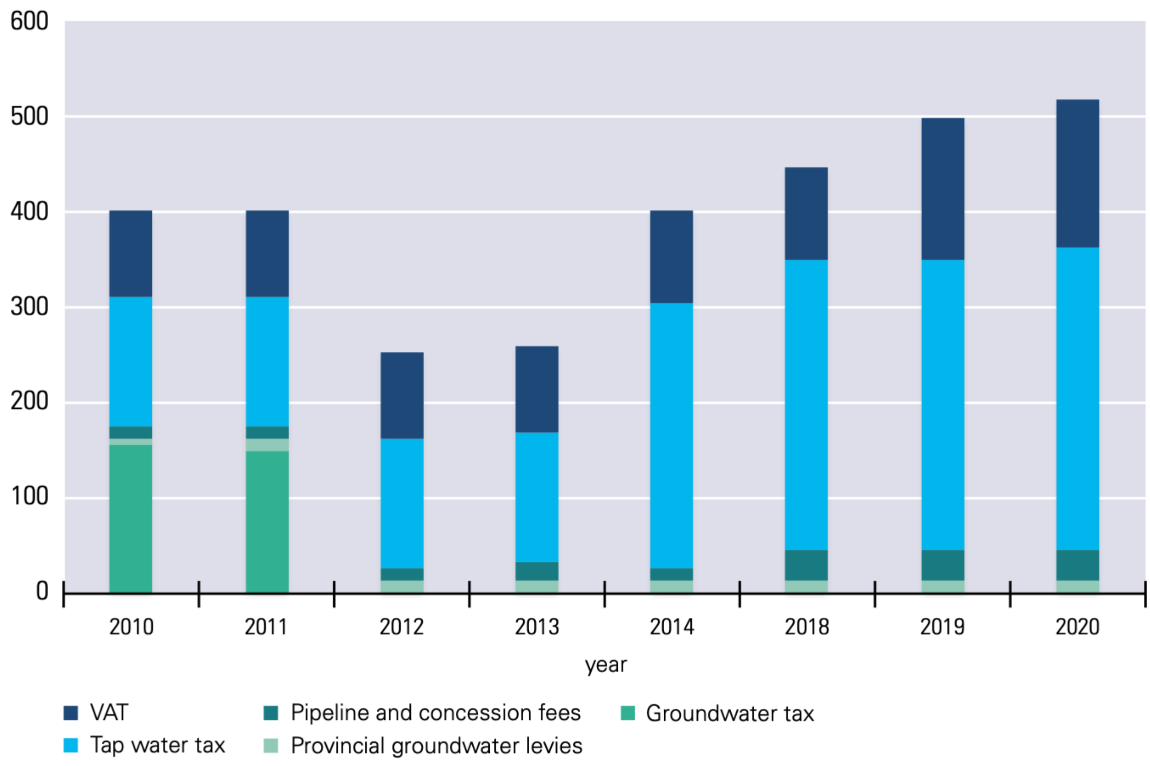


Figure 4.3: Development of drinking water taxes (Vewin, 2022)

with no additional tax charged for consumption beyond this threshold.

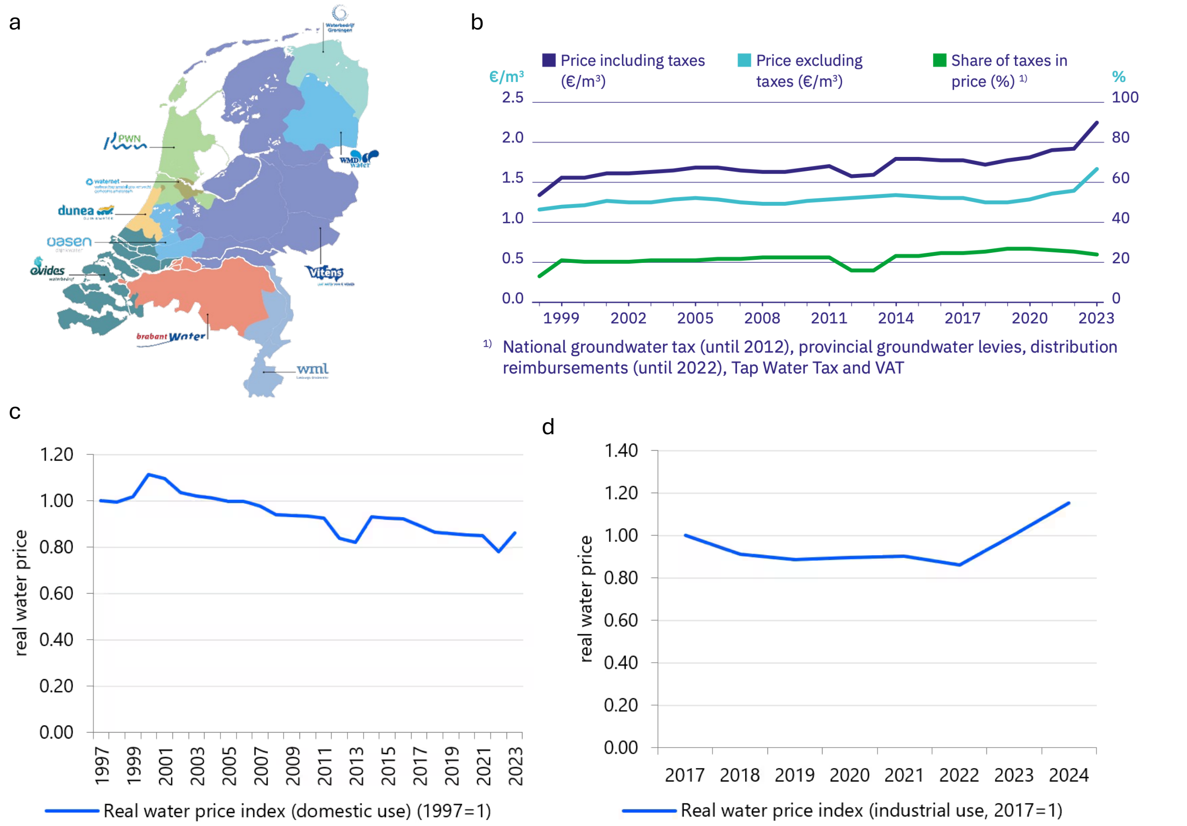


Figure 4.4: a) water companies in Netherlands b) average nominal water price and share of tax over time in the Netherlands (Vewin, 2022)c) Average real water price over time for household d) average real water price over time for businesses(Nobel, n.d.)

Figure 4.4b and 4.4c and 4.4d represent the nominal and real price of tap water overtime in Netherlands. Over the past few decades, Dutch water suppliers have been able to maintain low water prices due to limited needs for investment and operational improvements. As a result, water has become comparatively cheaper than many other goods and services. In real terms, households paid 22% less for water in 2022 than they did in 1997, while industrial water users experienced a 14% decrease compared to 2017. However, this trend shifted in 2023, as both households and industrial users saw an increase in water prices by 14% to 15%. Looking ahead, water prices for 2024 are set to rise further, with households facing an additional 9% increase and industrial users seeing a 15% hike.(Nobel, n.d.)

This upward trend in water prices can be attributed to rising production costs, driven by increases in the costs of materials, energy, and labor. Additionally, water prices are being adjusted to facilitate necessary investments in a sustainable and future-proof water supply sector. In fact, total investments by Dutch water companies are expected to rise by 50% by 2029 to address several pressing challenges: population and economic growth, climate change, and water pollution.(Nobel, n.d.)

Population and economic growth necessitate expansions in water production and distribution systems, particularly to accommodate the supply needs of 900,000 new homes planned by 2030.

Climate change is leading to more frequent droughts, which diminish the quality of river water and increase the demand for groundwater. As a result, significant adjustments to the water infrastructure will be required to ensure a reliable supply in a changing climate.

Pollution is increasingly threatening raw water sources, driven by the presence of pharmaceuticals, pesticides, and emerging contaminants such as PFAS.(Nobel, n.d.)

The combination of rising total water demand and dwindling water availability is expected to intensify water stress in the Netherlands. In January 2024, the Human Environment and Transport Inspectorate, part of the Ministry of Infrastructure and Water Management, cautioned that the availability and quality of drinking water can no longer be taken for granted. Climate change and pollution are adversely impacting surface and groundwater sources, while population and economic growth are escalating overall water demand. In response, the government has set a target to reduce water consumption among households and large users by 20% by 2035, compared to 2022 levels. The water supply sector will need to intensify its efforts to address these challenges. (Nobel, n.d.)

4.2.2. How is Tap Water Produced in the Netherlands?

The Dutch water system relies on three primary sources for drinking water production: surface water, infiltrated dune water, and groundwater. Each source requires a specialized purification process tailored to its initial quality, contamination levels, and salinity. Understanding these purification methods provides a foundation for comparing conventional approaches with potential water reuse strategies, which will be explored in subsequent chapters. This section is written as an example, based on information of Evides Evides Waterbedrijf, 2024.

Purification of Surface Water

Surface water undergoes an extensive multi-stage purification process to ensure its suitability for drinking. Initially, river water is stored in large reservoirs for approximately five months, allowing natural sedimentation to improve its quality. After this period, the water is transferred to purification plants, where preliminary filtration using micro-sieves removes coarse particles.

To eliminate finer impurities, a flocculant such as iron chloride or aluminum sulfate is added, binding suspended particles and facilitating their removal through subsequent double-layer filtration. This process effectively captures flocculated materials and residual contaminants. Disinfection follows, utilizing ultraviolet (UV) light to ensure bacteriological safety. Finally, activated carbon filters remove any remaining odors, colors, and flavors, with pH adjustment and oxygen dosing applied during the summer months to maintain water quality. The purified water is then stored in clean reservoirs before being distributed through the supply network.

Purification of Infiltrated Dune Water

Dune-infiltrated water follows a unique purification pathway. The process begins with an initial intake and pre-treatment stage, where water is screened to protect aquatic life and filtered to remove larger debris. A flocculant is then introduced to bind fine particles, followed by preliminary filtration to capture the bound contaminants.

The partially purified water is then directed to infiltration ponds in the coastal dunes, where it undergoes natural filtration over a period of at least 30 days. After this infiltration stage, the water is extracted and subjected to aeration, which removes dissolved gases such as methane and facilitates the oxidation and removal of iron, ammonium, and manganese. Biological treatment processes further refine the water, converting ammonium into nitrate and removing precipitated metals.

Subsequent purification steps involve advanced filtration techniques, including activated carbon filters and ultrafiltration (UF) membranes, which remove any remaining contaminants, odors, and colorants. The final purified water is stored in large reservoirs before being distributed to consumers.

Purification of Groundwater

Groundwater, extracted from depths ranging between 30 and 120 meters, undergoes a streamlined but highly effective purification process. The first step involves aeration to remove dissolved gases such as methane and to oxidize iron and manganese, which facilitates their filtration. The water is then passed through sand filters to capture the oxidized particles.

To mitigate water hardness, a softening process is applied using lime milk or sodium hydroxide in large reactors. These substances bind to hardness-causing minerals, forming precipitates that settle and can be easily removed. Final filtration stages eliminate any remaining particulates before the purified water is stored in reservoirs, ready for distribution.

Challenges in the Current Dutch Water Purification System

The effectiveness of each purification method depends on the initial quality of the water source, including contamination levels and salinity. Notably, the current Dutch water production system is not well-suited to treating highly saline water. Furthermore, the increasing contamination of surface water—largely due to the return flow from irrigation—has led to rising treatment costs in recent years. The economic and technical implications of this trend will be discussed in the following section.

4.2.3. Cost of Tap Water

The **cost** of producing tap water consists of several key components, outlined as follows:(Dunea, 2024b)

- Cost for source of water(ground water tax and/or extraction permit fee)
- Cost of material C_m
- cost of energy C_e
- cost of facilities C_f
- wage costs C_w

and other operational costs. To extract the data for this section, we gathered cost information from Dunea's annual report. Most of the cost components are explicitly listed in the report. For the cost of facilities, we used the depreciation costs, as Dunea calculates depreciation by dividing the total cost of the facilities by their estimated lifetime. This approach allowed us to estimate the annual contribution of facility costs to the overall tap water production expenses. figure 4.5a illustrates both the nominal and real average costs of tap water for Dunea in recent years, revealing a significant price increase. As it can be seen, the price is drastically increasing. Figure 4.5b breaks down the subcategories of costs. As shown, the costs of materials and energy have risen sharply, which is a major contributing factor to the increased price of tap water. Additionally, wage increases—implemented to help employees cope with inflation in line with government wage policies—have also played a role in driving up water production costs. Figure 4.5c shows that the share of energy and material costs in tap water production is steadily increasing. This growing proportion presents a potential opportunity for the technology sector to innovate and provide solutions aimed at reducing these costs. As energy and material expenses continue to rise, there would be increasing demand for more efficient technologies in water production, such as renewable energy systems, energy-efficient water treatment processes, and sustainable material alternatives.

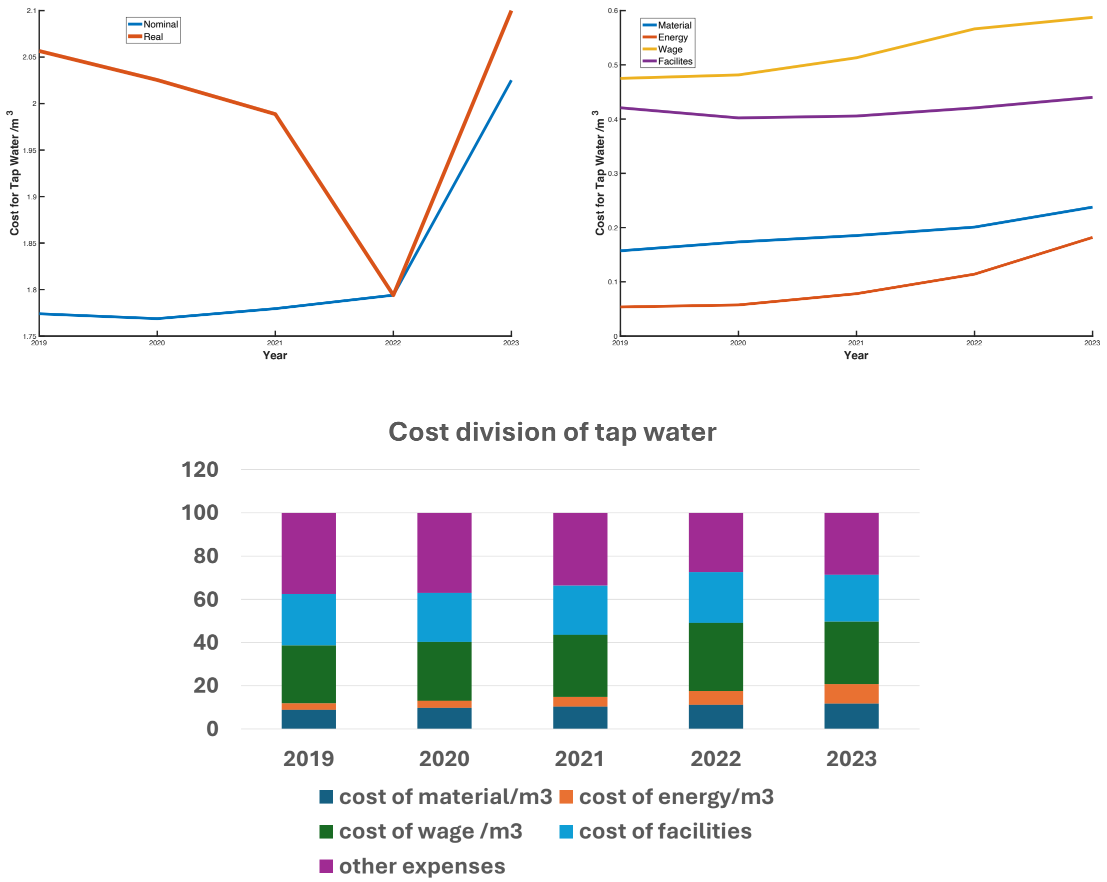


Figure 4.5: a) Nominal and real cost of producing tap water over time, b) Breakdown of subcategories contributing to the total production cost of tap water over time, c) Percentage share of each subcategory in the final cost of tap water based on (Dunea, 2024b, 2023, 2022, 2021)

4.2.4. Ground Water

Groundwater is an essential resource, especially for drinking water production, and is highly valued by industries that require high-quality water. It is subject to provincial taxation, with rates varying by province. Historically, the Dutch national groundwater tax (GWT) was introduced as an environmental ”green tax” aimed at reducing groundwater consumption and improving environmental outcomes. While it generated revenue for the government, the tax had little effect on reducing water use in industrial and agricultural sectors. As a result, the GWT was abolished in 2011 due to its limited economic and environmental impact.(Schuerhoff et al., 2013)

In addition to taxation, groundwater extraction is regulated through permits for pumping capacity. These permits are crucial for managing environmental impacts, allowing authorities to control the volume of groundwater extracted. However, there is limited public data on these permits, and the policies governing them are complex, influenced by a variety of factors, making it difficult to create a straightforward economic model. Therefore, we only used the tax on ground water (including naional groundwater tax before 2011) as the price for demand modeling. Generally, businesses are the primary end users of groundwater. Industries, especially those in sectors like food and beverage production, favor groundwater due to its high quality and lower treatment costs. These industries are required to pay provincial groundwater fees, and before 2011, they were also subject to the national groundwater tax. While the intent of groundwater extraction taxes was to motivate industries to adopt water-saving technologies or reduce consumption for environmental reasons, the national groundwater tax failed to achieve these objectives and was eventually repealed.(Schuerhoff et al., 2013)

Farmers who extract groundwater for irrigation and livestock watering are also subject to provincial groundwater fees, along with the now-abolished national groundwater tax. Many provinces offer exemptions or fee-free thresholds, easing the financial burden on agricultural users.

Freshwater availability for drinking water supply is increasingly threatened by salinization. Several groundwater extraction sites are already experiencing issues with excessively salty groundwater, and the water in Lake IJssel near Andijk has, on multiple occasions in recent years, been too saline to use for drinking water production. Salinization in the Dutch coastal areas is caused by two main factors: the intrusion of seawater into groundwater reserves (external salinization) and the upward flow of saline groundwater to the surface, known as saline seepage (internal salinization).(Vewin, 2022)

Climate change is exacerbating both forms of salinization, as rising sea levels increase seawater intrusion, while periods of extreme drought reduce river discharge, causing rivers to become saltier. Additionally, soil subsidence is contributing to increased saline seepage. Although policies are generally focused on reducing groundwater usage, the combined pressures of climate change, economic growth, and population expansion are putting even greater strain on groundwater resources.

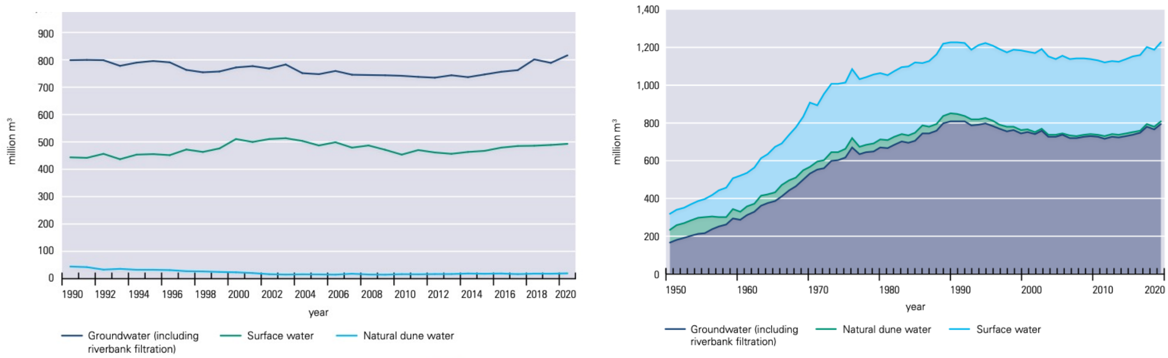


Figure 4.6: a) Total water extraction by source b) Source of water for tap water production(Vewin, 2022)

4.2.5. Surface Water

Surface water is commonly used for industrial cooling and agricultural irrigation in the Netherlands. Its extraction is generally untaxed due to its abundance and minimal environmental impact. However, pump capacity permits help regulate surface water usage, preventing over-extraction and ensuring its sustainable use.

Industrial sectors, particularly energy and chemical companies, heavily rely on surface water for cooling purposes. Its untaxed status makes it a cost-effective option, especially for industries where high-quality water is not required for production.

In agriculture, surface water is primarily used for irrigation, and since its extraction is free of charge, it remains an attractive resource for farmers. Despite the absence of fees, restrictions can be imposed during droughts to conserve water resources.

Approximately 34% of the Netherlands' drinking water is derived from surface water, predominantly in the western regions. An additional 6% comes from riverbank filtration water. Unlike groundwater extraction sites, most surface water extraction points do not benefit from the same protective measures. Surface water intended for drinking water production must meet the standards set out in the Water Quality Requirements and Monitoring Decree 2009. The Directorate-General of Public Works and Water Management and local water authorities are responsible for ensuring compliance with these standards.(Vewin, 2022)

However, the quality of surface water is under increasing pressure due to environmental contamination from pesticides, pharmaceuticals, and industrial substances. Climate change exacerbates this problem, as lower river flows mean wastewater and industrial discharges are less diluted, leading to a decline in water quality. During periods of low river discharge, such as the dry summers from 2018 to 2020, these issues became more pronounced. For example, saltwater intrusion into Lake IJssel from the Wadden Sea increased when locks were closed, further degrading water quality. Since 2018, the majority of water intake stoppages from the Rhine have been caused by high chloride concentrations at the Andijk pumping station in Lake IJssel.

When surface water quality falls below acceptable standards, water companies take mitigating actions, such as mixing groundwater with surface water or temporarily halting surface water intake. Together with water authorities, they also investigate the sources of pollution to address the problem at its root. The challenges posed by these factors indicate that surface water, as a source of drinking water, is becoming increasingly vulnerable due to both pollution and climate change.

4.2.6. Sewage and Wastewater Management in the Netherlands

The management of sewage and wastewater in the Netherlands involves various fees levied by municipalities and water boards, ensuring the sustainability of water treatment and pollution control. These fees, determined by pollution levels and wastewater volume, help maintain efficient treatment services for households, industries, and the agricultural sector. (Laurens J. ZWAAN, 2023)

4.2.7. Wastewater Treatment Processes in the Netherlands

The wastewater treatment processes outlined in this section illustrate how wastewater is managed in the Netherlands. Examining these processes provides a foundation for comparing the current system with potential improvements through water reuse strategies, which will be discussed in subsequent sections. This section is written as an example, based on information of Harnaschpolder WWTP Delfluent Services B.V., 2024.

The treatment process begins with the removal of large solid materials such as paper, plastics, wood, and textiles, which are collected and transported to external waste incineration facilities. Wastewater then enters pre-sedimentation tanks, where oils, fats, and floating materials are skimmed off, while heavier non-soluble particles settle at the bottom, forming primary sludge. This sludge is directed to the sludge treatment section.

The core treatment phase is biological, utilizing billions of micro-organisms to break down organic pollutants. This activated sludge system alternates between aerated and non-aerated conditions to optimize nitrogen, phosphate, and organic contaminant removal—achieving over 85% nitrogen and phosphate removal and over 90% reduction in organic matter.

Post-treatment, the sludge-water mixture is directed to post-sedimentation tanks, allowing the activated sludge to settle. A portion of this settled sludge is recycled back into the aeration tanks, while the treated water, known as effluent, is pumped through pipelines to the Houtrust WWTP in The Hague before being discharged into the North Sea.

Sludge treatment involves thickening the primary and surplus activated sludge to remove excess water. The thickened sludge is then digested anaerobically at 35°C, releasing biogas as a byproduct. This biogas fuels gas engines that generate heat and electricity, meeting over 50% of the plant's energy needs. After digestion, the sludge undergoes further dewatering via centrifuges, resulting in a concentrated waste product transported to the sludge incineration facility in Dordrecht.

To control odors, air treatment systems extract and process air from different plant areas. Initial filters remove hydrogen sulfide, while subsequent filters address other odor compounds before releasing cleaned air through chimneys, adhering to strict emission standards.

Wastewater treatment plants have significant energy requirements, primarily due to aeration in biological treatment and long-distance water pumping. While part of the electricity is sourced from the grid, a substantial portion is generated onsite using methane from sludge digestion. Diesel generators ensure continuous operation during power interruptions.

4.2.8. Sewage Charges and Water Board Levies

Residents pay sewerage charges through municipal taxes to fund wastewater and rainwater management. These charges vary by municipality, with some basing fees on property value and others on drinking water consumption (Municipalities Act, Article 228-a). Municipal councils establish sewerage levy ordinances defining fee structures. (Laurens J. ZWAAN, 2023)

In 2021, total revenue from sewage charges reached €1.72 billion, averaging €103 per household, with the lowest at €43 and the highest at €256. (Laurens J. ZWAAN, 2023)

Water boards finance their operations primarily through taxes, including the water system levy and the purification levy.

The **water system levy** is paid by residents and property owners to fund flood protection, water quantity management, and surface water quality maintenance (e.g., dredging, nutrient pollution control).

The **purification levy** applies to wastewater producers, based on the principle that polluters pay for treatment. Households pay for one pollution unit if they have one resident and three units for two or more residents. Businesses and industries have sector-specific pollution contribution models. Table 4.3 shows the tariffs for Delfland in 2024.

Table 4.3: Water Tariffs and Levies, Delfland 2024 (Delfland, 2024)

Water System Levy	**Amount**
For a household	€133.39
For a home or business	0.0241% of WOZ value
For agricultural land	€106.04 per hectare
For natural soil	€4.53 per hectare
Purification Levy	
Single-person household	€106.04
Household with two or more residents	€318.12
Company	€106.04 per pollution unit

Additional taxes imposed by water boards include:

- **Pollution levy** for direct wastewater discharge into surface water.
- **Road levy** for water boards managing roads.
- **Concession tax** for infrastructure under, on, or above water board land.
- **Fees and charges** for permits issued by water boards.

Water board rates are structured to cover operational costs, which vary by region due to differing water management needs. The cost breakdown per activity is as follows: (van Waterschappen, 2021)

- Flood defenses: 13%
- Water systems: 28%
- Sewage treatment: 39%
- Waterways and roads management: 2%
- Licensing and enforcement: 4%
- Taxation: 4%
- Miscellaneous: 10%

Figure 4.7 illustrates the nominal and real costs of water board operations over time. While nominal costs have risen, real costs have remained stable, indicating inflation as the primary cost driver. Wastewater treatment accounts for 39% of expenditures, totaling around €1.4 billion annually. (van Waterschappen, 2021)

With 19.7 million population equivalents (p.e.)—equivalent to 200 liters per day—treated daily, wastewater treatment costs approximately €0.97 per cubic meter. (Agency, 2024)

Water companies, unlike water boards, have been more affected by declining water quality due to pollution and climate change, leading to increased material and energy costs that are reflected in consumer prices. Notably, small consumers' water board tariffs are based on pollution levels rather than wastewater volume.

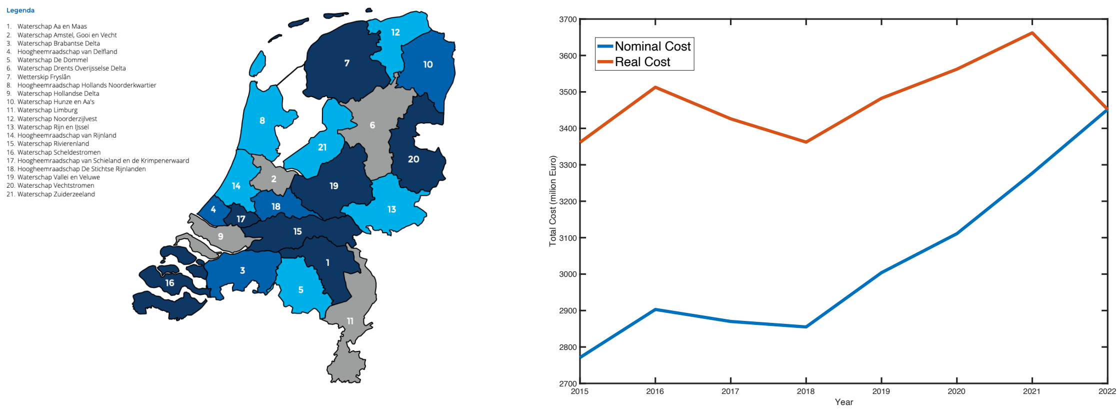


Figure 4.7: a) Water Boards in the Netherlands, b) Total real and nominal costs over time (van Waterschappen, 2021)

4.2.9. Investments

Between 1990 and 2008, investment levels in the Dutch drinking water sector gradually declined. This trend was primarily attributed to a decrease in demand, which reduced the necessity for expanding production capacity. The adoption of less expensive piping materials, such as PVC, along with measures aimed at extending the lifespan of existing infrastructure, and strategic investments based on improved asset management information, further contributed to limiting overall investment costs.(Laurens J. ZWAAN, 2023)

An upward trend in investment began in 2008, reflecting a shift in market dynamics. Although there was a slight decrease in investments related to drinking water production—encompassing extraction and treatment—in 2015 and 2016, investments in distribution continued to rise steadily. Since 2017, both production and distribution investments have demonstrated substantial growth. Specifically, production investments surged from €123 million in 2017 to €213 million in 2020, marking a remarkable 72% increase. Concurrently, distribution investments rose from €307 million to €375 million, reflecting a 22% increase. Overall, the total investment in 2020 reached €643 million, with allocations comprising 58% for distribution, 33% for production, and 5% for information and communication technology.(Vewin, 2022)

Currently, the Netherlands invests €75 per citizen annually for the development and renewal of collecting and treatment infrastructure, which exceeds the EU average of €41 per citizen per year.

Looking to the future, drinking water companies anticipate a significant increase in necessary investments to ensure a sustainable drinking water supply. These anticipated investments are driven by several factors, including aging infrastructure, a decline in the availability of drinking water sources, and heightened security requirements. The ability of drinking water companies to generate sufficient income to finance these investments from their own resources and/or attract external financing is critical.(Laurens J. ZWAAN, 2023)

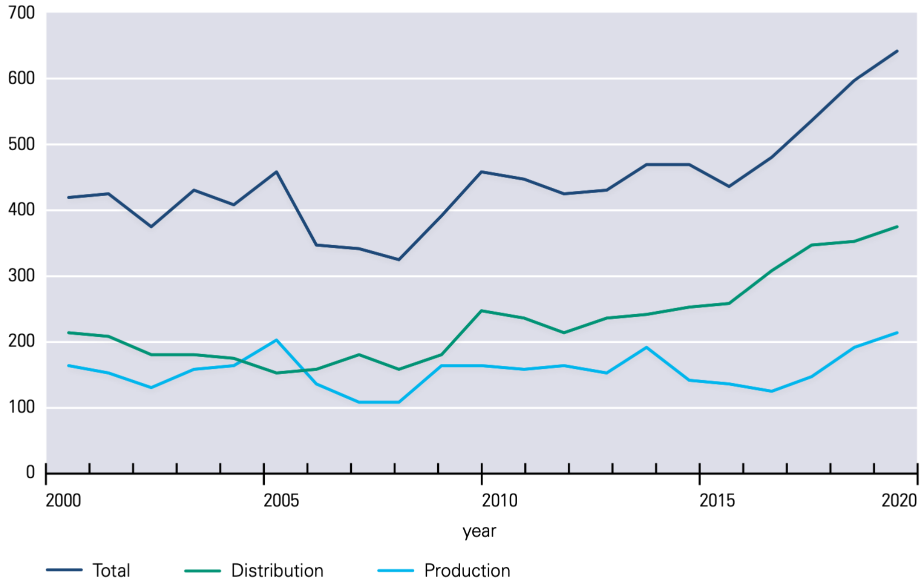


Figure 4.8: Development of investment in drinking water sector

5

Modeling of Water System

To formalize the structure and organization of the water system into a mathematical framework, this section begins by presenting the modeling approach adopted in this study. We start by outlining the various components of the model, which address both water flow dynamics and the financial structures that influence the system. This approach enables us to simulate and predict the behavior of the water system in response to potential changes and future conditions.

In the second part of this chapter, the parameters introduced in the initial modeling framework are determined using empirical data drawn from the previous chapter. This process ensures that the model is grounded in observed data, enhancing its relevance and predictive power. By incorporating these data-driven parameters, the model is positioned to provide insights into water system performance under various economic and environmental scenarios.

5.1. Demand

For any consumer, it is logical to assume that their demand is influenced by a set of financial and non-financial parameters. In the context of the water sector, demand can be reasonably related to financial factors such as the price of water and the income of consumers, as well as non-financial factors, including environmental conditions and the number of consumers.

Empirical data often demonstrate a log-log demand relationship for water usage (Cagno et al., 2022) , which is characterized by certain advantages. The log-log model provides a constant elasticity, meaning that the percentage change in water demand remains proportional to the percentage change in price or income, irrespective of the level of demand. This characteristic aligns well with observed behavior in water demand data and allows for simplified estimation and interpretation. Based on these considerations, we model water demand for each consumer group as follows:

$$\ln(D_i) = \alpha + \beta \ln(P_i) + \gamma \ln(I_i) + \epsilon E_i + \eta \tag{5.1}$$

where:

- D_i represents the water demand for consumer i,
- P_i denotes the price of water,
- I_i is the income level of consumer i,
- E_i captures the environmental conditions relevant to water use,
- $\alpha, \beta, \gamma, \epsilon$ are the parameters to be estimated, and
- η represents random error terms or unobserved factors.

5.2. Price

As explained in the previous chapter, the price of water consists of different financial parameters such as the cost of water production, the profit margin of water companies, and taxes. In this model, we assume that the profit margin of water production is constant. Therefore, the change in urban water price can be modeled as follows:

$$\hat{P}_i = \hat{C}_i^U + \hat{\tau}_i^U \tag{5.2}$$

where $\hat{P}_i^U$ is change in urban water price, $\hat{C}_i^U$ is change in cost of water production and $\hat{\tau}_i^U$ is change in tax, which can be modified based on government policies regarding water price.

As discussed in the previous chapter, the cost of water production may rise due to factors such as increased contamination, salinity, and higher energy costs. To simulate these changes over time, we use the following equation.

$$C_i(t) = C_{t0} * rc_i^t \tag{5.3}$$

where rc_i is rate of cost increase over time.

In the case of water reuse, the price of water can vary depending on the approach used. If the reused water is mixed with urban water, the final price of water can be calculated as a weighted average of the prices, as follows:

$$p_i = \frac{k^R \times P_i^R + (D_i - K^R) \times P_i^U}{D_i} \tag{5.4}$$

Where P_i^R and k^R are price of reuse water and reuse water capacity respectively.

In case of reuse water for sale, urban water price would be calculated based on equation 5.2.

The price of reused water can be determined based on its Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) costs. Since the CAPEX is distributed over time, and the distribution considers an interest rate, the price of reused water can be calculated as follows:

$$P_i^R = \frac{CAPEX \cdot (1+r)^T}{T} + OPEX \tag{5.5}$$

Where P_i^R is the price of reused water, $CAPEX$ is the capital expenditure, r is the interest rate, T is the time period over which CAPEX is amortized, and $OPEX$ is the operational expenditure. Both CAPEX and OPEX are function of water reuse capacity, as econmy of scale applies here. Later in this chapter, we investigate the price of water reuse.

5.3. Partial Equilibrium

The model consists of three core components—demand, cost, and price functions—that are interconnected and need to reach equilibrium.

The equilibrium is achieved when the demand and price functions (Equations 5.1 and 5.2) balance, considering the cost of reuse water (Equation 5.3). In other words:

- The price determined by capacity and cost aligns with the price consumers are willing to pay based on their demand.
- This iterative process ensures that the capacity chosen for reuse plants satisfies both the supply (cost-driven price) and demand-side (price-driven consumption) conditions.

Table 5.1: Summary of Model Components and Interactions

Component	Equation	Description
Demand Function	Equation 5.1	Relates water demand to price elasticity and incorporates factors such as population growth and economic trends.
Cost Function	Equation 5.3	Defines the unit cost of reuse water as a function of capacity, including capital investments and O&M costs.
Price Function	Equation 5.2	Calculates the final price of water for consumers based on reuse costs, capacity, and adjustments for WTC schemes.
Equilibrium Condition	Integrated	Balances supply (cost-driven price) and demand (price-driven quantity) to achieve system equilibrium.

5.4. Cost and Revenue

5.4.1. Water Companies

The revenue of water companies primarily comes from the sale of water. Therefore, we can express their revenue using the following equation:

$$R_i = P_i \times D_i \tag{5.6}$$

where R_i represents the revenue from water sales, P_i is the price of water, and D_i is the demand for water.

The cost of water production for water companies can be calculated as follows:

$$C_i = C_i^U \times (D_i - K^R) + C_i^R \times K_i^R \tag{5.7}$$

where C_i^U can be determined based on equation 5.3 and C_i^R can be determined based on equation 5.5.

In this study, we consider the profit margin of water companies to be constant. Therefore, the revenue from byproducts can help reduce the price of reused water.

5.4.2. Cost of Consumers

The water cost for consumers can be determined by the following equation:

$$C_i = P_i \times D_i + (WWTC + D) \tag{5.8}$$

where $WWTC$ and D represent the cost of water treatment and water distribution, respectively.

In the water sector, it is a valid assumption to consider water supply as exogenous. This is based on the fact that water production is not typically affected by price fluctuations, as water companies and their tariffs are often regulated by the government. For the purposes of this model, we assume a fixed profit margin for these companies. Consequently, we can use the price and demand functions to simulate how policies may affect these two concepts.

In the next section, we will introduce aspects of the water system that can serve as performance indicators for evaluating the efficiency and sustainability of the water sector.

5.5. Model KPIs

As a socio-economic study, this research considers both economic and environmental aspects as key performance indicators (KPIs) to assess the effectiveness of water reuse strategies. These indicators allow for a comprehensive evaluation of the impacts and trade-offs associated with water reuse in the context of the Dutch water sector.

5.5.1. Environmental Aspect

For the environmental aspect, we introduce two primary indicators:

Freshwater Saving: This indicator measures the difference in freshwater demand between the baseline scenario (without water reuse) and the various water reuse scenarios. It quantifies the reduction in the consumption of natural freshwater resources achieved by implementing water reuse technologies. By comparing the total freshwater demand in different scenarios, this indicator provides insights into how much pressure is relieved from freshwater ecosystems due to the introduction of reuse practices.

Freshwater Saving Rate: To account for the rebound effect, we define the freshwater saving rate as the amount of freshwater saved per cubic meter of reused water introduced into the system. This rate helps to measure the efficiency of water reuse in terms of its environmental benefits. It also considers how much additional freshwater is conserved by replacing conventional water sources with treated or reused water, helping to evaluate the sustainability and long-term impact of water reuse initiatives. The freshwater saving rate can also help assess whether increased efficiency in water use leads to a proportional reduction in demand or if behavioral changes (such as the rebound effect) affect the expected savings.

5.5.2. Economic Aspect

For the economic aspect, we focus on two main indicators:

Total Cost of Water for Consumers: This indicator represents the overall financial burden on consumers due to water consumption in the system. By considering the total cost, we are able to assess how water reuse policies and pricing mechanisms affect consumers economically. The total cost is influenced by factors such as the price of water, operational and waste water treatment costs of water systems, and the introduction of new technologies. This indicator allows us to gauge the affordability of water for consumers, particularly in the context of reuse scenarios where the price structure may differ from the baseline.

Water Price: The price of water is a crucial economic indicator with significant social implications. Water pricing not only influences consumer behavior and demand but also plays an important role in promoting or discouraging water conservation efforts. In this study, we consider the price of water as an indicator due to its direct social impact, as it can affect the accessibility and equity of water services.

In the next section, we provide an empirical analysis on how we determined the necessary parameters for the model.

Initial Investment: Initial investment refers to the total upfront capital required to establish reuse infrastructure, including the cost of constructing treatment facilities, distribution networks, and any associated upgrades to wastewater collection systems.

Freshwater Saving per Investment: Freshwater saving per investment measures the efficiency of a reuse policy in terms of the volume of freshwater conserved per unit of monetary investment. This KPI is particularly useful for assessing the impact of technological advancements that reduce costs.

Table 5.2: Key Performance Indicators for Reuse Scenarios

Stakeholder	KPI	Equation	Description
Environment	Fresh Water Saving	$(D^U_{\text{no\_reuse}} - D^U_{\text{reuse}})$	Urban water saved yearly.
	Fresh Water Saving Rate	$\frac{(D^U_{\text{no\_reuse}} - D^U_{\text{reuse}})}{k^R \cdot N^R}$	Saving of urban water per reuse capacity unit.
Consumer	Water Bill	$P_i \cdot D_i + (D + CT)$	Average water-related cost of the consumer.
	Water Price	P_i	Average price of drinking water.
Water Companies / Government	Initial Investment	$CAPEX \cdot N$	Total initial investment needed for reuse scenarios.
	Freshwater Saving per Investment	$\frac{(D^U_{\text{no\_reuse}} - D^U_{\text{reuse}})}{CAPEX \cdot N^R}$	Saving of urban water per initial investment unit.

5.6. Water Demand in the Netherlands

In this section, the demand function for different types of water across various consumer categories is calculated based on empirical data from the Netherlands.

5.6.1. Tap water data collection methodology

The data utilized in this part of the study was gathered from various reputable sources to ensure the accuracy and reliability of the subsequent modeling. The following outlines the data collection process and the sources from which the data was extracted. The demand data was obtained from the CBS website, covering different categories of consumers in tap water usage in Netherlands. Although the primary focus of this study is on the Delfland water board area, the specific demand data for this region was unavailable. Consequently, national-level data was employed as a substitute to represent the Delfland area. For water pricing, the data was sourced from the Vewin dataset, which annually calculates the average price of water. This calculation involves averaging the tap water rates across various regions, weighted by the demand in each area. Additionally, the standing charge is prorated based on the average consumption per household to determine a comprehensive price per unit.

The tariff structure for tap water is composed of several components, making it challenging to be accurately represented in a straightforward financial model. To address this complexity and provide a more standardized understanding of water pricing, the use of a price index becomes a valuable tool. In the Netherlands, Vewin, the association of drinking water companies, has defined an average price of water for households as follow:

$$P_{HH}^{avg} = \frac{SC}{U_{HH}^{avg}} + R_{DW} + T_{DW}^{avg} \tag{5.9}$$

where P_{HH}^{avg} is average rate of water, U_{HH}^{avg} is average household demand for water and T_{DW}^{avg} is average tap water tax.

Additionally, Vewin calculates the average price of tap water by dividing the total sales from water companies by the total demand for tap water in the Netherlands. (Vewin, 2022)

For businesses (i.e. industry and agriculture sector), the situation is even more complex, as the standing charge varies depending on the connection capacity. To account for this complexity, we developed a price index that is indirectly based on the average price of tap water and the average price of tap water specifically for households, as described in Equation 5.10.

$$P_B^{avg} = \frac{P_N^{avg} * U_N - P_{HH}^{avg} * U_{HH}}{U_B} \tag{5.10}$$

where P_B^{avg} is the average tap water price for businesses, P_N^{avg} is the average tap water price in Netherlands, U_N is total water usage in Netherlands, U_{HH} is household tap water demand and U_B is the tap water demand for businesses.

To derive the real price of water, the amount of tap water tax per cubic meter was added. Furthermore, the Consumer Price Index (CPI), also obtained from CBS, was applied to adjust the prices for inflation, providing a real price for each year. In the case of the price index for industrial and agricultural sectors, the average water price and the average household water price in the Netherlands were again sourced from the Vewin dataset. The average price for businesses was calculated using these two variable. This business price of tap water applies to both industrial and agricultural sectors, as the price is dependent on the size of the connection rather than the specific use in industry or agriculture. At the end the real price for each year has been obtained using CPI. Finally, the real GDP data was extracted from the CBS dataset. To calculate the industrial and agricultural GDP (IndGDP/AgrGDP), the percentage contributions of these sectors to the overall GDP were obtained from CBS. These percentages were then used to derive the specific contributions of industry and agriculture to the real GDP. This IndGDP and AgrGDP will be used in the subsequent sections to model the economic aspects of water usage in these sectors.

5.6.2. Household Tap Water Demand

In analyzing household tap water demand, it is essential to consider the relationship between demand, price, and the purchasing power of consumers. In this study, real disposable income of Dutch citizens has been employed as an indicator of purchasing power. To account for the impact of population changes, demand per capita was utilized, calculated by dividing total water demand by the population size. A linear regression model was employed for the analysis, with demand per capita as the dependent variable, while real price and income served as the independent variables. The analysis was conducted using data spanning from 2011 to 2021. In 2012, the repeal of the national groundwater tax led to a notable reduction in water prices by approximately 10-20%. However, contrary to expectations, the short-term impact on water demand did not materialize in 2012 and 2013. In 2020, an irregular increase in water demand was observed, which was attributed to the impact of the COVID-19 pandemic. To account for these temporary conditions and isolate the effect of other factors, we defined a dummy variable. This dummy variable takes the value of 1 for the years 2012 and 2013 (reflecting the period of low prices), -1 for the year 2020 (to account for the spike in demand), and 0 for all other years. This approach ensures that the model accurately reflects the long-term trends in water demand without the influence of these anomalous events. The result can be found in table 5.3

$$ln(Demand\_per\_capita) \sim 1 + ln(Price\_index) + ln(Income) + dummy$$

Variable	Estimate	SE	tStat	pValue
(Intercept)	7.16	1.0933	6.5487	0.0003192
Price_index	-0.42577	0.10742	-3.9637	0.0054362
Income	-0.28695	0.099309	-2.8894	0.023335
dummy	-0.046331	0.0099326	-4.6646	0.0023022

Number of observations: 11, Error degrees of freedom: 7
Root Mean Squared Error: 0.00955
R-squared: 0.805, Adjusted R-Squared: 0.722
F-statistic vs. constant model: 9.65, p-value = 0.00699

Table 5.3: Estimated Coefficients for household tap water demand linear regression model, after removing outlier data.

Linear regression model, without dummy variable:

$$ln(Demand\_per\_capita) \sim 1 + ln(Price\_index) + ln(Income)$$

	Estimate	SE	tStat	pValue
(Intercept)	2.9535	1.1721	2.5199	0.035814
Price_index	-0.10168	0.15532	-0.65463	0.53108
Income	0.093435	0.10746	0.86949	0.40991

Number of observations: 11
Error degrees of freedom: 8
Root Mean Squared Error: 0.0181
R-squared: 0.2 Adjusted R-Squared: -0.000213
F-statistic vs. constant model: 0.999, p-value = 0.41

Table 5.4: : Estimated Coefficients for household tap water demand linear regression model, before removing outlier data.

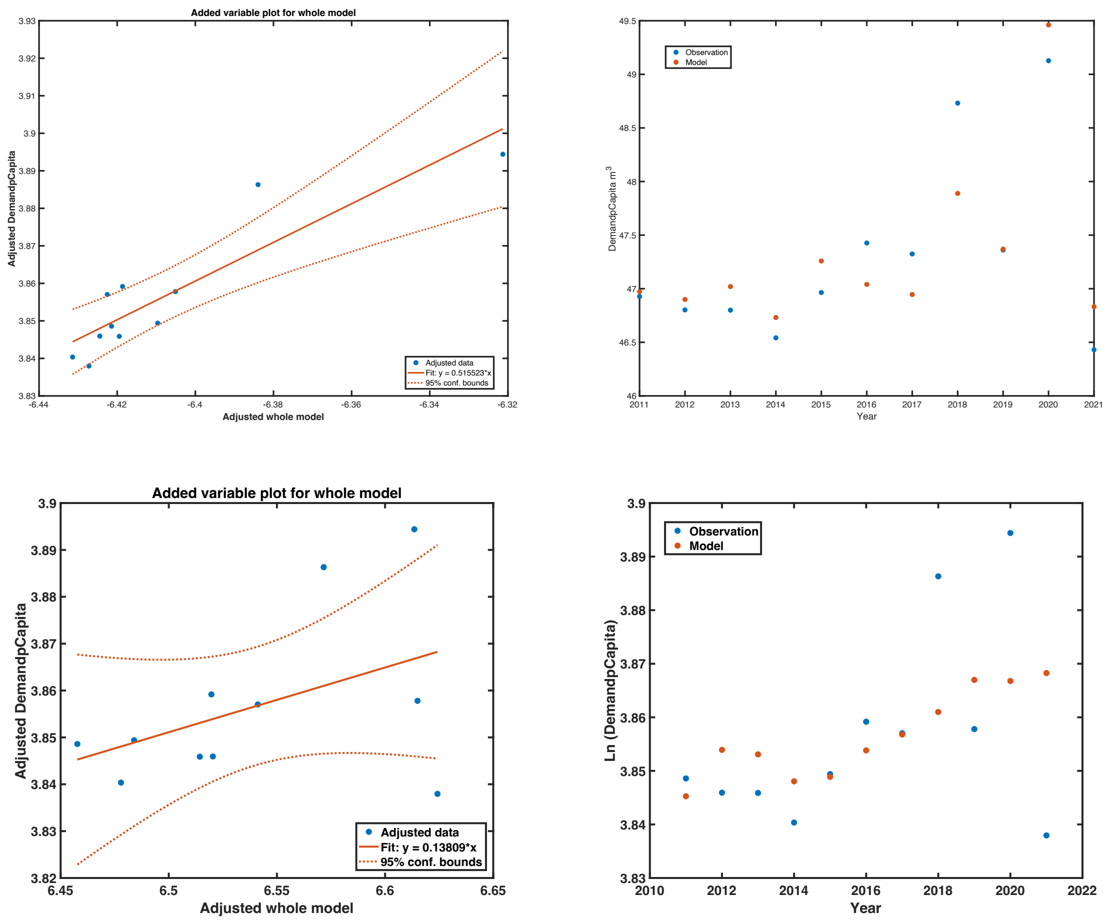


Figure 5.1: For household tap water demand: a) Added variable plot for model excluding outlier b) Comparison between empirical data (blue) and model response (orange) excluding outlier c)Added variable plot for model including outlier d) Comparison between empirical data (blue) and model response (orange) including outlier

The final model reveals a negative relationship between water price and demand, which aligns with fundamental economic expectations. Specifically, the price elasticity of demand is estimated at -0.42. This indicates that for every 1% increase in price, water demand decreases by 0.42%. This is consistent with prior research, where the price elasticity for household water demand between 2009 and 2011 was estimated to range between -0.25 and -0.65.(Reynaud, 2015) However, the earlier study used nominal prices for these years, which could explain the slightly lower elasticity. Figure 5.2b&c compares the real and nominal water prices over recent years, highlighting that between 2009 and 2011, the nominal price increased more rapidly than the real price. This discrepancy likely led to a lower elasticity when using nominal prices, as the real burden of water cost on consumers was somewhat understated. In contrast, the elasticity estimated in our model using real prices appears more accurate and reasonable.

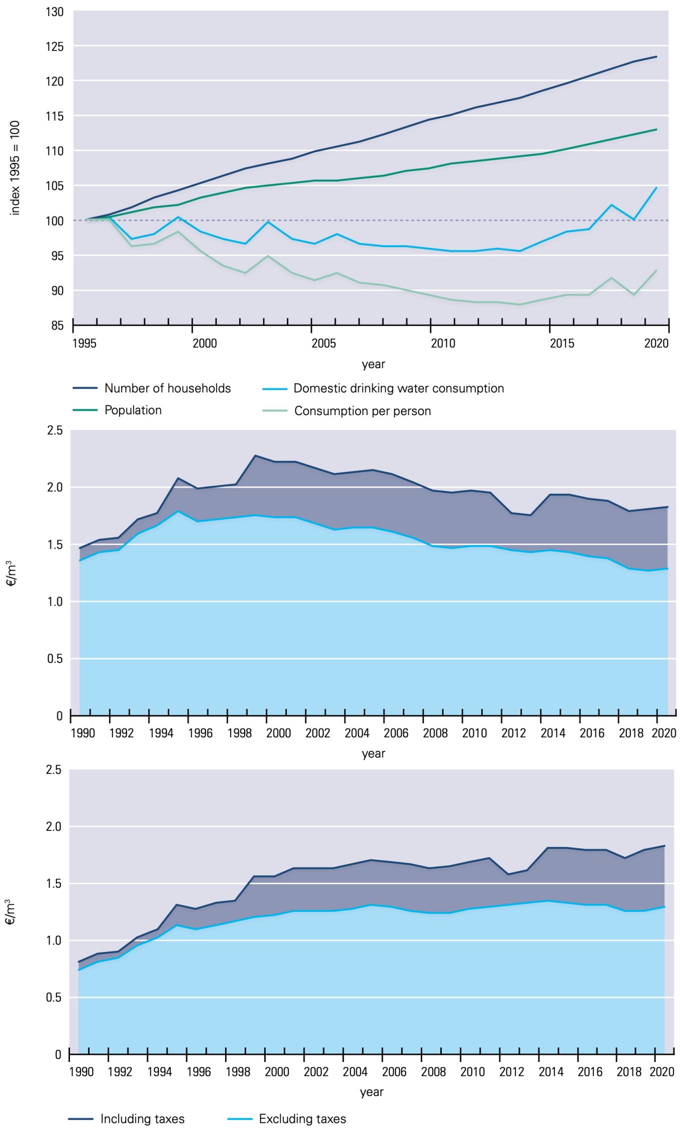


Figure 5.2: a) Comparison of household demand and growth of population b) Nominal household price index of tap water c)Real household price index of tap water (Vewin, 2022)

Another study estimated an average price elasticity of around -0.4 for the period before 2003. (Metaxas & Charalambous, 2005) Interestingly, the model also indicates a negative relationship between income and per capita water demand, with an income elasticity of -0.28. This result is somewhat counterintuitive, as it suggests that as incomes rise, water consumption per person decreases. Typically, one would expect higher incomes to result in greater consumption of most goods, but this inverse relationship can sometimes occur with non-essential or efficiently consumed goods. In this case, the negative income elasticity could indicate that wealthier households are using water more sustainably or have invested in more water-efficient technologies. This finding is supported by recent reports indicating that Dutch households are becoming more efficient in their water use. For example, the amount of water used for toilet flushing has decreased from 42 liters per person per day in 1995 to 34 liters in 2016, driven largely by the adoption of more water-efficient toilets. Similarly, water consumption for laundry (including both washing machines and hand-washing) has dropped from 27 to 15 liters over the same period.(Vewin, 2022)

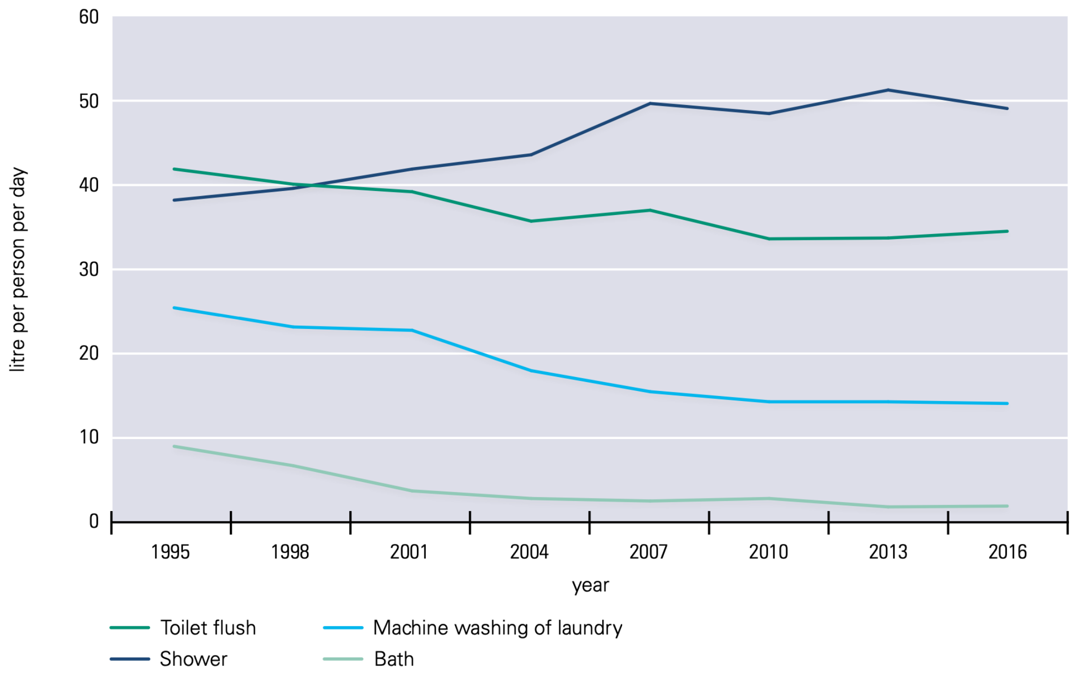


Figure 5.3: Development in drinking water use by application (Vewin, 2022)

Previous studies have estimated the income elasticity for water demand at around 0.2(Reynaud, 2015), suggesting that higher incomes previously led to marginal increases in water consumption. During the 2009-2011 period, nominal disposable wages were slowly decreasing, while real disposable income was on the rise. This created a situation where, based on nominal wages, a positive income elasticity could be observed. However, when adjusting for real disposable income, the negative elasticity seen in our model becomes more plausible. Given that water demand has been gradually decreasing over time, it seems reasonable to conclude that the long-term income elasticity for water demand is indeed negative, reflecting a trend towards more sustainable and efficient water use among higher-income households.

5.6.3. Industrial Tap Water Demand

Similar to household tap water demand, industrial water demand is expected to be influenced by water prices. Consequently, the price index was incorporated as an independent variable in the regression model. In addition to the price index, Real GDP was utilized as a second independent variable, serving as an indicator of economic activity. The modeling was conducted using data from 2011 to 2021, with two years excluded from the analysis due to their classification as outliers. In 2012, the repeal of the national groundwater tax led to a significant decrease in water prices by approximately 10-20%. Despite this reduction, the expected short-term increase in demand did not occur in 2012 and 2013, which resulted in the exclusion of data from these years. Although this data filtration approach is theoretically sound, the comparison of models with and without the outlier data reveals only minimal differences in accuracy, indicating that the exclusion of these years did not substantially improve the model's precision. This lack of significant improvement may be attributed to the absence of a strong relationship between industrial tap water demand and the price index. This matter is further discussed after the report of Matlab regression model results.

Linear regression model, after removing data of 2012,2013 (Revoke of national groundwater tax):

$$ln(Demand) \sim 1 + ln(Price\_index) + ln(GDP)$$

	Estimate	SE	tStat	pValue
(Intercept)	7.1403	2.7203	2.6248	0.039334
GDP	0.48564	0.10647	4.5612	0.003846
Price-index	0.091592	0.10914	0.83921	0.43351

Number of observations: 9, Error degrees of freedom: 6
Root Mean Squared Error: 0.0123
R-squared: 0.79, Adjusted R-Squared: 0.72
F-statistic vs. constant model: 11.3, p-value = 0.00929

Table 5.5: Estimated Coefficients for industrial tap water demand linear regression model, before removing outlier data.

Linear regression model, before removing data:

$$ln(Demand) \sim 1 + ln(Price\_index) + ln(GDP)$$

	Estimate	SE	tStat	pValue
(Intercept)	8.739	3.2758	2.6677	0.028462
GDP	0.42227	0.12799	3.2993	0.01087
Price-index	0.14163	0.095692	1.4801	0.17712

Number of observations: 11, Error degrees of freedom: 8
Root Mean Squared Error: 0.0153
R-squared: 0.622, Adjusted R-Squared: 0.527
F-statistic vs. constant model: 6.57, p-value = 0.0205

Table 5.6: Estimated Coefficients for industrial tap water demand linear regression model, before removing outlier data.

The model indicates a positive relationship between industrial water demand and GDP, which aligns with expectations. However, the relationship between demand and water price is not statistically significant, with the coefficient being close to zero. This suggests that there is little to no correlation between industrial tap water demand and its price, which is an unexpected outcome. One possible explanation for this result is that industries requiring tap water often demand high-quality water. According to data from CBS, particularly in recent years, the majority of industrial tap water usage occurs in manufacturing sectors. Within these sectors, tap water is predominantly used in the production of essential goods such as food products, chemicals, and basic metals. These goods are typically necessities and cannot be easily substituted. As a result, manufacturers may be able to pass any changes in water prices onto the final selling price of their products, thereby decoupling the relationship between water price and demand.

The data show a notable decline in water usage within the business sector between 1990 and 2014, with an overall reduction of 23%. The most significant drop occurred between 1995 and 2005, where business water consumption decreased by 57 million m³ (an annual rate of -1.6%), despite substantial economic and employment growth during the same period. Figure5.5 highlights this trend clearly. Key drivers behind the reduction included increased water conservation efforts, substitution of drinking water with alternative sources, and private water extraction.

Although water use in the business market experienced a slight uptick between 2005 and 2010, reaching 303 million m³, it dropped again to 285 million m³ by 2014. This decline was partly attributed to the global economic crisis that began in 2008, but also to heightened efforts towards water conservation and reuse within the framework of a circular economy. Following the economic recovery in 2015, water sales in the business market rose again, reaching 309 million m³ by 2019. However, in 2020, consumption fell to 303 million m³ due to the COVID-19 pandemic.

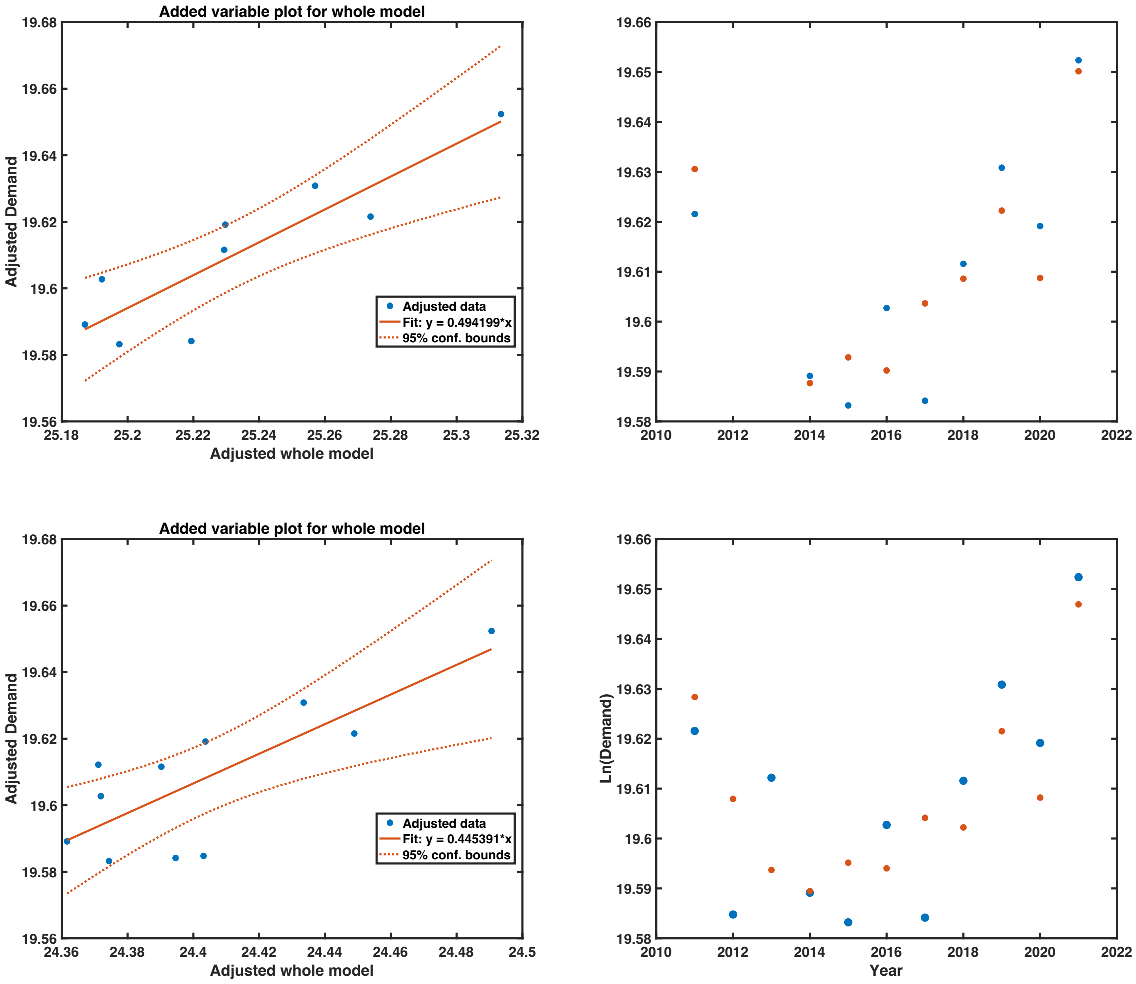


Figure 5.4: For Industrial tap water demand: a) Added variable plot for model excluding outlier b) Comparison between empirical data (blue) and model response (orange) excluding c)Added variable plot for model including outlier d) Comparison between empirical data (blue) and model response (orange) including outlier

It appears that the trend towards sustainability is also prevalent in the Dutch industrial sector. The significant reduction in water usage over recent decades, driven by conservation efforts, water reuse, and the substitution of drinking water with alternative sources, demonstrates a clear commitment to sustainability. Even during periods of economic growth, businesses have increasingly adopted practices that align with a circular economy, emphasizing efficient water management and environmental responsibility. This shift reflects a broader sustainable attitude within the sector, which continues to influence industrial practices in the Netherlands.

5.6.4. Agriculture Tap Water Demand

Similar to industrial tap water demand, agricultural tap water demand is anticipated to be influenced by water prices. Therefore, the price index was included as an independent variable in the regression model. In addition to the price index, Real GDP was incorporated as a second independent variable, representing economic activity.

The analysis was performed using data from 2011 to 2021. However, two years were excluded using dummy variable from the dataset due to their identification as outliers. In 2012, the repeal of the national groundwater tax resulted in a significant decrease in water prices by approximately 10-20%. Despite this reduction, the expected short-term impact on demand did not manifest in 2012 and 2013, necessitating the exclusion of data from these years.

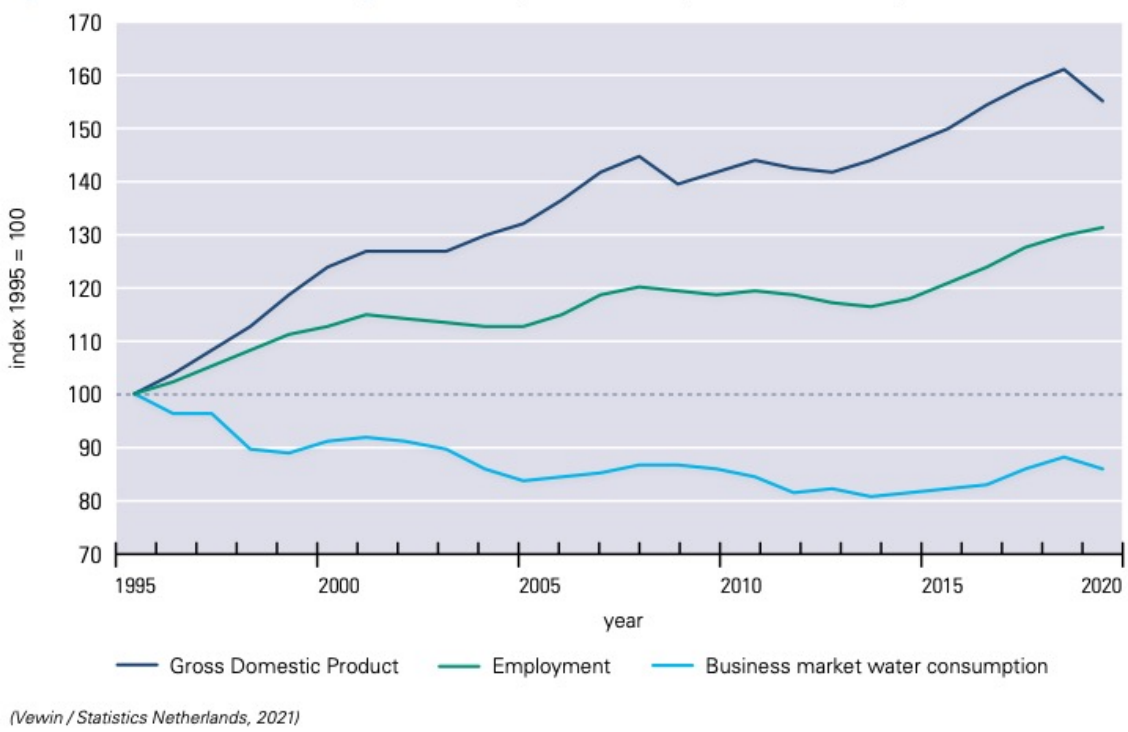


Figure 5.5: Business market drinking water consumption vs. development of the economy (Vewin, 2022)

Linear regression model, using dummy variable:

$$ln(Demand) \sim 1 + ln(Price\_index) + ln(GDP) + dummy$$

	Estimate	SE	tStat	pValue
(Intercept)	4.5091	4.2657	1.0571	0.32559
GDP	0.57563	0.18306	3.1797	0.015497
Price_index	-0.94864	0.3015	-3.1373	0.016442
dummy	-0.14459	0.03888	-3.7185	0.0074706

Number of observations: 11, Error degrees of freedom: 7
Root Mean Squared Error: 0.034
R-squared: 0.825, Adjusted R-Squared: 0.749
F-statistic vs. constant model: 11, p-value = 0.00489

Table 5.7: Estimated Coefficients for agriculture tap water demand linear regression model

Linear regression model, without dummy variable:

$$ln(Demand) \sim 1 + ln(Price\_index) + ln(GDP)$$

	Estimate	SE	tStat	pValue
(Intercept)	-0.17655	6.5755	-0.026849	0.97924
GDP	0.76821	0.28412	2.7038	0.026914
Price_index	-0.15817	0.34617	-0.45693	0.65988

Number of observations: 11, Error degrees of freedom: 8
Root Mean Squared Error: 0.0549
R-squared: 0.478, Adjusted R-Squared: 0.348
F-statistic vs. constant model: 3.66, p-value = 0.0742

Table 5.8: Estimated Coefficients for agriculture tap water demand linear regression model, without dummy variable

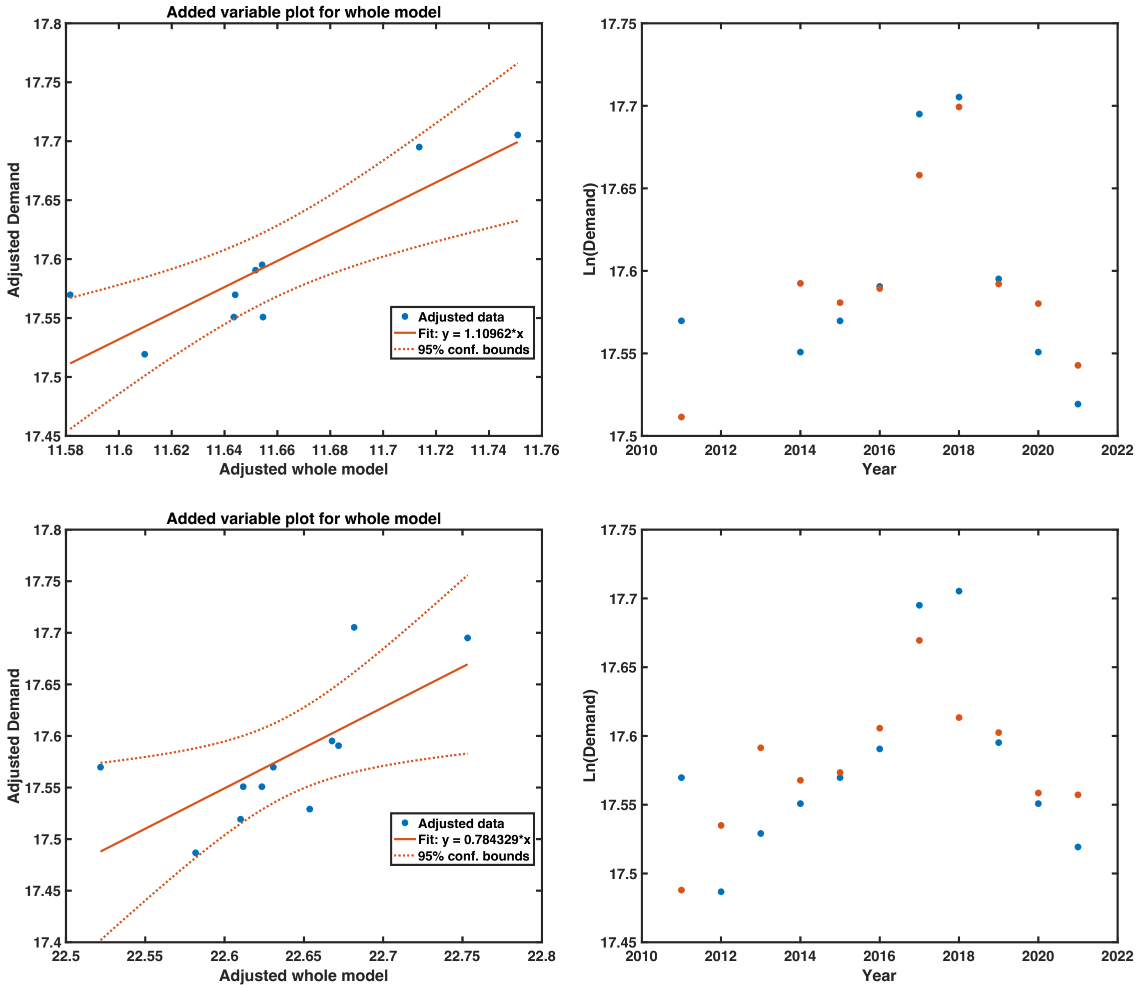


Figure 5.6: For agriculture tap water demand: a)Added variable plot for model excluding outlier b) Comparison between empirical data (blue) and model response (orange) excluding outlier c)Added variable plot for model including outlier d) Comparison between empirical data (blue) and model response (orange) including outlier

The model reveals a positive relationship between agricultural water demand and GDP, which aligns with standard economic expectations. The higher elasticity of agricultural water demand relative to GDP, compared to industrial water demand elasticity, reflects the sector's more direct and flexible response to economic growth. As economic activity expands, the agriculture sector's demand for water, a fundamental input, increases more readily than in industrial sectors due to the lower infrastructure and technological complexity required. This is in line with the fact that agricultural production is often more sensitive to fluctuations in raw material needs, such as water, given its direct use in crop irrigation and livestock production.

Moreover, the negative relationship between water demand and water prices further supports the expected inverse correlation. The price elasticity of -0.95 indicates that agricultural water demand is significantly more responsive to price changes compared to household water demand. This difference is understandable as water in households is a necessity, making it less sensitive to price fluctuations, whereas agricultural water use can be more discretionary. In the agriculture sector, higher water prices incentivize a shift toward water-saving technologies, lower-quality water sources, or even reductions in output.

5.6.5. Ground water data collection methodology

Groundwater data for this part of the study is primarily sourced from the Central Bureau of Statistics (CBS). The CBS dataset provides a comprehensive categorization of groundwater demand across various sectors, similar to the categorization used for tap water demand. This categorization allows for a detailed analysis of groundwater usage in different applications, such as industrial, and agricultural.

Additionally, the CBS dataset includes all necessary information related to groundwater taxation. The groundwater tax data in the CBS dataset is presented as the total tax collected from different sectors. For the purposes of this study, the total groundwater tax for each sector has been divided by the demand of that sector. This calculation allows us to derive the amount of tax paid per cubic meter of water used, providing a more granular understanding of the financial burden on each sector due to groundwater usage.

In alignment with the methodology used in the tap water demand analysis, the data required to calculate Gross Domestic Product (GDP) contributions by sector is also obtained from CBS. The dataset provides the percentage contribution of different sectors, such as industry and agriculture, to the overall GDP. By multiplying these percentages by the total GDP, we can accurately determine the economic contribution of each sector. With the overall economic performance of each sector in hand, we can then assess its impact on groundwater demand.

5.6.6. Industrial Ground Water Demand

In this section, the demand for groundwater in the industrial sector is analyzed in relation to key factors such as groundwater tax and the industrial component of GDP. It is theoretically sound to hypothesize that the repeal of the national groundwater tax could significantly influence the regression model of groundwater demand. To enhance the accuracy of the analysis, data from the years after 2011 were used in separate regression models, distinct from earlier periods. This approach led to higher R-squared values and overall improved precision compared to models that included all data without differentiation.

The results of the Matlab regression model for this analysis are presented below:

$$ln(Demand) \sim 1 + ln(GW\_Tax) + ln(GDP)$$

	Estimate	SE	tStat	pValue
Intercept	68.362	13.578	5.0347	0.0023694
GWTax	-0.0081547	0.071921	-0.11338	0.91343
IndGDP	-1.9401	0.53627	-3.6178	0.011126

Number of observations: 9, Error degrees of freedom: 6
Root Mean Squared Error: 0.0456
R-squared: 0.787, Adjusted R-Squared: 0.716
F-statistic vs. constant model: 11.1, p-value = 0.00969

Table 5.9: Estimated Coefficients for industrial ground water demand linear regression model, with 2012-2019 and 2021 data.

Linear regression model, with 2003-2009 data:

$$ln(Demand) \sim 1 + ln(GW\_Tax) + ln(GDP)$$

	Estimate	SE	tStat	pValue
Intercept	55.758	11.079	5.0326	0.0073203
GWTax	-0.010253	0.041972	-0.24428	0.81903
IndGDP	-1.4336	0.43395	-3.3036	0.029833

Number of observations: 7, Error degrees of freedom: 4
Root Mean Squared Error: 0.0579
R-squared: 0.756, Adjusted R-Squared: 0.634
F-statistic vs. constant model: 6.19, p-value = 0.0596

Table 5.10: Estimated Coefficients for industrial ground water demand linear regression model, with 2003-2009 data.

Linear regression model, with 2003-2021 data:

$$ln(Demand) \sim 1 + ln(GW\_Tax) + ln(GDP)$$

	Estimate	SE	tStat	pValue
Intercept	21.501	16.963	1.2675	0.2231
GWTax	0.2339	0.050829	4.6016	0.0002948
IndGDP	-0.078209	0.66315	-0.11794	0.90759

Number of observations: 19, Error degrees of freedom: 16
Root Mean Squared Error: 0.129
R-squared: 0.575, Adjusted R-Squared: 0.522
F-statistic vs. constant model: 10.8, p-value = 0.00107

Table 5.11: Estimated Coefficients for industrial ground water demand linear regression model, with 2003-2021 data

The final regression model (with 2003-2021 data, altogether) shows a lower R-squared value compared to the others, which undermines its reliability. Therefore, the results from this model should be treated with caution or even disregarded. The first two regression models, which analyze the periods before and after the revocation of the national groundwater tax (GWT), reveal an insignificant relationship between groundwater demand and the tax itself. This result might seem counterintuitive at first. The price elasticity of groundwater demand is nearly zero and statistically insignificant, suggesting that the demand for groundwater was not influenced by the tax. A study on the Dutch groundwater tax aligns with these findings, indicating that although the GWT was introduced as a ”green tax” aimed at reducing groundwater consumption and promoting better environmental outcomes, it largely failed to meet these objectives.

While the GWT did succeed in generating government revenue, it had a minimal impact on water consumption in industrial and agricultural sectors. Many industrial firms either shifted to using surface water or disregarded the tax due to their already low levels of groundwater consumption. The tax was ineffective in changing behaviors, particularly among firms with low water demands.

Additionally, the environmental impacts of the GWT were challenging to measure due to a lack of specific data on groundwater levels and the significant regional variability of water resources across the Netherlands. The tax was not adjusted for local conditions, which reduced its ability to target areas where groundwater depletion or environmental harm was most severe. In practice, the GWT operated more as a fiscal measure than an environmental one, as the revenue generated was funneled into the general budget rather than being earmarked for groundwater management or environmental projects.

The GWT was ultimately repealed in 2011 because its economic and environmental effects were negligible. This supports the findings from the regression models in this study, which similarly show that the groundwater tax had no significant influence on industrial groundwater demand. While the tax was intended to curb water usage, it did not achieve this goal and was discontinued due to its inefficacy. It appears that the groundwater tax had little impact on groundwater usage and did not effectively incentivize the substitution of groundwater with lower-quality alternatives.

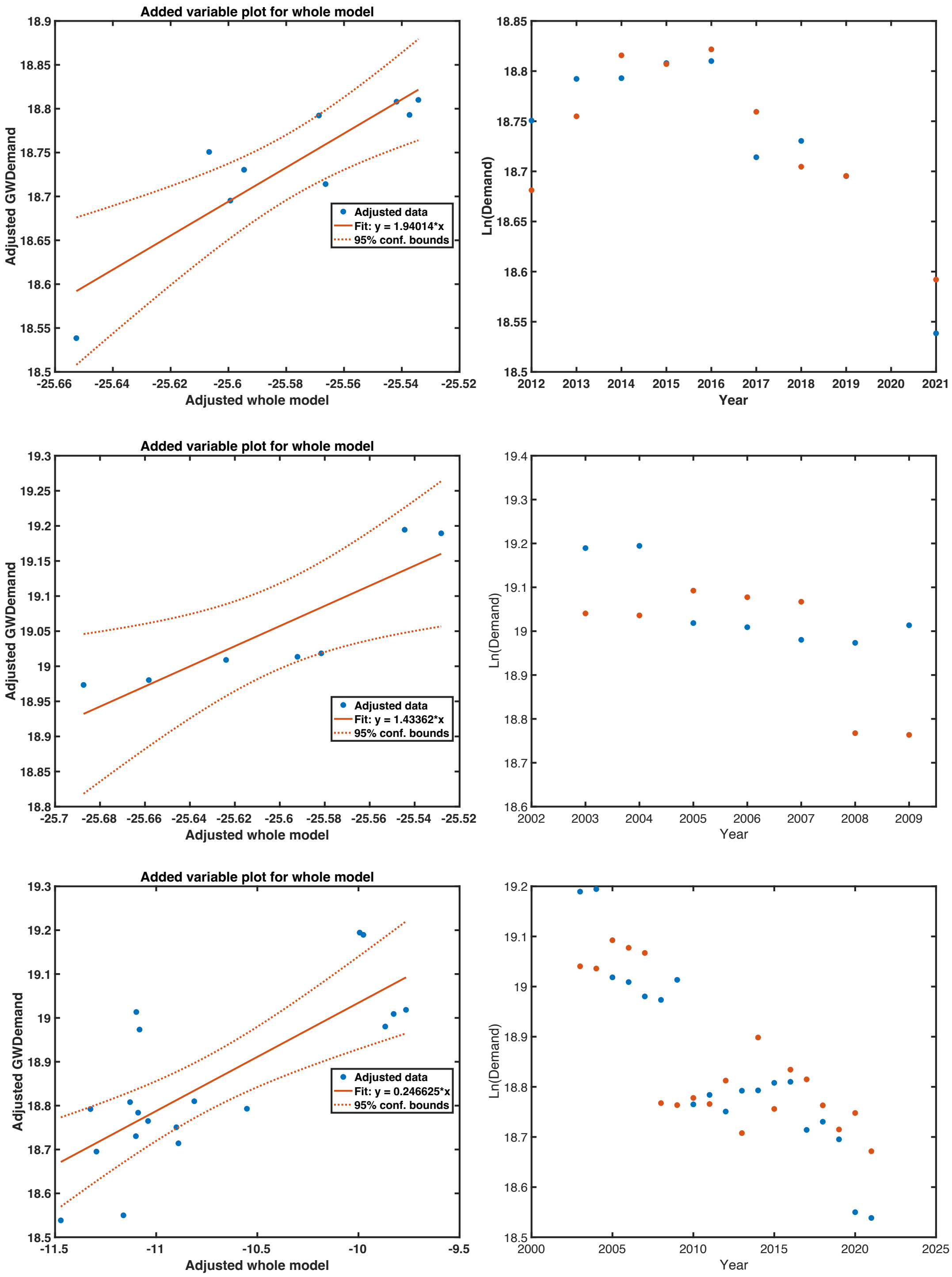


Figure 5.7: For industrial ground water demand: a)Added variable plot for model 2012-2021 b) Comparison between empirical data (blue) and model response (orange) for 2012-2021 c)Added variable plot for model 2003-2009 b) Comparison between empirical data (blue) and model response (orange) for 2003-2009 e)Added variable plot for model 2003-2021 f) Comparison between empirical data (blue) and model response (orange) for 2003-2021

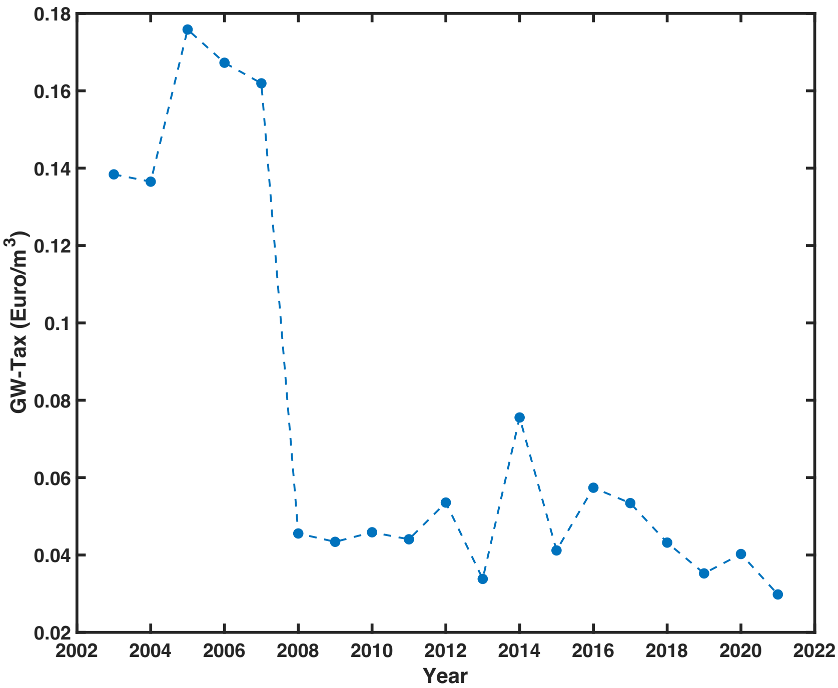


Figure 5.8: groundwater tax per cubic meter between 2003-2021

The models also highlight industrial GDP as a significant factor in determining industrial groundwater demand, although in an inverse relationship. As industrial GDP rises, groundwater demand decreases, mirroring trends observed between residential water consumption and household income. This inverse correlation suggests that as industries grow and become more profitable, they may invest in advanced technologies that optimize water use and improve efficiency. It is also possible that industrial sectors transitioned to surface water, compensating for the lower quality of surface water with more advanced water treatment technologies, further reducing reliance on groundwater.

5.6.7. Agriculture Ground Water Demand

This section analyzes groundwater demand in the agricultural sector, examining key variables such as the groundwater tax, rainfall, and the agricultural component of GDP. It is hypothesized that the repeal of the national groundwater tax could significantly influence the estimated groundwater demand in the regression model. To enhance the accuracy of the analysis, separate regression models were developed using data from 2003-2011 and 2012-2021, alongside a comprehensive model incorporating all data from 2003 to 2021.The results of the regression models developed in MATLAB are discussed below:

Linear regression model, with 2003-2011 data (2011 is the year that Groundwater tax has been revoked):

$$ln(Demand) \sim 1 + ln(GW\_Tax) + ln(GDP) + ln(Rain)$$

	Estimate	Standard Error (SE)	t-Statistic (tStat)	p-Value
Intercept	0.8676	13.55	0.064032	0.95143
GWTax	-0.70231	0.11264	-6.235	0.0015535
Rain	-0.14051	0.40655	-0.34561	0.7437
AgrGDP	0.70341	0.54716	1.2856	0.25492

Number of observations: 9, Error degrees of freedom: 5
Root Mean Squared Error: 0.102
R-squared: 0.95, Adjusted R-Squared: 0.919
F-statistic vs. constant model: 31.4, p-value = 0.00114

Table 5.12: Estimated Coefficients for agricultural ground water demand linear regression model, with 2003-2011 data.

Linear regression model, with 2012-2021 data (2011 is the year that Groundwater tax has been revoked):

$$ln(Demand) \sim 1 + ln(Rain) + ln(GDP)$$

Predictor	Estimate	Standard Error (SE)	t-Statistic (tStat)	p-Value
Intercept	26.475	77.492	0.34165	0.74264
Rain	-3.1593	1.2669	-2.4937	0.041372
AgrGDP	0.56614	3.1994	0.17695	0.86456

Number of observations: 10, Error degrees of freedom: 7
Root Mean Squared Error: 0.47
R-squared: 0.512, Adjusted R-Squared: 0.372
F-statistic vs. constant model: 3.67, p-value = 0.0813

Table 5.13: Estimated Coefficients for agricultural ground water demand linear regression model, with 2003-2011 data.

Linear regression model, with 2003-2021 data:

$$ln(Demand) \sim 1 + ln(GW\_Tax) + ln(GDP) + ln(Rain)$$

Predictor	Estimate	Standard Error (SE)	t-Statistic (tStat)	p-Value
Intercept	17.706	36.225	0.48878	0.63207
GWTax	-0.0049257	0.010023	-0.49143	0.63024
Rain	-2.5783	0.72513	-3.5556	0.0028761
AgrGDP	0.77205	1.4844	0.52011	0.61058

Number of observations: 19, Error degrees of freedom: 15
Root Mean Squared Error: 0.374
R-squared: 0.533, Adjusted R-Squared: 0.44
F-statistic vs. constant model: 5.71, p-value = 0.00818

Table 5.14: Estimated Coefficients for agricultural ground water demand linear regression model, with 2003-2021 data.

The final regression model, which incorporates data from 2003 to 2021, as well as a second model using data from 2012 to 2021, exhibits lower R-squared values compared to other model. This diminishes their reliability, and as such, the findings from these models should be treated with caution or be potentially disregarded.

In contrast, the results from the first linear regression model, which demonstrates a sufficiently high R-squared value, are considered reliable and warrant further discussion. Analyzing the p-values of the independent variables, it becomes evident that only the relationship between groundwater demand and the groundwater tax is statistically significant. This outcome aligns with findings from the article ”The Life and Death of the Dutch Groundwater Tax”, which notes: “Farmers might have had the strongest response to the tax, but most of them were exempt from the GWT or could switch to surface water.” The strong influence of the groundwater tax on agricultural groundwater demand, particularly given the substantial reliance of the agricultural sector on groundwater resources (table 5.12), lends further support to the regression model’s findings.

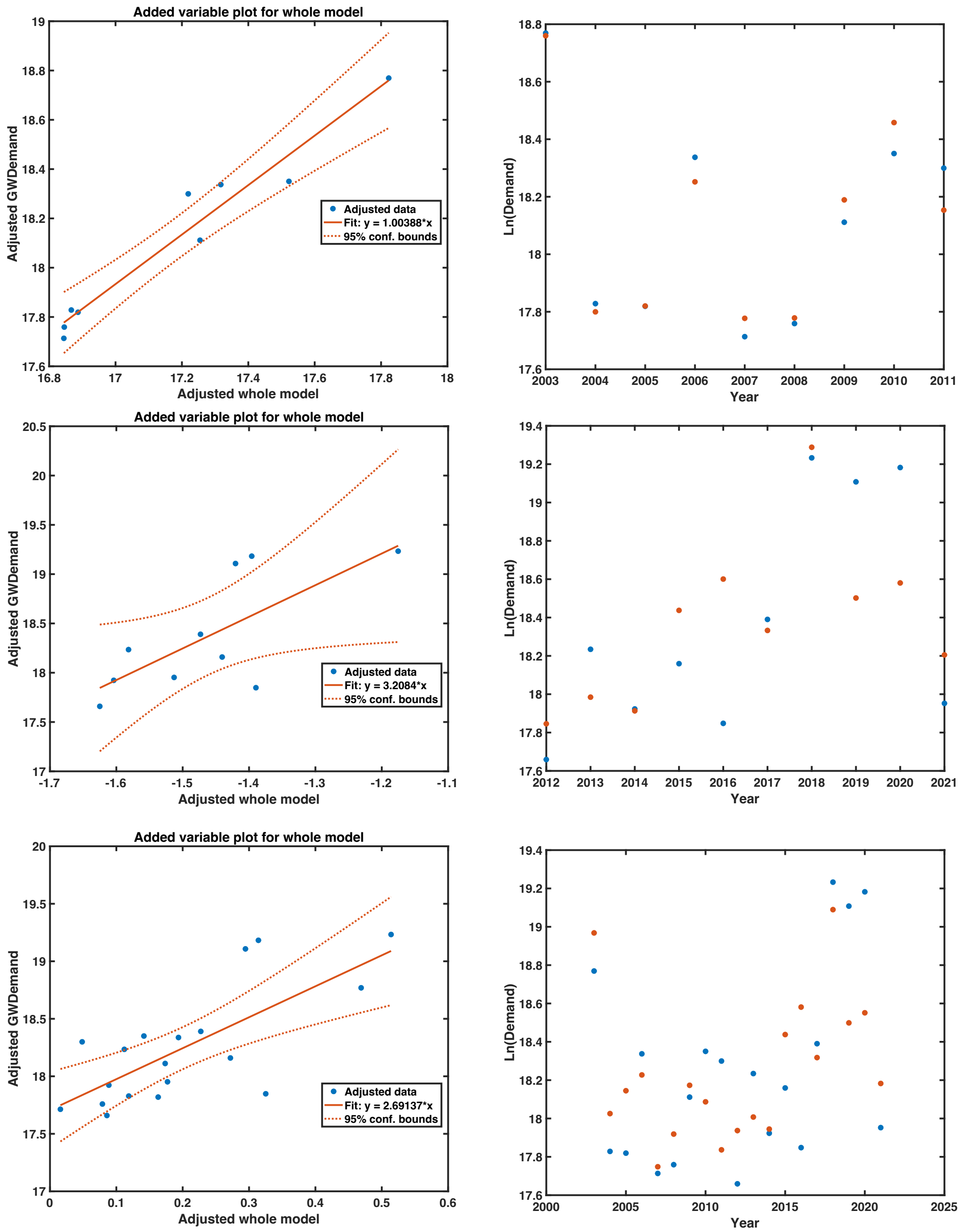


Figure 5.9: For agriculture ground water demand: a)Added variable plot for model 2003-2011 b) Comparison between empirical data (blue) and model response (orange) for 2003-2011 c)Added variable plot for model 2012-2021 b) Comparison between empirical data (blue) and model response (orange) for 2012-2021 e)Added variable plot for model 2003-2021 f) Comparison between empirical data (blue) and model response (orange) for 2003-2021

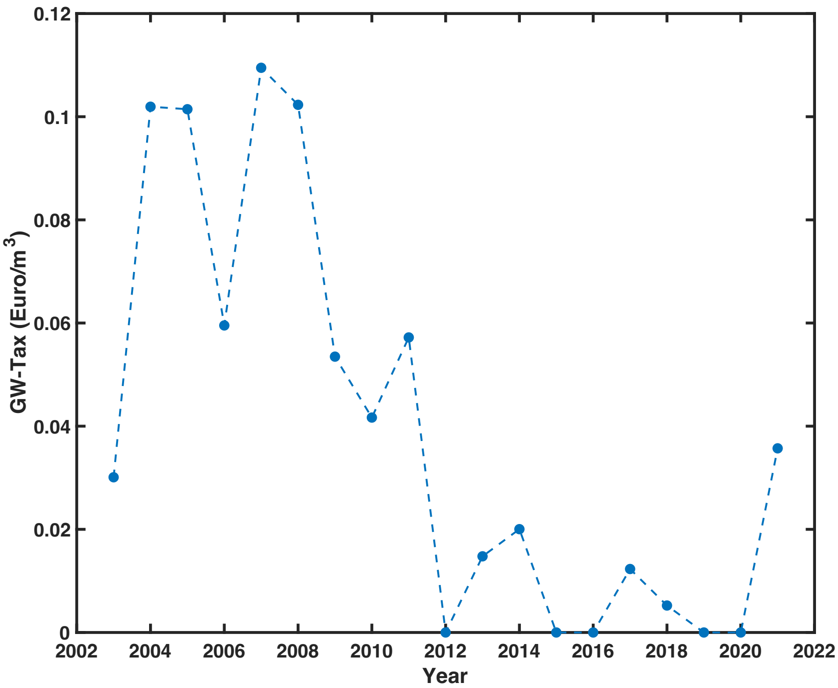


Figure 5.10: Groundwater tax per cubic meter for agriculture sector

However, the fact that many farmers were exempt from paying the groundwater tax raises questions regarding its overall impact on agricultural groundwater demand. For those farmers who were exempt, as well as for those who either paid the tax or switched to surface water, the regression model indicates a reverse effect, suggesting that the tax may have influenced behavior among non-exempt farmers. Given these considerations, the findings of the regression model are likely most reliable for the 2003-2011 period.

5.7. Water Reuse Cost

Previous studies have demonstrated that the capital expenditures (CAPEX) and operational expenditures (OPEX) for water reuse systems are significantly influenced by the system's capacity, the quality of the input water, and the desired final water quality. For applications requiring high-quality output, such as potable tap water, multiple treatment stages are typically necessary to ensure that wastewater meets stringent quality standards (Keller et al., 2022). Consequently, both CAPEX and OPEX are highly capacity-dependent: larger systems often benefit from economies of scale but also necessitate more complex infrastructure.

5.7.1. Modeling Cost-Capacity Relationships

To model the relationship between reuse system costs and capacity, we adopt a power-law scaling approach, as suggested by previous studies (Keller et al., 2022; Plumlee et al., 2014; Guo et al., 2014). This relationship can be expressed as:

$$\log(\text{Cost}) = m \times \log(\text{Capacity}) + b \quad (5.11)$$

where Cost represents either CAPEX or OPEX, Capacity denotes the system capacity, and m and b are parameters estimated based on empirical data.

5.7.2. Effect of Quality in Reuse Systems

This study focuses on high-quality reuse systems capable of producing potable-grade water. According to literature (Keller et al., 2022; Plumlee et al., 2014; Guo et al., 2014), the CAPEX for such systems ranges from 600 to 12,000 USD per cubic meter of daily capacity. OPEX costs vary between 0.1 and 2 USD per cubic meter, with an error margin of -30% to +50%, depending on the system's scale and operational conditions. To convert real USD based on 2021 to real Euro based on 2023, the real USD values were first adjusted to 2023 using the U.S. CPI published by the U.S. Bureau of Labor Statistics. Subsequently, the adjusted USD values were converted to Euros using the exchange rate published by the European Central Bank.

Operational conditions, particularly the quality of the input wastewater, play a critical role in determining reuse costs. Typical treatment trains for water reuse include:

- **Microfiltration (MF)** for removing mid-sized contaminants.
- **Reverse Osmosis (RO)** for eliminating inorganics such as heavy metal ions and dissolved salts.
- **Advanced Oxidation Processes (AOPs)** like H_2O_2-UV/Ozone or Biological Activated Carbon (BAC) for removing small organic molecules.

Among these technologies, RO is particularly costly and energy-intensive. Based on input wastewater quality and desired output water quality, three treatment train categories are defined, as suggested by Keller et al., 2022:

- **LQWW-HQW (Low-Quality Wastewater to High-Quality Water):** MF-RO-H_2O_2+UV/O_3 is suitable for low-quality input wastewater with high levels of heavy metal ions (HMI), high salinity, and significant concentrations of low molecular weight organics.
- **MQWW-HQW (Medium-Quality Wastewater to High-Quality Water):** MF-RO-O_3 is suitable for medium-quality input wastewater, characterized by non-potable HMI levels, moderate salinity, and high concentrations of low molecular weight organics.
- **HQWW-LQW (High-Quality Wastewater to Low-Quality Water):** MF-RO-BAC is appropriate for high-quality input wastewater with potable HMI levels and low salinity, or when the final product is intended for non-sensitive applications.

Energy consumption significantly affects the cost of water reuse, particularly due to the high energy demands of RO. Therefore, energy inflation impacts are incorporated by adjusting the energy share (extracted from Keller et al., 2022; Plumlee et al., 2014; Guo et al., 2014 in O&M costs).

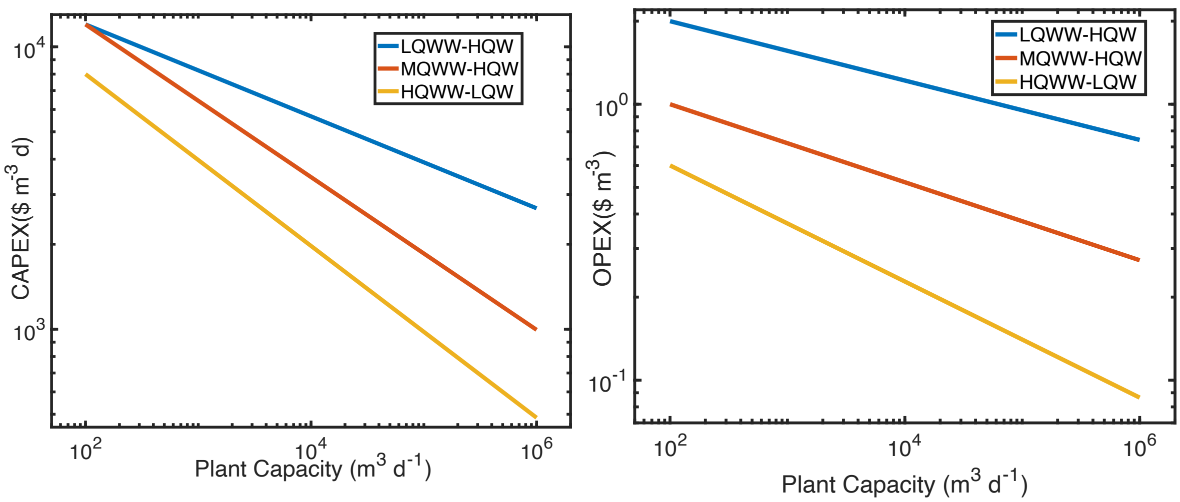


Figure 5.11: Integrated advanced tertiary treatment train (A) capital costs; (B) annual operating expenses. All costs adjusted for inflation to 2021 source (Keller et al., 2022)

5.8. Summary of Parameter Value

To summarize this chapter, Table 5.15 provides an overview of the parameters and their values used in our modeling approach.

Parameter	Value (Unit)	Description
β_p^{HH}	-0.42	Price elasticity of household tap water demand
β_{DI}^{HH}	-0.28	Income elasticity of household tap water demand
β_p^{IND}	0	Price elasticity of industrial tap water demand
β_{GDP}^{IND}	0.4	GDP elasticity of industrial tap water demand
β_p^{AGR}	-0.95	Price elasticity of agricultural tap water demand
β_{GDP}^{AGR}	0.57	GDP elasticity of agricultural tap water demand
β_{GWT}^{IND}	0	Groundwater tax elasticity of industrial groundwater demand
β_{GDP}^{IND}	-1.7	GDP elasticity of industrial groundwater demand
β_{GWT}^{AGR}	-0.7	Groundwater tax elasticity of agricultural groundwater demand
β_{GDP}^{AGR}	0.6	GDP elasticity of agricultural tap water demand
β_{Rain}^{AGR}	-3	Elasticity of environmental conditions on agricultural tap water demand
P_{HH}	€2.1 (2023)	Household price of tap water
P_{IND}	€1.85 (2023)	Industrial price of tap water
P_{AGR}	€1.85 (2023)	Agricultural price of tap water
GWT_{IND}	€0.03 (2021)	Industrial groundwater tax
GWT_{AGR}	€0.03 (2021)	Agricultural groundwater tax
CT	€1 (2023)	Cost of water treatment
D	€0.72(2023)	Cost of water distribution
C_m	€0.2(2023)	Cost of materials in tap water production
C_e	€0.16(2023)	Cost of energy in tap water production
C_o	€1.12(2023)	Other operational costs in tap water production
r_{ce}	6%	Rate of energy cost increase in tap water production
r_{me}	6%	Rate of material cost increase in tap water production
$m_{LQWW-HQW}^{capex}$	-0.16	Ratio between CAPEX and capacity of r LQWW-HQW water reuse facilities
$m_{LQWW-HQW}^{opex}$	-0.11	Ratio between OPEX and capacity of r LQWW-HQW water reuse facilities
$b_{LQWW-HQW}^{capex}$	4.4	Base CAPEX ofr LQWW-HQW water reuse facilities
$b_{LQWW-HQW}^{opex}$	0.51	Base OPEX of r LQWW-HQW water reuse facilities
$m_{MQWW-HQW}^{capex}$	-0.27	Ratio between CAPEX and capacity of MQWW-HQW water reuse facilities
$m_{MQWW-HQW}^{opex}$	-0.14	Ratio between OPEX and capacity of MQWW-HQW water reuse facilities
$b_{MQWW-HQW}^{capex}$	4.62	Base CAPEX of MQWW-HQW water reuse facilities
$b_{MQWW-HQW}^{opex}$	0.28	Base OPEX of MQWW-HQW water reuse facilities
$m_{HQWW-LQW}^{capex}$	-0.3	Ratio between CAPEX and capacity of HQWW-LQW water reuse facilities
$m_{HQWW-LQW}^{opex}$	-0.21	Ratio between OPEX and capacity of HQWW-LQW water reuse facilities
$b_{HQWW-LQW}^{capex}$	4.5	Base CAPEX of HQWW-LQW water reuse facilities
$b_{HQWW-LQW}^{opex}$	0.2	Base OPEX of HQWW-LQW water reuse facilities
$Es_{LQWW-HQW}$	0.3	energy share in O&M cost of LQWW-HQW reuse
$Es_{MQWW-HQW}$	0.3	energy share in O&M cost of MQWW-HQW reuse
$Es_{HQWW-LQW}$	0.15	energy share in O&M cost of HQWW-MQW reuse

Table 5.15: Summary of Parameters and Values Used in the Model

6 Model Implementation

In the previous chapter, we introduced the model used in this study. This chapter focuses on the implementation of the model, specifically how it was translated into a machine-readable format. Section 6.1 outlines the software tools used in the study, while Section 6.2 provides an overview of the code structure and details the workflow of the model.

6.1. Software Dependencies

The model is implemented in MATLAB, with the primary model code contained in the file named `Model.m`. To support this, three additional `.m` files serve as databases for the model, each storing different parameter sets and functions essential to the model's operation. These are:

- `BaseData.m`: This file contains economic parameters, including inflation rate, cost change rates across various categories, and interest rates. It also includes data for three future scenarios, which are explained in detail in Chapter 7.
- `DW_data.m`: This file holds parameters specific to the Dutch water system, as introduced in the previous chapter.
- `Scenario_func.m`: This file selects the appropriate model functions based on each scenario, as described in the preceding sections.

Each of these files works in tandem to feed the main model with data and logic tailored to different scenarios and conditions in the water system.

6.2. Model Formalization

Figure 6.1 provides an overview of the computational model structure, designed to simulate and assess water demand and reuse strategies. The model begins with an initialization phase, where the user selects the desired baseline conditions and scenario settings that define the model's assumptions and starting parameters.

After initialization, the model progresses through three main phases:

1. **Phase One – Baseline Update**: Using the parameters defined in the baseline settings, the model updates essential data related to future tap water demand, as well as the projected costs and prices of tap water under these baseline conditions. This step involves calculating future demand based on factors such as population growth, price change, allowing for a realistic baseline assessment that serves as a reference for comparison with reuse scenarios.
2. **Phase Two – Reuse Scenario Implementation**: In this phase, the selected reuse scenario is applied to the baseline. The model adjusts for water reuse policies, simulating their impact on demand and pricing.

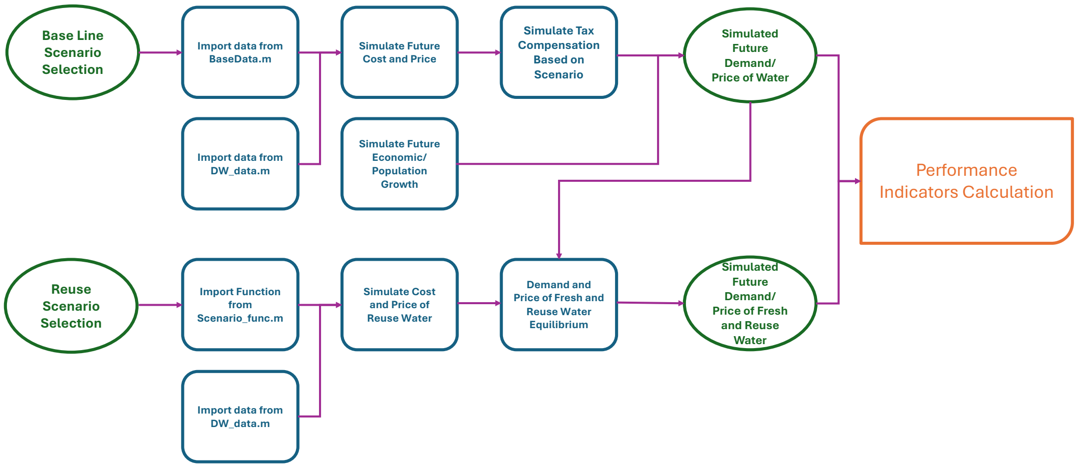


Figure 6.1: Flow diagram of Water Reuse Modeling

3. **Phase Three – Performance Indicators Calculation**: The final phase focuses on calculating and displaying performance indicators as model outputs.

7 Design of Experiments

This chapter focuses on the application of the model, with particular attention to the design of experiments. Section 7.1 explains the baseline scenarios, while Section 7.2 introduces water reuse scenarios.

7.1. Baseline Scenarios

Based on the analysis presented in Chapter 4, three potential future scenarios for the Dutch water system, assuming no water reuse, are outlined.

7.1.1. Scenario 1: Constant Costs

In this scenario, it is assumed that the cost of water production increases only in line with inflation. As a result, the real cost and the real price of water remain constant over time. This implies that water prices do not exert additional influence on water demand, which is instead driven by factors such as economic growth and population dynamics.

This scenario can be regarded as an optimistic outlook, particularly from an economic perspective. It assumes a stable economic environment where external shocks—such as raw material shortages, energy crises, or environmental degradation—do not significantly impact the water sector. While this scenario reflects a best-case situation in terms of cost predictability, it is less realistic given current global and regional challenges.

7.1.2. Scenario 2: Higher Costs Due to Material and Energy Price Increases

Chapter 4 highlighted that the cost of water production has risen in recent years, driven primarily by two factors: increasing water salinity and the ongoing energy crisis in Europe. These issues, which stem from both natural and geopolitical factors, have significantly impacted material and energy prices.

Given that these challenges are unlikely to subside, this scenario assumes a continued increase in water production costs. As a result, water prices will rise, creating a direct economic impact on consumers and industries. This higher-cost scenario reflects a more realistic outlook, particularly in light of intensifying pressures on water systems globally, including resource depletion and climate change.

7.1.3. Scenario 3: Higher Costs with Tax Compensation

In response to rising water production costs, governments may implement policy measures to mitigate the financial burden on specific sectors of the economy. Recent trends in the Netherlands have shown a shift in water tax policies, with a decreasing share of taxes imposed on households and an increasing share assigned to industries. This shift is intended to prevent excessive increases in household water prices while leveraging the relative resilience of industries to price fluctuations.

This scenario assumes that if water production costs continue to rise, the government will further adjust tax policies, redistributing the financial burden to maintain affordable water prices for households. While industries may experience higher tax burdens, the assumption is that their operations are less price-sensitive compared to household consumption. This tax-compensation scenario reflects a balancing act between social equity and economic pragmatism, aiming to ensure access to water remains equitable without unduly harming industrial competitiveness.

These baseline scenarios provide a framework for understanding how the Dutch water system might evolve in the absence of water reuse, setting the stage for evaluating the impacts of alternative approaches.

7.2. Water Reuse Scenarios

In this study, the water sector is categorized by both water types and consumer groups. Since water reuse scenarios are closely tied to these parameters, we define specific scenarios for different consumer groups and water types. These scenarios aim to explore how water reuse strategies could address demand and pricing challenges in the Dutch water system. Later on, we further categorize these reuse scenarios into Centralized reuse and Decentralized reuse, distinguishing between large-scale, infrastructure-driven approaches and more localized, flexible reuse strategies.

7.2.1. Tap Water: Household Sector

For households, scenario development is informed by the current structure of the Dutch urban water system. Currently, all Dutch households are connected to a centralized urban water system, and their wastewater is collected for centralized treatment. Implementing a separate distribution network for reuse water would require extensive new piping infrastructure, significantly increasing costs. Thus, two realistic water reuse scenarios are considered:

Centralized Water Reuse for Households

A centralized water reuse system involves mixing treated reuse water with fresh urban water, providing a single water supply to households. This approach results in a unified water price determined by the combined costs of fresh and reuse water production. Using our model, this scenario evaluates how varying reuse water capacities influence water pricing and household water demand. It provides a feasible and economically scalable approach to integrating water reuse into urban supply systems.

Decentralized Water Reuse for Households

In this scenario, water reuse is implemented locally, such as in large housing complexes. While decentralized systems are generally less competitive with urban water prices due to higher unit costs, they may become financially viable in densely populated residential (housing complexes) areas where economies of scale apply. This scenario investigates the potential of decentralized reuse systems in such settings, assessing their impact on water demand and cost-effectiveness.

7.2.2. Tap Water: Industrial and Agricultural Sectors

For the industrial and agricultural sectors, water reuse scenarios are divided into centralized and decentralized approaches.

Centralized Water Reuse for Industry and Agriculture

Industries and agricultural operations are also connected to urban tap water systems. A centralized water reuse system involves mixing treated reuse water with fresh urban water, providing a single water supply. Using our model, this scenario evaluates how varying reuse water capacities influence water pricing and business sector water demand.

Additionally, this scenario explores how changes in industrial price elasticity could affect demand under these pricing models, providing insights into sector-specific adaptation to water reuse strategies.

Decentralized Water Reuse for Industry and Agriculture

In decentralized systems, water reuse occurs on-site at the consumer level, reducing reliance on centralized infrastructure. This scenario examines the impact of localized reuse on water demand, costs, and wastewater treatment requirements. It also considers the distribution challenges and potential cost savings associated with treating and reusing water close to the point of use.

7.2.3. Groundwater: Industrial and Agricultural Consumers

After careful consideration, I decided not to conduct any experiments on groundwater reuse, as the current costs of groundwater extraction are so low that reuse systems cannot compete with them.

Groundwater extraction is typically managed independently by consumers, making decentralized water reuse the only feasible option in this context. Industrial and agricultural users extract groundwater directly, and reuse water systems must integrate seamlessly with their existing operations. This scenario mirrors the decentralized tap water reuse model for these sectors, focusing on cost-benefit analyses, reuse system capacity, and environmental impacts. However, due to the low cost of groundwater, the economic viability of its reuse remains a challenge.

The water reuse scenarios outlined above provide a comprehensive framework for evaluating the feasibility, costs, and benefits of integrating reuse strategies into the Dutch water system. Key aspects include:

- **Economic Viability:** Scenarios analyze the financial impacts of reuse systems, including centralized versus decentralized approaches and the implications for pricing.
- **Sector-Specific Dynamics:** Different consumer groups, such as households, industries, and agriculture, have unique demands and price sensitivities that are considered in the scenarios.
- **Policy and Infrastructure Needs:** The scenarios highlight potential challenges, such as the need for new infrastructure in centralized systems or the operational complexities of decentralized reuse.

These scenarios will be evaluated against the high cost baseline scenario conditions described in Section 7.1 to assess their potential contributions to addressing water scarcity and promoting sustainability in the Netherlands. By modeling these scenarios, this study aims to provide actionable insights for policymakers and stakeholders in the water sector.

Part III

Result and Analysis

8

Model Result: No-Reuse Scenarios

Before examining the effects of scenarios and policies on water reuse implementation, it is crucial to first develop and assess baseline scenarios that depict the future of the Dutch water sector in the absence of any water reuse measures. These scenarios serve as benchmarks against which the impacts of implementing water reuse systems can be measured. Within the baseline scenarios explored in this thesis, it is assumed that no water reuse systems are in operation. A central objective of these baseline scenarios is to predict future water prices and demand. To achieve this, accurate cost estimations must be generated, which can subsequently inform pricing models. Once future prices are estimated, established demand models may then be utilized to forecast overall water demand.

To forecast water costs effectively, multiple forecasting approaches must be employed, each rooted in different underlying assumptions. In this thesis, three distinct cost scenarios are examined. The first scenario, Inflation-Adjusted Costs, represents an optimistic projection. The second scenario, Higher Costs, offers a more realistic outlook. The third scenario, Tax Compensation, introduces a policy mechanism for redistributing costs: households receive compensation without direct funding from policymakers, while the business sector assumes responsibility for these compensations. Thus, the three baseline scenarios presented herein encompass two potential cost trajectories for drinking water production and one feasible policy intervention.

Before analyzing the results, it is essential to establish a benchmark scenario for comparison with the reuse scenarios. The choice of this benchmark is based on the underlying assumptions of each scenario. Among the available options, the High-Cost scenario is selected as the primary baseline for two key reasons.

First, this scenario presents a more realistic projection for the future of the Dutch water system, considering expected trends in cost developments. Second, for a meaningful comparison, the baseline scenario must be compatible with the reuse scenarios. Since material and energy costs constitute a significant portion of reuse expenses, and inflation in these costs has been factored into the modeling of both reuse and urban water costs, the High-Cost scenario provides a consistent and appropriate reference point for the subsequent chapters.

In order to define the variable and fixed parameters for modeling the baseline scenarios, data presented in the previous chapters have been utilized. As indicated in Section 4.2.2, material and energy-related costs for drinking water production have been rising in recent years, whereas most other cost categories largely track inflation. Consequently, the material and energy cost rate serves as the variable parameter determining the high-cost scenario, while other parameters are treated as fixed, based on historical data. Table 8.1 presents the variables used in cost estimation.

Following the cost estimation, prices can be derived using the model equations introduced in Chapter 5, and sector-specific demand can then be predicted. In the next section, the outcomes of the baseline scenarios are presented and discussed. These projected prices and demands represent the primary outputs of the model and will serve as the foundation for analyzing the KPIs described in Chapter 5.

Table 8.1: Parameters Used in Baseline Scenarios

Parameter	Inflation-Adjusted Cost	High Cost	Tax Compensation
Rate of Compensation	0%	0%	0–100%
Yearly Cost Increase of Energy	2%	6%	6%
Yearly Cost Increase of Material	2%	6%	6%
Yearly Cost Increase of Other Cost	2%	2%	2%
Inflation Rate	2%	2%	2%
Population Growth Rate	0.50%	0.50%	0.50%
Yearly Economy Growth	1.50%	1.50%	1.50%
Tax Rate Household	9%+21%	9%+21%	9%+21%
Tax Rate Business	21%	21%	21%
Profit Margin	10%	10%	10%

8.1. Demand and Price

Starting from household sector, Figure 8.1 illustrates the projected demand for tap water use and price in households under the three baseline scenarios. From 2024 onward, the figure highlights the distinct trends and differences in water demand and price resulting from each scenario. In the Constant-Cost

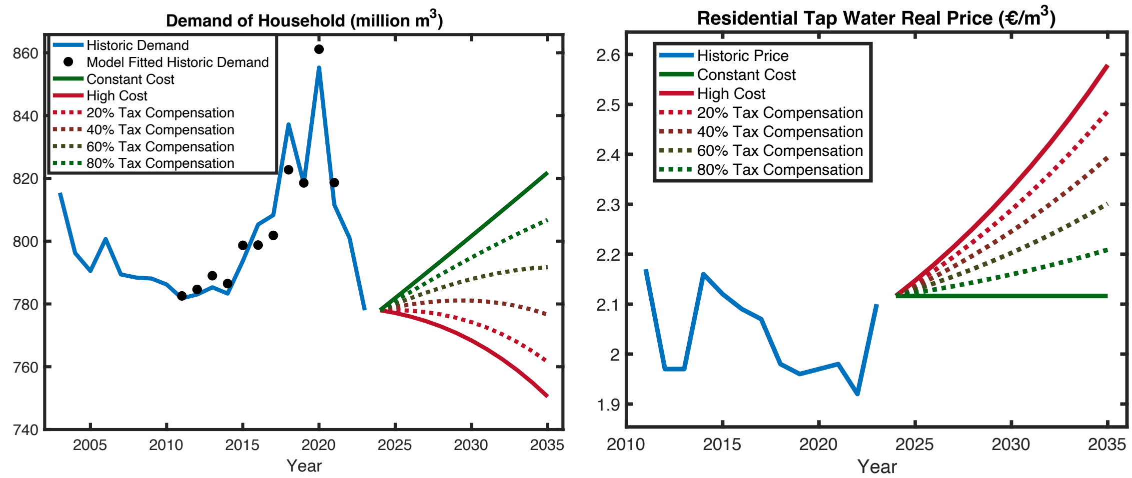


Figure 8.1: Projection of a) Residential tap water demand b) Residential tap water price

scenario, the real price of tap water remains unchanged over time, meaning household demand is unaffected by price increases. As a result, demand grows steadily, driven solely by population growth. This scenario appears favorable from a household financial perspective, as stable prices ensure affordability and predictability for consumers. However, this future is highly unlikely due to the persistent upward pressure on water production costs, particularly for materials and energy, observed in recent years. Furthermore, unregulated demand growth would exacerbate stress on natural water resources, particularly in regions already facing water scarcity. Without intervention, this excess demand could jeopardize the sustainability of water resources, highlighting the environmental limitations of a constant-cost scenario.

The High-Cost scenario assumes that rising material and energy expenses continue to drive up water production costs, resulting in higher tap water prices. As anticipated, increased prices negatively affect demand, leading to a slower demand growth rate compared to the constant-cost scenario. This scenario aligns more closely with historical trends in water pricing, offering a realistic projection of how rising costs might influence future water use. However, it introduces significant equity concerns, as higher prices for an essential resource like drinking water could reduce accessibility, particularly for low-income households. While this scenario alleviates some stress on water resources by tempering demand, it does so at the expense of household affordability, underscoring the trade-off between resource sustainability and consumer welfare. The balance in this scenario leans toward protecting

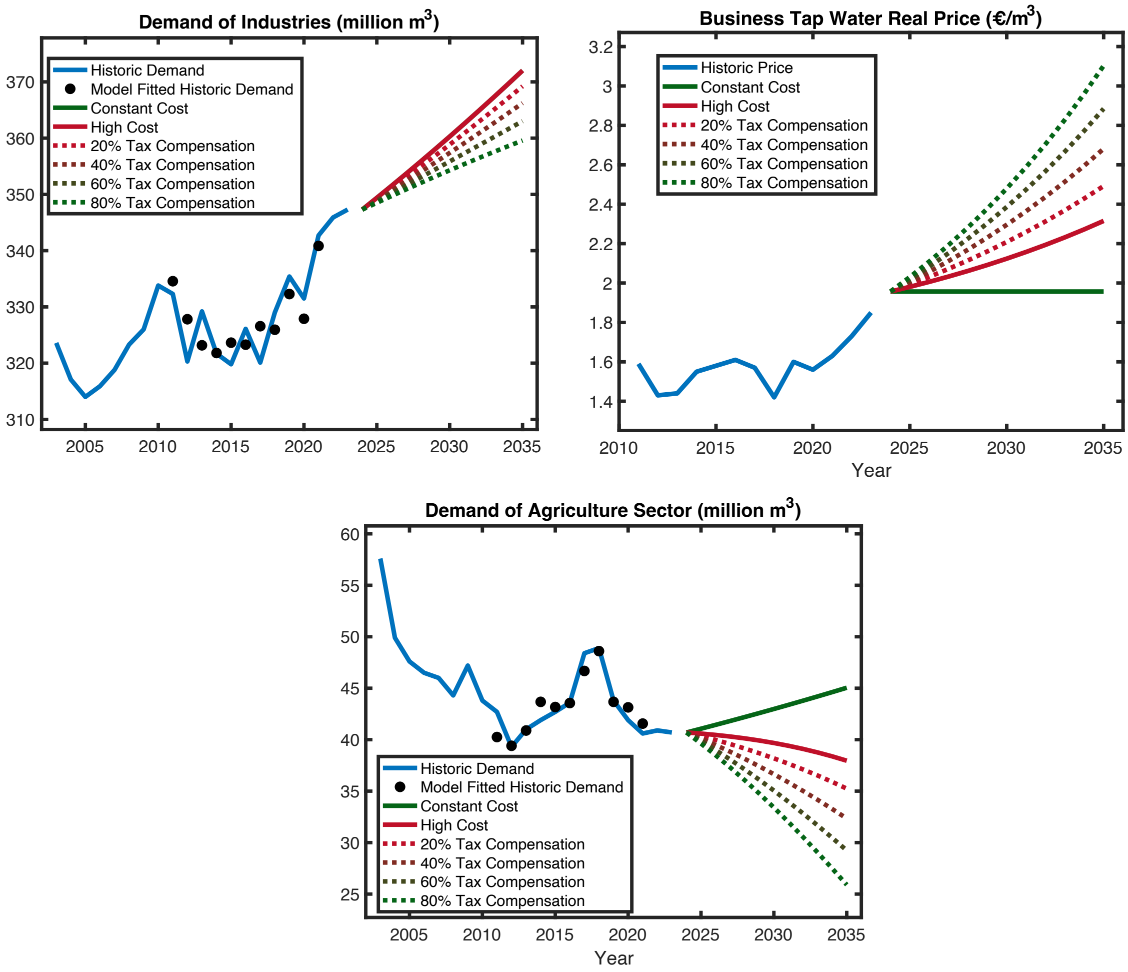


Figure 8.2: Projection of a) Industrial tap water demand b) Business sector tap water price and c) Agriculture tap water demand

natural resources but at a considerable cost to household utility.

To address the challenges posed by rising costs, one potential policy involves redistributing part or all of the additional production costs to the business sector, which tends to be less sensitive to water price fluctuations. This approach is reflected in the Tax-Compensation scenario, represented by dashed lines in Figure 1, where varying rates of cost compensation are applied. At a high compensation rate, approaching 100%, household prices remain nearly unchanged, and demand follows a trajectory similar to the constant-cost scenario. In this case, the financial burden of increased production costs is entirely absorbed by the business sector, shielding households from price hikes. Conversely, at a low compensation rate, close to 0%, households bear the full cost increase, resulting in demand and price trends closely resembling those in the high-cost scenario. Partial compensation rates yield intermediate outcomes, moderating the financial burden on households while still distributing some costs to the business sector.

Figure 8.2 illustrates the projected demand and price for tap water in the business sector under the three baseline scenarios. While the same pricing structure is applied across the business sector, the analysis distinguishes between agriculture and industrial sectors due to their differing price elasticities. From 2024 onward, the figure highlights the distinct trends in water demand and pricing driven by the assumptions in each scenario. A key consideration in this analysis is the price elasticity of demand. For the industrial sector, the modeling process initially assumed zero price elasticity, implying no response to price changes. However, to better evaluate the potential impacts of pricing variations, a low price elasticity of -0.1 was applied for this sector in the current analysis. This adjustment allows for a more nuanced understanding of how price increases might influence demand in the industrial sector.

Under the Constant-Cost scenario, the increase in demand within the business sector is primarily driven by economic growth. As economic activity expands, water use intensifies, particularly in industries and agriculture, resulting in increased stress on natural water resources. This scenario assumes that stable water prices fail to signal resource scarcity, potentially exacerbating unsustainable consumption patterns. While economically favorable for businesses, this scenario raises significant concerns about the long-term viability of natural water reserves, particularly in regions already experiencing water scarcity.

The High-Cost scenario introduces rising production costs, which translate into higher tap water prices. This price increase significantly impacts demand in the business sector, particularly in agriculture, where the price elasticity of demand is close to -1. The high responsiveness of agricultural demand to price changes leads to a notable reduction in water use, reflecting the sector's sensitivity to cost fluctuations. Conversely, the industrial sector, with its lower price elasticity of -0.1, exhibits only a marginal reduction in demand, indicating that industrial water use is less reactive to price changes. This scenario aligns more closely with the trends of rising water costs observed in recent years and offers a more realistic depiction of how cost increases may influence water use in the business sector. In both scenarios, regardless of water pricing, higher water demand is anticipated as long as positive economic growth persists.

In the Tax-Compensation scenario, the projected demand and price for tap water in the business sector vary depending on the compensation rate applied. The price trends depicted in Figure 2 show that as the compensation rate increases, the additional cost burden shifts progressively from households to industries. At lower compensation rates, the tap water price and demand trends align closely with those of the high-cost scenario, as industries bear minimal additional financial responsibilities for household compensation. However, as the compensation rate rises, the industrial sector absorbs a greater share of the costs, resulting in higher tap water prices and a corresponding decline in demand.

This dynamic is particularly evident in agriculture, where higher water prices significantly reduce demand due to the sector's high price elasticity. For industries, the impact is less pronounced but still noticeable as compensation rates increase. These findings underscore the trade-offs inherent in cost redistribution policies. while shifting costs to businesses may protect household affordability, it can also place greater financial strain on key economic sectors, potentially influencing production and broader economic growth.

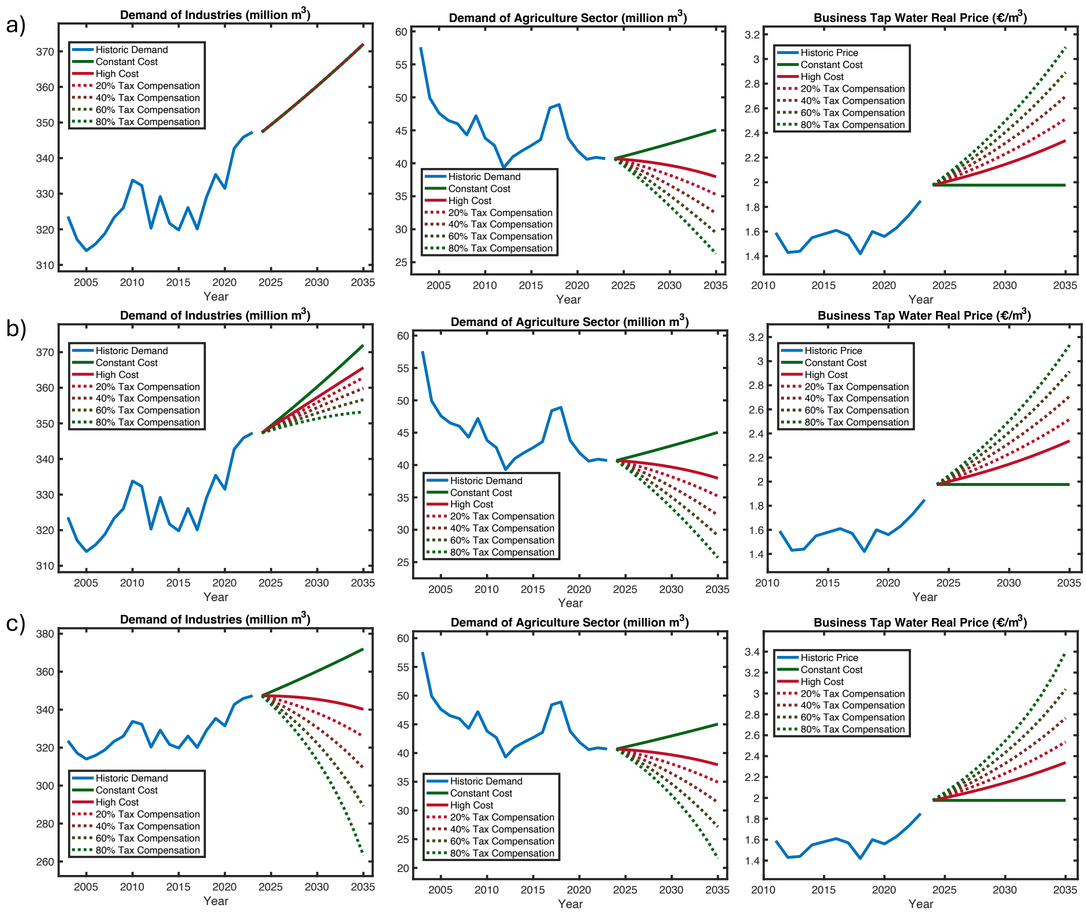


Figure 8.3: Projected demand and price for industrial and agriculture sector for industrial price elasticity of a)$\beta_{ind} = 0$ b)$\beta_{ind} = -0.1$ c)$\beta_{ind} = -0.5$

Limitations of the Tax Compensation Policy: *The success of a tax compensation scenario depends heavily on the price sensitivity of business users. It can only be effective if businesses do not react to higher prices. However, in reality, businesses will become sensitive at some point, making it unrealistic to sustain the policy, ultimately leading to its collapse.*

8.2. Tax Compensation: Effect of Elasticity

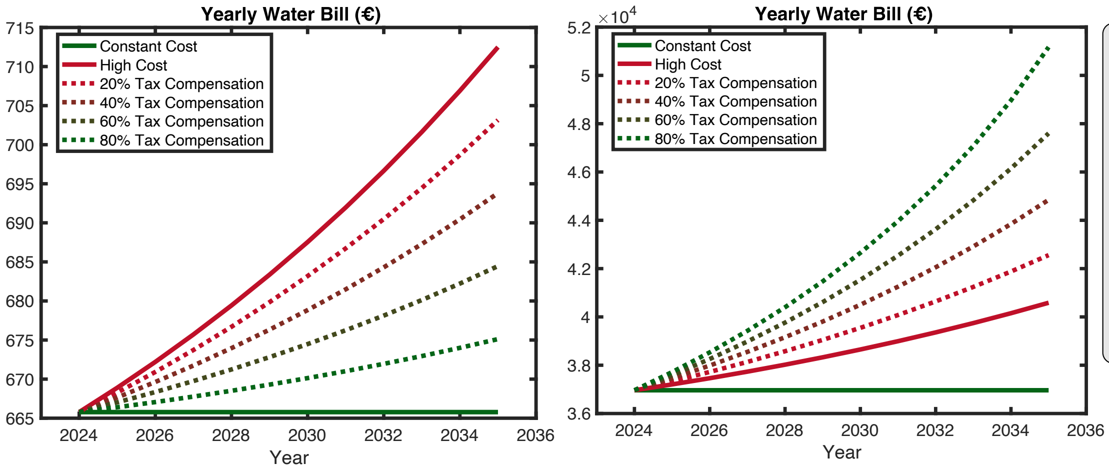
As mentioned in the previous section, cost redistribution policies involve a trade-off between protecting household affordability and imposing additional financial burdens on the economic sector. Such policies can be effective as long as the business sector's sensitivity to price changes remains negligible, which, based on historical data, is the case within the current range of water prices. However, price elasticity is not a static value; it depends on various factors, including economic conditions and sector-specific dynamics. If costs rise significantly, price elasticity may increase, making consumers more sensitive to price changes and potentially undermining the predictions and effectiveness of a given policy.

Figure 8.3 illustrates the projected demand and price for the industrial sector under three different elasticity assumptions: 0 (no sensitivity), -0.1 (low sensitivity), and -0.5 (moderate sensitivity). These scenarios provide a framework for understanding how variations in price elasticity can influence the outcomes of a tax compensation policy.

In the tax compensation scenario, a negative feedback loop can arise. Redistributing household costs to the business sector leads to higher water prices for businesses, which in turn reduces demand in the business sector. This reduction in demand creates a shortfall in government/water companies revenue, necessitating further price increases to compensate for the lost revenue. When the relationship between price and demand is weak (low price elasticity), this feedback loop quickly stabilizes, and the policy achieves its intended goals. However, when price elasticity is higher, the feedback loop becomes more pronounced, potentially leading to policy failure.

As shown in Figure 8.3, when the industrial sector exhibits high elasticity (-0.5), its water demand decreases significantly under the tax compensation scenario. Such a dramatic reduction not only undermines the policy's effectiveness but also has broader implications for economic growth. Reduced industrial activity due to higher water costs can ripple through the economy, affecting production, employment, and overall economic performance. While cost redistribution policies can be effective in the short term, they cannot serve as a long-term solution.

In the next section, we summarize the outcomes of the potential future scenarios, highlighting the key findings from the analysis of water demand, pricing, and policy implications across different sectors.



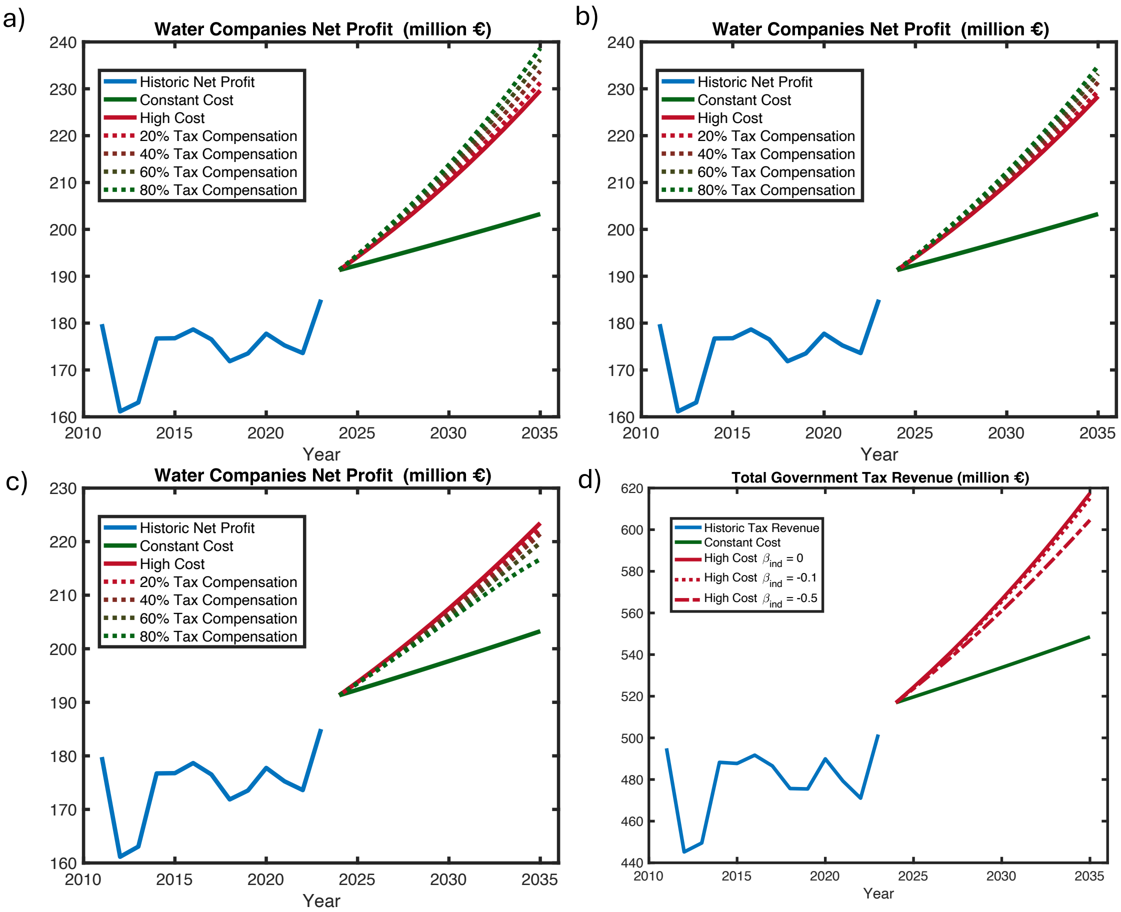
Water Bills: *In a cost redistribution scenario, household water bills fall between the best and worst cases, depending on the redistribution ratio. However, business users will face higher costs, as they also contribute to covering household water expenses.*

Figure 8.4: Yearly water bill for a) Household with tap water demand of 100 $m^3/year$ and b) Company with tap water demand of 10000 $m^3/year$ and

8.3. Stakeholder KPIs

To address the KPIs outlined in Chapter 5, Figure 8.4 illustrates the yearly water bill for a representative household and a business, assuming constant real costs for water treatment and distribution by water boards. From a consumer's financial perspective, none of the projected scenarios are favorable, as higher production costs translate into increased water bills. In the Tax Compensation scenario, the situation is even more disadvantageous for the business sector, as they not only face higher costs for their own water usage but also bear the additional financial burden of subsidizing household water bills.

Figure 8.5 depicts the total net profit of water companies and government tax revenue under different scenarios and varying levels of price elasticity in the industrial sector. Since the price elasticity of demand for all consumers is less than one, along with continued population and economic growth, the increase in water prices exceeds the reduction in demand. This dynamic leads to higher overall revenue and net profits for water companies, as well as increased tax revenue for the government. However, as the industrial sector becomes more sensitive to price (higher price elasticity), demand reductions intensify, and both tax revenue and the profits of water companies begin to decline.



Revenue and Tax: *Higher water demand driven by economic and population growth increases profits for water companies and government tax revenue. Higher prices, resulting from increased costs, further amplify this effect under existing tax and revenue schemes. A tax compensation policy does not impact overall government tax revenue but may slightly affect the profits of water companies.*

Figure 8.5: Total net profit for water companies with a)$\beta_{ind} = 0$ b)$\beta_{ind} = -0.1$ c)$\beta_{ind} = -0.5$ and d) Government tax revenue

In the Tax Compensation scenario, government tax revenue remains unaffected in net terms because the additional revenue generated is redistributed to subsidize household water prices. While this redistribution benefits households, it does not increase government revenue overall, as it merely reallocates existing funds.

It is evident that the demand for drinking water in the Netherlands is on an upward trajectory, even amid forecasts of higher production costs. These conditions indicate that water resources are likely to face increasing stress in the near future, with escalating prices reflecting both material and energy cost pressures. Furthermore, ongoing economic expansion and population growth exacerbate pollution levels in local water bodies, ultimately driving up treatment and production expenses for consumers.

Table 8.2 summarizes the key performance indicators (KPIs) for different stakeholders under the various scenarios analyzed. Refer to appendix D for the instructions on converting quantitative data to qualitative analysis.

Table 8.2: KPIs Across Different Scenarios.

Stakeholder	KPI	Constant Cost	High Cost	Tax Compensation
Environment	Fresh Water Usage	(—)	(-)	(–)
Consumer: Household	Water Bill	(++)	(–)	(+)
	Water Price	(++)	(–)	(+)
Consumer: Business	Water Bill	(+)	(-)	(–)
	Water Price	(+)	(-)	(–)
Water Companies/ Government	Profit/ Tax rate	(-+)	(-+)	(-+)

9

Model Result:Centralized Reuse policy

In this section, the outcomes of a centralized water reuse policy are presented and discussed, highlighting the economic and technical considerations influencing its feasibility. As described in Chapter 5, the effectiveness of this policy depends heavily on the cost of producing reclaimed water, which is derived from capital investment, operational expenses, and financing terms.

For the purposes of this analysis, the treatment capacity of water reuse facilities is assumed to range from 10 m^3/d to 100,000 m^3/d. These capacity bounds reflect current practice in the Netherlands.(the largest drinking water treatment plant (Berenplaat WTP) and the largest wastewater treatment plant (Harnaschpolder WWTP) each operate at around 200,000 m^3/d.) All assumed reuse plants have a 30-year operating lifetime and are financed under a 10-year loan at a 2.5% interest rate. Consequently, the cost of reclaimed water is derived by distributing the initial capital investment over annual production volumes and adding per-cubic-meter operation and maintenance (O&M) costs, explained in chapter 5.

table 9.1 summarize the parameter related cost of reuse water.

Table 9.1: Key parameters for Household, Industry, and Agriculture reuse plants

Parameter	Household	Industry	Agriculture
Capacity	10–100000 m^3/d	10–100000 m^3/d	10–10000 m^3/d
Lifetime (years)	30	30	30
Interest Rate	2.50%	2.50%	2.50%
Payback Time (yrs)	10	10	10
Number of Plants	20	10	10

In the following section, the centralized water reuse policy is introduced and evaluated. The results primarily focus on the household sector, as trends and behaviors are similar across different categories. The findings for the other two sectors are provided in Appendix A.

9.1. Centralized Water Reuse: Demand and Price

Figure 9.1a presents the total household demand for tap water, which forms the basis for determining reuse-water demand in a centralized scenario. Here, the High-Cost scenario is treated as the baseline for urban water demand and pricing, primarily because it reflects more realistic cost trends compared to the Constant-Cost scenario. Additionally, it is assumed that reuse facilities are in place to produce potable water from low-quality wastewater(LQWW-HQW). In the figure, the lines corresponding to Constant-Cost and High-Cost scenarios affect the baseline for urban water demand, and thus shape the overall demand observed.

The blue lines in this first figure depict varying capacities of water reuse plants, reflecting the assumption that a total of 20 reuse facilities will be constructed nationwide. Each line in the figure corresponds to a

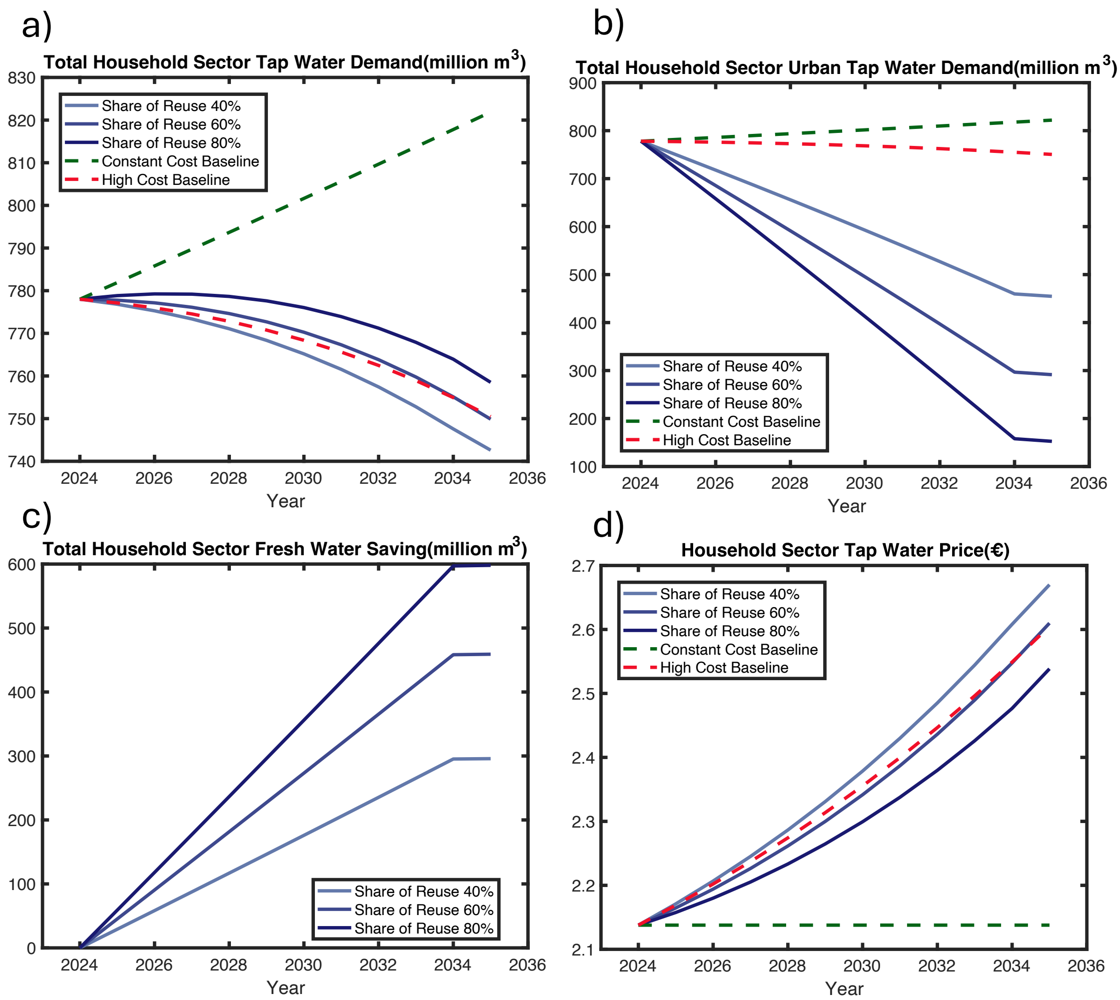


Figure 9.1: Water demand and price as a result of centralized reuse policy for household sector for reuse facilities of LQWW-HQW

particular final capacity per plant—ranging, for instance, from smaller pilot-scale installations to plants on the order of $100,000m^3/d$. The construction and commissioning process is modeled over a ten-year period, starting in 2025, with 10% of total reuse infrastructure capacity added each year (i.e., two out of the 20 plants become fully operational every year). Consequently, it is expected that by around 2035, all reuse plants will be completed. At that point, the interplay between reuse capacity and rising water prices leads to a slight reduction in total demand growth, since more reuse water becomes available and offsets some of the demand for urban (conventionally sourced) water.

The figure 9.1b represent the demand for urban water. Notably, as the capacity for water reuse increases, the proportion of demand met by reuse systems also increases, thereby reducing the volume of conventional urban water required. This effect manifests as lower urban water demand curves under higher reuse capacities.

From an environmental perspective, the third figure highlights the amount of freshwater savings attributable to reuse. As reuse plant capacities grow, more treated wastewater is diverted for non-potable or indirect potable uses (depending on the reuse strategy), diminishing the need to withdraw raw freshwater. Consequently, scenarios with higher reuse capacity show a greater reduction in freshwater consumption, underscoring the potential environmental benefits of large-scale adoption.

Finally, the social dimension of water reuse is reflected in water price changes, shown in the fourth figure. While higher reuse capacities help drive down the final price of tap water (since conventional supply pressures lessen), the effect remains negligible for small-scale reuse plants—specifically those with capacities below approximately $1{,}000\,\mathrm{m}^3/\mathrm{d}$. In these smaller-scale scenarios, the price of reuse water exceeds that of urban water, and thus, the projection lines closely follow the high-cost baseline. Only beyond this threshold do economies of scale in reuse infrastructure translate into noticeable reductions in water prices.

In a centralized reuse policy, the cost of reuse is a critical factor, heavily influenced by the quality of wastewater. Figure 9.2 illustrates the impact of the centralized reuse policy when considering higher-quality wastewater in the Netherlands. This higher quality consideration is more realistic in case of the Netherlands, coming from the country's high precipitation levels, which dilute contaminants. Consequently, reuse facilities require lower capital investment and reduced O&M costs.

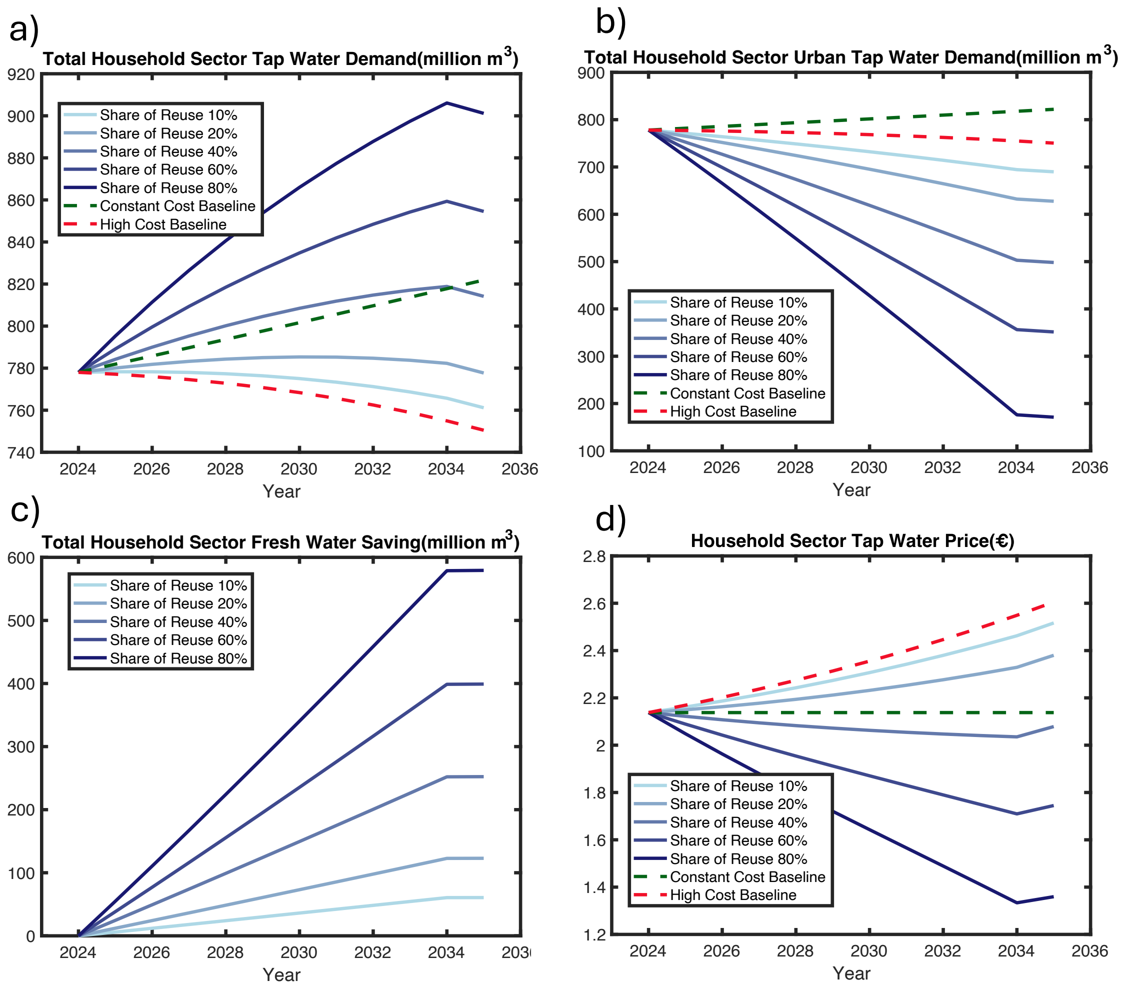
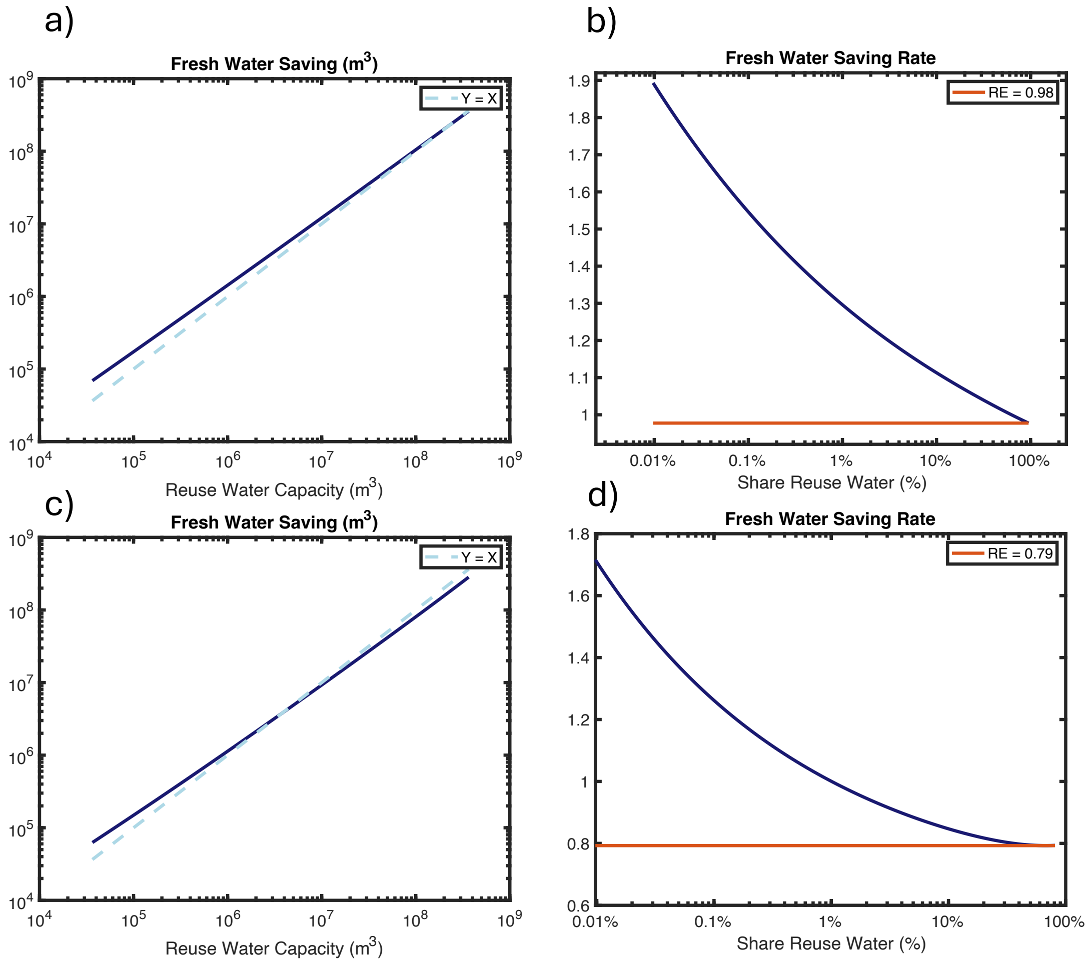


Figure 9.2: Water demand and price as a result of centralized reuse policy for household sector for reuse facilities of MQWW-HQW

Comparing the results in Figure 9.1 and Figure 9.2, it is evident that a lower cost of reuse leads to a lower final water price, which is desirable. However, this price reduction also results in higher water demand, even exceeding the demand in the constant-cost baseline scenario. Consequently, this increased demand reduces the overall savings in freshwater resources.

9.2. Centralized Water Reuse Efficiency: Rebound Effect

As previously noted, increasing the capacity of water reuse facilities tends to lower water prices, which can, in turn, stimulate demand among consumers displaying negative price elasticity. Figure9.3 illustrates both the absolute volume of freshwater conserved and the corresponding rate of freshwater savings in the household sector under discussed centralized reuse scheme. In the left panel, the total volume of saved freshwater is plotted against reuse capacity, for both wastewater qualities. A comparison with the notional $y = x$ line indicates that at lower reuse capacities, each cubic meter of reclaimed water can displace slightly more than one cubic meter of freshwater. At larger capacities, while the per-cubic-meter benefit of reuse may diminish, the overall volume of conserved freshwater still increases significantly.



Rebound Effect: *When water reuse leads to lower prices, especially at high capacities, consumers tend to increase their consumption due to greater accessibility. While scaling up reuse capacity suggests higher freshwater savings, the rate of savings diminishes, reducing the overall efficiency of the policy.*

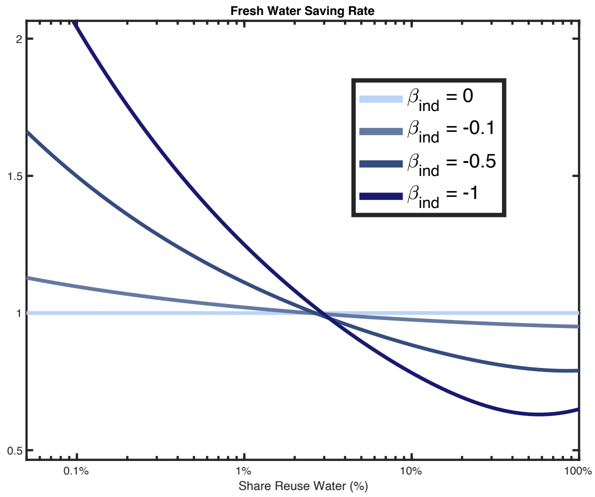
Figure 9.3: a) Fresh water saving for reuse facilities of LQWW-HQW and b) fresh water saving rate in household sector reuse facilities of LQWW-HQW c) Fresh water saving for reuse facilities of MQWW-HQW and d) fresh water saving rate in household sector reuse facilities of MQWW-HQW

In the right panel, Figure9.3 depicts how the freshwater saving rate responds to shifts in the proportion of reuse water. As this proportion grows, any concurrent rise in tap water prices tends to moderate, which can spur additional consumption and reduce incremental freshwater savings. Nevertheless, the net outcome for freshwater conservation remains positive. In other words, while the marginal benefit of adding reuse capacity declines at higher scales, large-scale reuse infrastructure continues to offer substantial contributions to sustainable water management.

Comparing the effect of reuse costs on the rebound effect, it is evident that a lower reuse price leads to a stronger rebound effect. While it is unrealistic to assume that reuse costs would be significantly lower than urban water production costs, this rebound effect negatively impacts the overall success of the policy.

Additionally, the rebound effect within a centralized reuse scheme is strongly influenced by consumers' price elasticity. Figure 9.4 illustrates freshwater savings in the industrial sector for different levels of price elasticity. As consumers become more sensitive to price changes, the rebound effect becomes more pronounced, leading to a greater increase in water demand when prices decrease.

This relationship highlights a key challenge in designing effective reuse policies. While lower reuse costs can make recycled water more attractive and accessible, they also encourage higher water consumption, potentially offsetting the intended freshwater savings. In cases where price elasticity is high, even a modest reduction in water prices can lead to a substantial increase in demand, reducing the overall effectiveness of water conservation efforts.



Price Elasticity and Rebound Effect: *Consumers who are more sensitive to price may increase their consumption when reuse lowers water costs, reducing the overall efficiency of the water reuse policy.*

Figure 9.4: Fresh water saving rate for variant industry price elasticity, the rebound effect value for β_{ind} equal to 0, -0.1,-0.5 and -1 is 1, 0.98, 0.78 and 0.63 respectively.

It is important to note that while lower-capacity reuse systems can yield higher efficiency in freshwater savings (as a fraction of the reuse volume), these modest gains often remain insufficient when set against the broad scale of tap water demand in the Netherlands. In other words, saving less than 10% of the total freshwater demand does little to alleviate systemic water stress. Therefore, the results suggest that although expanding reuse water shares can enhance overall conservation, the incremental effectiveness of each additional increase in reuse diminishes—a characteristic inherent in this policy framework.

9.3. Centralized Water Reuse: Investment

Figure9.5 illustrates both the proportion of reuse water in the overall supply mix and the corresponding volume of freshwater conserved, plotted against the initial investment required in each reuse facilities. The exponential relationship observed between the reuse share and upfront capital expenditures indicates that achieving a considerable impact on water resource sustainability through reuse necessitates large-scale facilities. Larger reuse systems benefit from economies of scale: they typically spread fixed costs—such as treatment infrastructure and distribution pipelines—over a greater volume of water, resulting in lower per-unit costs. Consequently, small-scale reuse initiatives, while potentially beneficial at a local or niche level, are unlikely to substantially reduce the broader pressure on natural freshwater resources across the country.

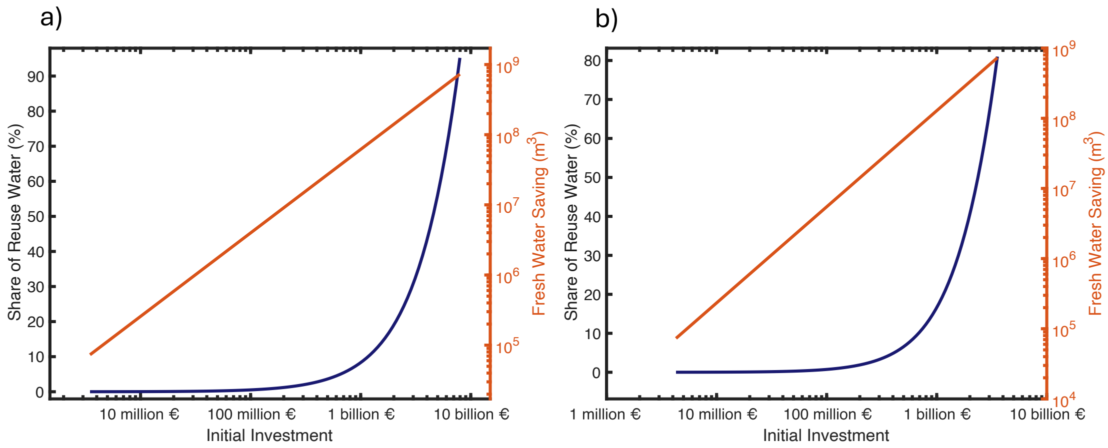


Figure 9.5: Share of reuse water and freshwater saving versus initial investment for household customer with reuse facility suitable for a)LQWW-HQW b) MQWW-HQW

Centralized Reuse as a National Project: *Centralized reuse policy is effective only at high capacities. Investing millions of euros is insufficient to achieve a significant impact—successful implementation requires a multi-billion, nationwide initiative.*

A shift toward such large-scale reuse infrastructure, however, would likely require a multibillion-euro investment at the national level. Beyond the sheer complexity of funding and implementing projects of this magnitude, the involvement of public funds is often required to ensure that costs do not fall disproportionately on local water utilities or individual consumers. Governmental or inter-agency cooperation can help secure financing, streamline project planning, and facilitate equitable cost-sharing mechanisms, thereby reducing financial risk. Yet, large public expenditures also bring intensified scrutiny. As highlighted in Chapter2, public acceptance of water reuse remains a critical hurdle to overcome, especially when reclaimed water is intended for applications as sensitive as household or agricultural supply. In a centralized approach, where reclaimed water becomes a significant component of the mainstream supply, social and political debates may arise over perceived risks, regulatory measures, and acceptable water quality standards.

9.4. Centralized Water Reuse: Cost, Technology, and Capacity

In the previous sections, the price of reuse water was assumed to depend solely on the plant's capacity. However, as discussed in Chapter 5, the cost of reuse water is also strongly influenced by the technology employed, which, in turn, is determined by the quality of the incoming wastewater. In recent years, a great deal of research has focused on improving the efficiency and affordability of water treatment processes, aiming to ensure both safety and technical feasibility while reducing costs. These technological advances have significant implications for the practical implementation of large-scale reuse schemes, as cost remains a central factor affecting policy decisions and public acceptance.

Figure 9.6 illustrates the relationship between initial investment baseline and freshwater savings per unit of investment, plotted for different plant capacities. The results highlight that lower baseline investment costs lead to more efficient freshwater savings. Specifically, a 10% reduction in baseline of initial capital expenditure can yield over a 100% increase in freshwater savings, underscoring the high sensitivity of reuse feasibility to upfront expenditures. This finding suggests that breakthroughs in treatment technology—resulting in more cost-effective water reuse plants—can substantially enhance the financial viability of reuse projects.

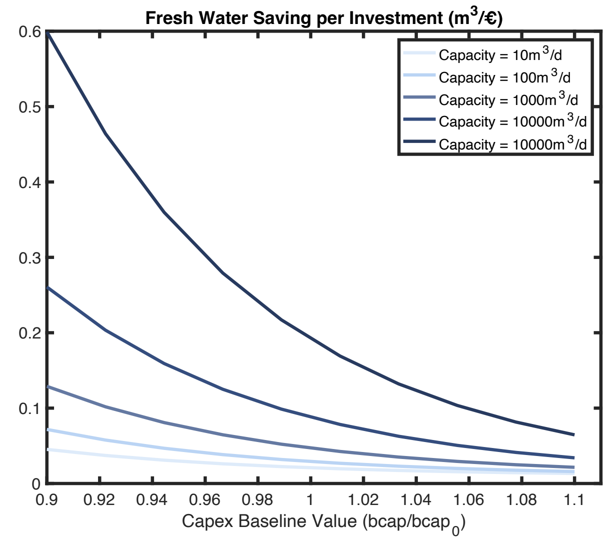


Figure 9.6: Freshwater saving per investment versus capital expenditure baseline parameter

Technology Advancement in Centralized Reuse: *The biggest challenge in water reuse is cost. Reuse-related technologies are still emerging and require further development to become more affordable. Lowering technology costs will enable greater freshwater savings.*

Beyond technological advancements, the capacity of individual reuse facilities also influences overall efficiency. Figure9.7 compares freshwater savings per unit of investment against plant capacity, assuming a total annual reuse target of 300 millionm^3. Larger-capacity plants typically benefit from economies of scale, distributing capital expenses over greater production volumes. Consequently, they achieve higher freshwater savings per unit of investment. This indicates that, within a centralized reuse framework, scaling up facility sizes—thus becoming more "centralized"—enhances economic efficiency and increases the likelihood of meeting reuse targets at a lower cost per cubic meter.

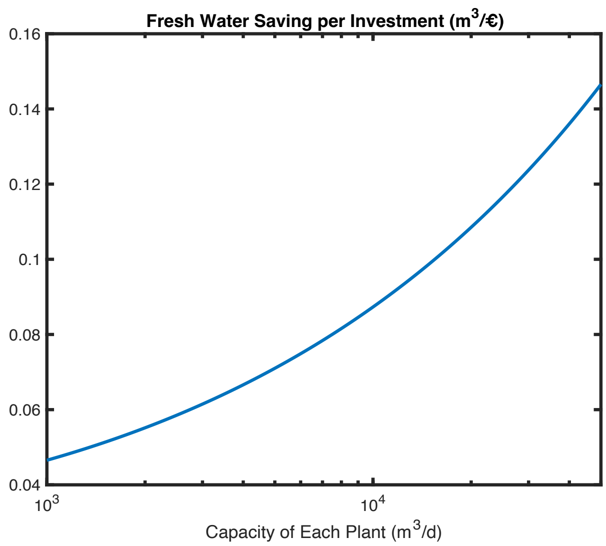


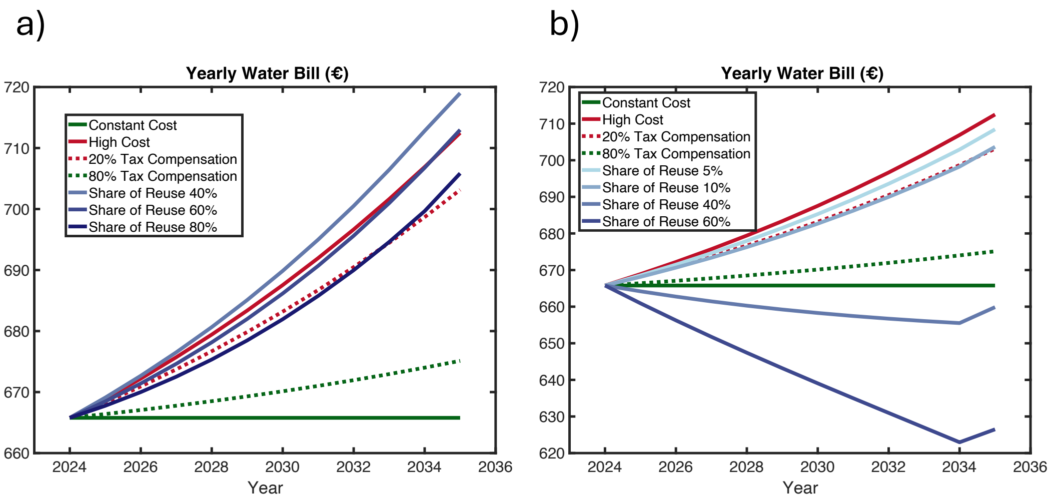
Figure 9.7: Freshwater saving per initial investment for a total capacity of 300 million $m^3/year$ versus capacity of each plant

Economy of Scale: *Centralized reuse becomes more beneficial as the system scales up. However, there is a trade-off between the cost of network piping and the advantages of a centralized reuse system.*

Taken together, these insights emphasize the importance of both technological innovation and economies of scale in designing effective centralized reuse schemes. If research continues to drive down the costs of advanced treatment processes, the economic and environmental benefits of reuse water are likely to become increasingly attainable. Moreover, adopting larger-capacity plants can further improve return on investment.

9.5. Centralized Water Reuse: Consumer Water Bill

Finally, this section presents the water bill for household consumer sector for both reuse facilities under a centralized water reuse scheme. Figure 9.8 compares the resulting water bills at various reuse share to those observed in the baseline scenarios. At lower reuse share, the water bill remains even slightly higher from the High-Cost baseline, as the same water distribution and wastewater collection systems are utilized, and the contribution of reuse to overall supply is relatively small, therefore the cost of water is higher.



Household Water Bill in Centralized Reuse: *The cost of reuse is highly dependent on wastewater quality. When wastewater has low quality, with high levels of ions and small organics, reuse can becomes more expensive for consumers at low capacities, despite its environmental benefits. However, in cases of higher wastewater quality, reuse can be financially more beneficial, even than the current situation.*

Figure 9.8: Yearly water bill in various capacities for household sector customer with reuse facility suitable for a)LQWW-HQW b) MQWW-HQW

At higher reuse capacities, economies of scale begin to exert a more noticeable influence on overall production and distribution costs, resulting in a decrease in water prices. As a result, consumer water bills decline relative to the High-Cost baseline. Importantly, these financial benefits only become substantial once reuse infrastructure reaches sufficiently large capacities to meaningfully reduce the need for conventionally sourced water. Under such conditions, households, industries, and agricultural users can realize tangible savings in their water bills, illustrating a clear incentive for scaling up centralized reuse investments.

9.6. Stakeholder KPIs

Table 9.2 summarize the stakeholders KPIs in centralized reuse policy. Refer to appendix D for the instructions on converting quantitative data to qualitative analysis.

Table 9.2: KPIs for Different Reuse Capacities

Stakeholder	KPI	Low Cap.	Moderate Cap.	High Cap.
Environment	Fresh Water Saving	(-+)	(+)	(++)
	Fresh Water Saving Rate	(++)	(+)	(-)
Consumer: Household	Water Bill	(-)	(-+)	(+)
	Water Price	(-)	(-+)	(+)
Consumer: Business	Water Bill	(-)	(-+)	(+)
	Water Price	(-)	(-+)	(+)
Water Companies / Government	Initial Investment	(-+)	(-)	(–)
	Freshwater Saving per Investment	(-)	(-+)	(+)

Summary of Findings

- **High Capacity Requirements:** A successful reuse scheme demands large-scale infrastructure to ensure a sufficiently high share of reclaimed water in the overall supply.
- **Efficiency Trade-Off:** As reuse capacity increases, water prices may decrease, but the resulting uptick in consumption can reduce net freshwater savings and thus policy efficiency.
- **Major Investment & Social Acceptance:** Implementing a multibillion-euro, nationwide reuse project demands significant public funding and broad societal support, both of which are critical for long-term success.
- **Influence of Technology Costs:** Lower-cost reuse technologies directly translate into higher freshwater savings, as they enhance the financial viability and adoption rate of reuse systems.
- **Consumer Benefits:** The principal advantage for end-users lies in lower water prices—consumers see a financial gain when large-scale reuse drives prices down.

10

Model Result:Decentralized Reuse policy

In this section, the outcomes of a decentralized water reuse policy are presented and discussed, highlighting the economic and technical considerations that influence its feasibility. As described in Chapter 5, the effectiveness of this policy is heavily shaped by the cost of producing reclaimed water, which is derived from capital investments, operational expenses, and financing terms.

For the purposes of this analysis, the treatment capacity of each water reuse facility is determined based on the total demand of a representative consumer. Specifically, we assume that this consumer requires X cubic meters of water per year and is willing to reuse R% of that total demand. For household sector, it can be assume that decentralized water reuse can happen in housing complexes or neighborhoods, therefore the capacity is determined based on number multiplied by the demand. In addition, it is possible that the water quality required for a specific purpose may be lower than the standards for potable water, or that the cost of reusing a particular type of wastewater is less than the average cost. Consequently, both capital expenditures and O&M costs for decentralized reuse systems can be lower than those assumed under the centralized scenario.

All reuse plants are assumed to have a 30-year operating lifetime and are financed under a 10-year loan at a 2.5% interest rate. The cost of reclaimed water is thus calculated by distributing the initial capital investment over annual production volumes and incorporating the per-cubic-meter operation and maintenance (O&M) expenses, as detailed in Chapter 5.

As the consumer reuses its wastewater, the volume of wastewater discharged into the wastewater treatment system decreases. To incentivize water reuse, it is assumed that the waterboard offers a discount on wastewater collection and treatment costs for consumers who implement reuse systems.

Table 10.1 summarizes the key parameters related to the cost of reuse water in this decentralized context.

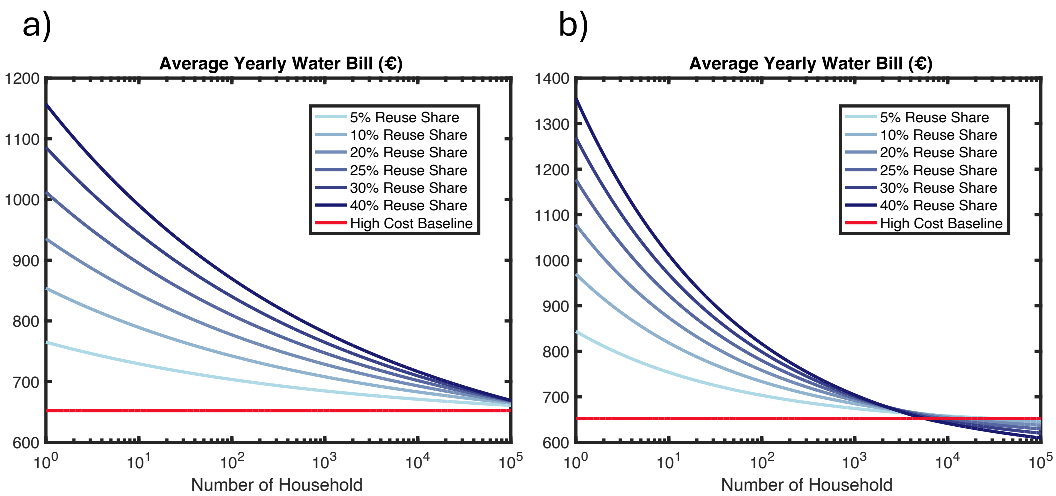
Table 10.1: Parameters for Decentralized Reuse Plants

Parameter	Household	Business
Capacity (m^3/year)	#Household * 100	1000–1,000,000
Share of Reuse (%)	10-40	10-60
WWTC discount (%)	5-30	5–30
Cost of Reuse Water (%)	50-100	50–100
Lifetime (years)	30	30
Interest Rate (%)	2.50	2.50
Payback Time (years)	10	10
Number of Plants	1	1

In the subsequent section, the decentralized water reuse policy is presented and evaluated. The results primarily focus on the household sector, as trends and behaviors are similar across different categories. The findings for the other two sectors are provided in Appendix B.

10.1. Decentralized Water Reuse: Water Bill

Figure 10.1 presents the projected water bill for households implementing decentralized reuse facilities to produce 50% of their drinking water. Household wastewater, commonly referred to as black water, is one of the most contaminated wastewater streams due to its high organic and biological content. Given the lowest quality of wastewater and the highest quality requirements for drinking water, Figure 10.1a demonstrates that decentralized reuse is not financially viable for individual households. Even when considering the reuse of only grey water—wastewater that excludes toilet waste—this policy remains financially unfeasible, as depicted in Figure 10.1b.

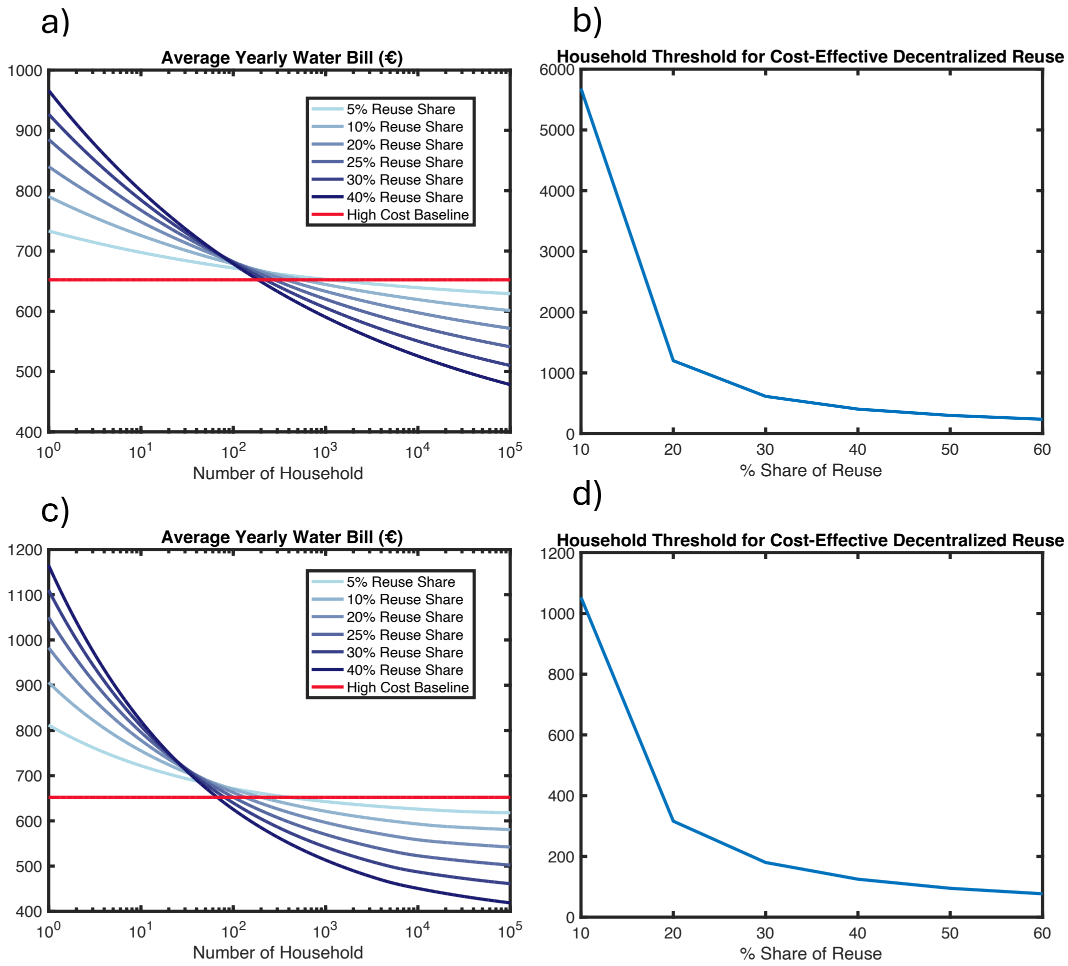


Decentralized Reuse without Supporting Policy: *Without a reuse-supporting policy, decentralized reuse is not financially viable due to the lack of economies of scale.*

Figure 10.1: Average yearly water bill for a single household implementing a reuse facility to reclaim different share of water consumption: a) LQWW-HQW facilities and b) MQWW-HQW facilities.

While individual household-level reuse systems are financially impractical due to high fixed costs, decentralized water reuse at the housing complex level offers a more viable alternative. Housing complexes can leverage economies of scale, significantly reducing the per-household cost of reuse infrastructure. Moreover, financial feasibility can be further improved if water boards incentivize reuse by offering discounts on wastewater treatment costs (WWTC) or by implementing variable tariffs based on water consumption instead of fixed household fees.

Figure 10.2 illustrates the average yearly water bill for a single household under different levels of WWTC discounts, showing the cost-effectiveness of decentralized reuse depending on the share of reused water in a housing complex. The results indicate that applying WWTC discounts can enhance the financial viability of decentralized reuse systems. Specifically, in the case of 50% reuse, a decentralized system becomes cost-effective for housing complexes of 300 households using LQWW-HQW facilities and for complexes of 100 households using MQWW-HQW facilities. However, social acceptance remains a significant barrier to large-scale implementation.

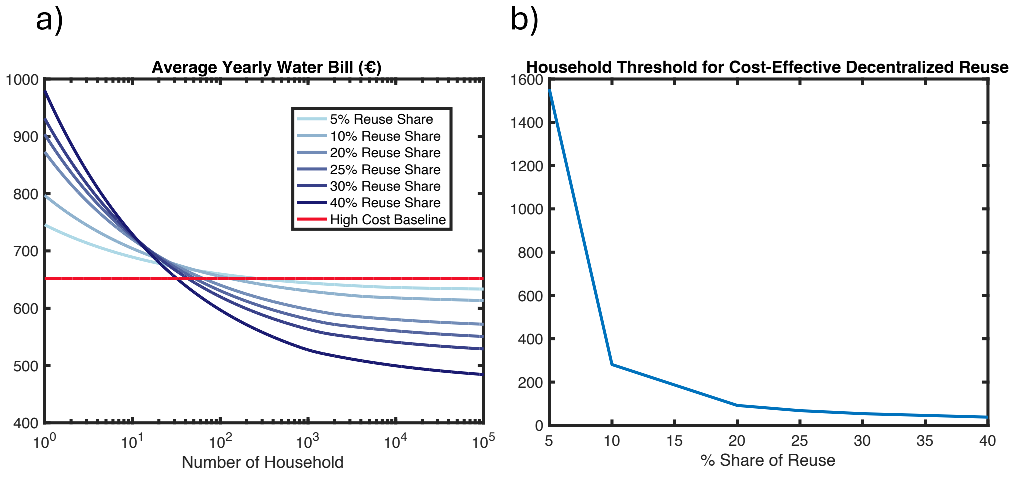


Decentralized Reuse with WWTC Discount Policy: *Coupling decentralized reuse with a WWTC discount policy from water boards makes decentralized reuse financially viable, even at the household level. While it may not be feasible for a single household, it becomes viable and even beneficial for housing complexes with more than 100–200 households. Given the Netherlands' high population growth and plans for high-density housing development, this approach is well-suited for implementation.*

Figure 10.2: Average yearly water bill for a single household and the household threshold for cost-effective decentralized reuse: a&b for LQWW-HQW and c&d for MQWW-HQW.

For the household sector, historical data suggest that despite being supplied exclusively with potable water, not all domestic water use requires high-quality drinking water. For instance, water used for laundry and toilet flushing accounts for approximately 13% and 23% of total household water consumption, respectively. Under a centralized water reuse scenario, public acceptance of reused water has been identified as a key challenge. However, it is more likely that households would accept reclaimed water for non-sensitive applications, such as laundry and toilet flushing, rather than for drinking or cooking.

Figure 10.3 illustrates the impact of reuse adoption for non-potable applications, specifically in HQWW-LQW reuse facilities, on household water bills. The results indicate that reusing more than 20% of household water is financially viable even for small housing complexes with fewer than 100 households. Moreover, for reuse shares of 40%, decentralized reuse becomes cost-effective for housing complexes as small as 40 households.



Decentralized Reuse for Low-Sensitive Applications: *Decentralized reuse is most successful in reusing greywater for low-sensitive applications. It becomes financially viable in housing complexes with more than 40 households, given the same discount on WWTC. If adopted by 10% of households in the Netherlands, it could save 20–30 million cubic meters of tap water annually—equivalent to the total tap water consumption of The Hague.*

Figure 10.3: Average yearly water bill for a single household with varying shares of reused water for non-potable applications, using HQWW-LQW reuse facilities.

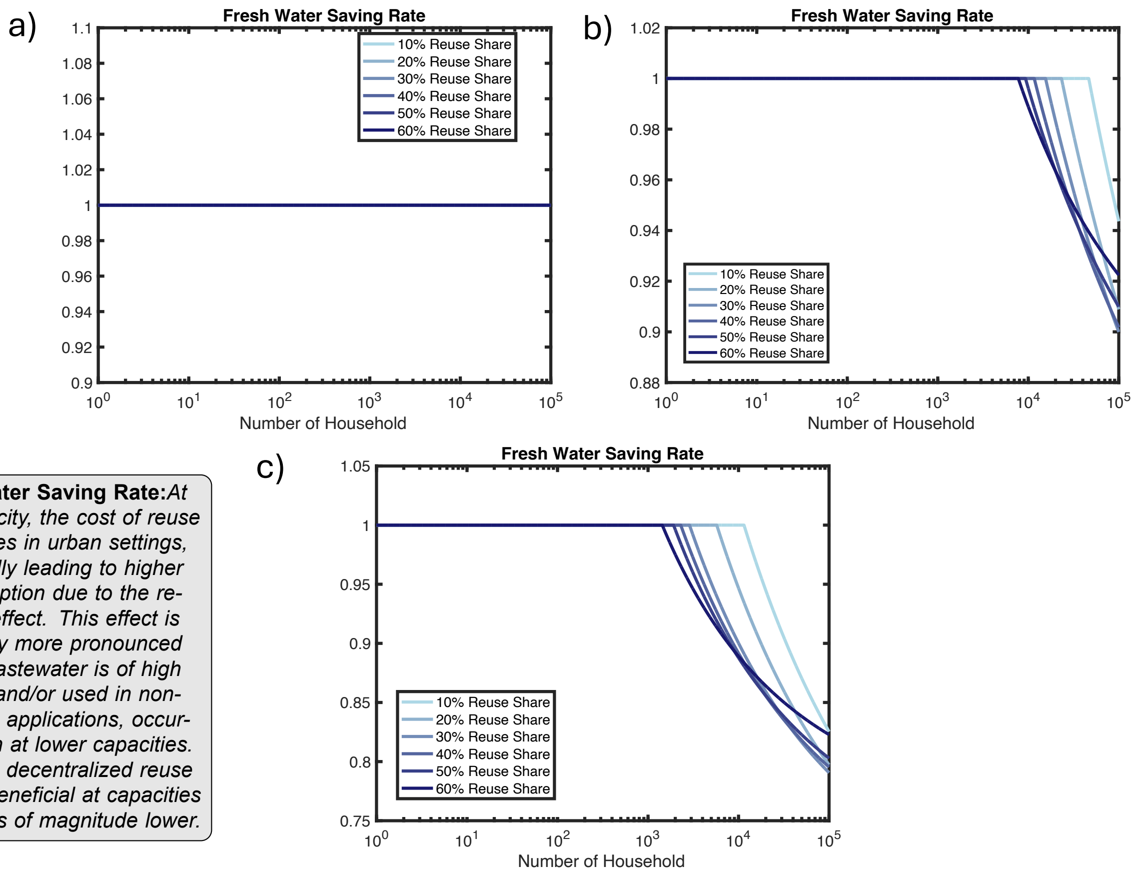
10.2. Decentralized Water Reuse: Fresh Water Saving

In terms of environmental benefits, the total amount of freshwater saved in a decentralized water reuse scheme is influenced by two primary factors: the number of households adopting reuse technologies and the share of reused water per household. Unlike centralized reuse systems, where large-scale water savings can be achieved through extensive infrastructure and widespread distribution, decentralized schemes operate at smaller scales. However, an important metric for evaluating their impact is the freshwater saving rate—the proportion of total water demand that is replaced by reused water. This metric provides insight into the relative efficiency of decentralized reuse compared to centralized approaches.

Figure 10.4 illustrates the freshwater saving rate as a function of the number of households participating in decentralized water reuse, across different reuse facility configurations.

A key observation from Figure 10.4 is that when the price of reuse water falls below the cost of conventional urban water (which occurs approximately at the capacity of 10,000 households for MQWW-HQW and HQWW-LQW facilities), the rebound effect emerges, leading to an overall increase in water demand within the household sector. This occurs because the reduced price of reuse water incentivizes greater consumption, partially offsetting the intended water savings. However, for LQWW-HQW configurations, this price parity is not reached within the examined capacity range, as reuse costs remain consistently higher than those of urban water.

Despite this rebound effect, decentralized reuse policies can still yield net benefits, even when the price of reuse water remains higher than that of urban water. One of the key drivers of financial feasibility in decentralized systems is the reduction in wastewater treatment and collection costs, which can lower household water bills even if reuse water itself is more expensive. As a result, decentralized reuse becomes economically viable at smaller scales, well before the rebound effect begins to erode its efficiency.



Freshwater Saving Rate:*At high capacity, the cost of reuse decreases in urban settings, potentially leading to higher consumption due to the rebound effect. This effect is generally more pronounced when wastewater is of high quality and/or used in non-sensitive applications, occurring even at lower capacities. However, decentralized reuse remains beneficial at capacities two orders of magnitude lower.*

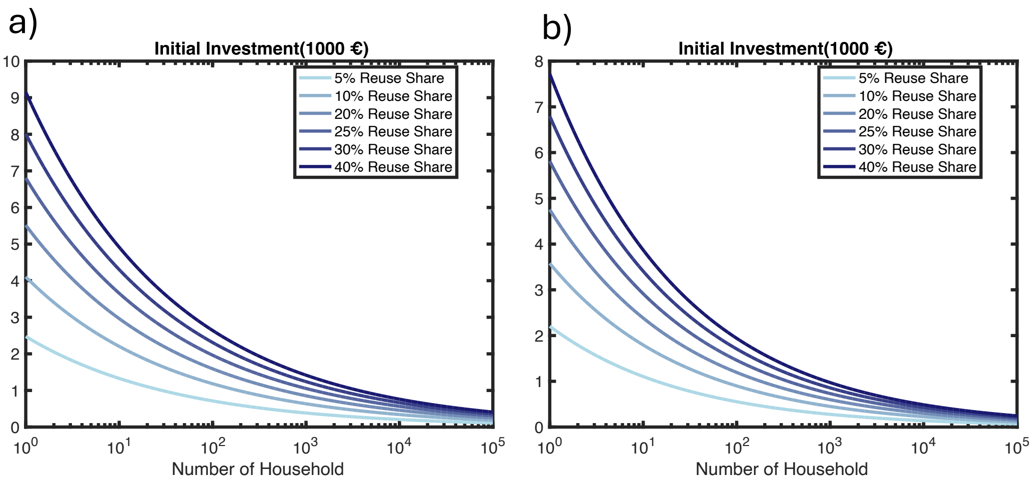
Figure 10.4: Freshwater saving rate versus capacity for reuse facilities of a)LQWW-HQW b)MQWW-HQW and c)HQWW-LQW

10.3. Decentralized Water Reuse: Initial Investment

Figure 10.5 illustrates the initial investment required for implementing water reuse facilities for both MQWW-HQW and HQWW-LQW across different reuse shares and household numbers. The figure highlights a key advantage of decentralized reuse systems: the investment costs are distributed among individual users rather than requiring a significant upfront financial commitment at a centralized level.

Notably, even for a single household, the required initial investment remains relatively low, not exceeding €10,000. This makes decentralized reuse systems an economically feasible option for both individual homeowners and larger communities.

Furthermore, the findings from Chapter 5 suggest that Dutch consumers exhibit a preference for more sustainable water management solutions. This conclusion is drawn from the observed negative correlation between water consumption and real disposable income, indicating a behavioral shift towards conservation and efficiency as income levels rise. Given this trend, decentralized water reuse systems are likely to gain traction, aligning with the increasing societal inclination toward sustainability. Their cost-effectiveness, combined with environmental benefits, positions decentralized systems as a viable and attractive alternative for enhancing water reuse in the Netherlands.



Decentralized CAPEX: *The initial cost of decentralized reuse (excluding piping modifications) is approximately €10,000 even for a single household. While costs rise with the share of reuse (capacity), it offers greater benefits in reducing WWTC.*

Figure 10.5: Initial investment for implementing decentralized reuse facilities of a) MQWW-HQW and b) HQWW-LQW

10.4. Stakeholders KPIs

table 10.2 summarize the stakeholders KPIs in decentralized reuse policy. Refer to appendix D for the instructions on converting quantitative data to qualitative analysis.

Table 10.2: KPIs for Decentralized Water Reuse Scenarios

Stakeholder	KPI	Reuse for Potable Water	Application-Based Reuse
Environment	Fresh water saving	(++)	(+)
	Fresh water saving rate	(+)	(+)
Low Demand Consumer	Water Bill	(-)	(+)
	Initial investment	(-)	(-+)
High Demand Consumer	Water Bill	(+)	(++)
	Initial investment	(-)	(-+)

Summary of Findings

- **Price Sensitivity and Financial Viability:** The success of decentralized reuse schemes is highly dependent on the cost of reuse. Reusing water for low-quality applications, such as toilet flushing or laundry, or reusing high-quality wastewater (e.g., greywater) for less demanding purposes can be financially viable, as these scenarios reduce the cost of treatment.
- **Role of Waterboards:** The waterboard's tariff structure for wastewater treatment and collection plays a critical role in enabling decentralized reuse. Incentive mechanisms, such as discounts on WWTC costs for reuse consumers and higher tariffs for non-reuse consumers, can effectively encourage adoption and make decentralized reuse more feasible.
- **Policy Efficiency:** Decentralized reuse policies are inherently more efficient than centralized ones because they do not directly affect the price of urban water. This minimizes the rebound effect, maintaining a balance between water conservation and demand.
- **Social Acceptance:** Decentralized reuse is more socially acceptable when applied to less sensitive applications. For potable water reuse, the system's voluntary nature ensures that only consumers willing to adopt reuse are involved, reducing societal resistance.
- **Distributed Investment and Financial Benefits:** In decentralized reuse schemes, the investment cost is distributed among individual consumers or smaller communities, making it possible to implement on a smaller scale. This also has the potential to provide financial benefits to participants by lowering their overall water bills, further incentivizing adoption.

Part IV

Discussion

11
Discussion

This chapter presents a discussion of the research approach and the findings of this study. In section 11.1 the main implications of this study are discussed. Section 11.2 examines the strengths and limitations of the chosen approach, and Section 11.3 provides recommendations for future research.

11.1. Implication of Study

The increasing global population and expanding economic activities are placing significant pressure on freshwater resources. This growing demand, coupled with the adverse effects of climate change, has led to rising contamination and salinity levels in available water supplies, further exacerbating the risk of water scarcity. The unsustainable reliance on freshwater sources, particularly in regions with limited natural recharge, heightens societal vulnerability to climate-driven water shortages, including prolonged droughts and extreme weather events. As these challenges intensify, ensuring a stable and sufficient water supply becomes a critical concern for both environmental sustainability and economic stability.

Beyond the environmental implications, the increasing stress on freshwater resources also presents substantial economic challenges. The cost of water treatment and purification continues to rise, placing financial pressure on both consumers and industries (Chapter 4). While short-term policy interventions, such as adjusting water tariffs, can temporarily alleviate the financial burden on households, they often result in unintended economic consequences. Shifting the financial strain to industries can increase production costs, reduce competitiveness, and potentially slow down economic activity, creating a trade-off between water affordability and economic resilience (Chapter 8). These complexities highlight the necessity of integrated water management strategies that balance environmental, social, and economic considerations.

Water reuse, as a key component of the circular economy, offers tangible solutions to the growing challenges of water scarcity, environmental degradation, and economic instability. From an environmental perspective, water reuse reduces human impact on natural ecosystems by decreasing freshwater extraction, preserving natural water sources, and mitigating climate change effects. By minimizing dependency on unpredictable natural water cycles, it enhances resilience against extreme weather events such as droughts and floods. This reduced reliance on freshwater also strengthens water security, a critical pillar of sustainable societal development. Additionally, lower contamination levels in water bodies contribute to a cleaner environment, promoting biodiversity and supporting healthier ecosystems. A cleaner water supply directly benefits public health by reducing waterborne diseases, ultimately leading to a healthier population.

From an economic perspective, water reuse contributes to a more financially stable and efficient water management system. By optimizing water use and reducing treatment costs, it enhances the efficiency of both water supply and wastewater management. The recovery of valuable byproducts from wastewater—such as critical raw materials, nutrients, and energy—further strengthens the economic case for water reuse. These recovered resources can be reintegrated into industrial, agricultural, and energy production processes, supporting broader circular economy initiatives and reducing dependency on finite natural resources. In doing so, water reuse not only ensures long-term water availability but also contributes to overall resource efficiency and economic resilience.

Traditionally, it has been assumed that the costs associated with water reuse are significantly higher than those of freshwater purification. However, this study challenges that notion by demonstrating that current trends in freshwater contamination and salinity levels are causing purification costs to rise substantially. Consequently, if wastewater exhibits relatively low salinity, its reuse may, in certain scenarios, become more cost-effective than conventional purification methods. This shift in cost dynamics underscores the potential viability of wastewater reuse as a sustainable alternative to traditional freshwater sources (Chapter 5).

The implementation of water reuse strategies, however, is contingent on overcoming several critical bottlenecks. One of the primary concerns revolves around how reuse should be structured and who should bear the financial responsibility for its adoption. This study explores two distinct approaches to water reuse: centralized and decentralized systems, each presenting unique economic, social, and policy considerations. A centralized water reuse system capitalizes on economies of scale, making reuse financially viable at higher operational capacities. The findings indicate that centralized methods can be particularly beneficial when high-quality wastewater is available (chapter 9). Nevertheless, several barriers impede the widespread implementation of centralized reuse.

Social resistance presents a significant obstacle, as large-scale centralized reuse systems require broad public acceptance. Given that financial feasibility is contingent on achieving high capacity, gaining public trust and support remains a considerable challenge. Additionally, the establishment of centralized systems demands substantial initial investment. While these costs are typically incorporated into the final water price, the sheer magnitude of the required investment may deter implementation, necessitating strong government support and public funding. Another critical concern is the potential for a rebound effect, whereby lower water prices resulting from reuse could lead to increased total demand, thereby reducing the efficiency of reuse policies. The extent of this rebound effect is highly sector-dependent, with price-sensitive industries such as agriculture experiencing greater fluctuations in demand, whereas non-price-sensitive sectors remain relatively unaffected (chapter 9).

Despite these challenges, centralized reuse policies play a crucial role in promoting water reuse from the supply side by reducing the costs of reuse relative to those of urban water production. This approach proves particularly effective for consumers who are sensitive to price fluctuations.(Chapter 9)

In contrast, decentralized water reuse, while lacking the advantages of economies of scale, offers a more flexible and targeted approach. By reducing wastewater collection and treatment costs, decentralized reuse systems present viable alternatives for specific sectors.

The findings of this study reveal that decentralized water reuse can be successfully implemented at the household level, particularly in housing complexes with more than forty units. In such settings, water reuse for low-sensitivity applications, including toilet flushing, irrigation, and laundry, can be financially viable and even beneficial. Policy mechanisms could encourage adoption through incentives, such as reduced wastewater treatment costs for reuse users, or through penalties for non-adoption. Moreover, decentralized reuse presents notable advantages for industrial and agricultural sectors. Beyond reducing freshwater dependency, this approach facilitates the extraction of valuable byproducts such as fertilizers, energy, and raw materials. Additionally, decentralized systems enable the implementation of specialized technologies tailored to the contamination profiles of different wastewater sources, thereby improving efficiency and effectiveness(Chapter 10).

Unlike centralized reuse, decentralized systems encounter minimal social resistance, as participation remains voluntary. Furthermore, the financial burden of investment is distributed among individual users, making implementation more feasible at smaller scales. Another advantage of decentralized reuse is its resilience to the rebound effect. Since reuse becomes financially viable due to lower wastewater treatment costs—often enabled by policies such as discounted treatment fees from water boards—its economic feasibility is not strictly dependent on achieving a lower price than urban water. This finding highlights the potential for decentralized reuse to be adopted across diverse consumer groups, including those that are less sensitive to price variations.

While this study, along with numerous other research findings, demonstrates that water reuse supported by effective policies contributes to a more sustainable future, this transition is not without costs. Any technological advancement or system transformation requires financial investment, and water reuse is no exception. Implementing policies to support water reuse entails significant infrastructure investments, including the construction and upgrading of treatment facilities, the development of distribution networks, and the integration of advanced monitoring systems. Governments often provide financial incentives such as grants, tax credits, and low-interest loans to encourage adoption, all of which require dedicated funding.

Additionally, regulatory development plays a crucial role in ensuring the safe and efficient implementation of water reuse. Establishing legal frameworks, setting safety standards, and defining water quality guidelines demand substantial government resources, not only in terms of policy drafting but also for long-term enforcement and compliance monitoring. These efforts also impact the research and innovation sector, as strategic investments in new technologies, such as advanced filtration and energy-efficient treatment methods, become essential for optimizing reuse systems.

Furthermore, prioritizing water reuse as a key solution to water scarcity inherently means placing less emphasis on developing new water sources, such as large-scale desalination or new reservoir projects. While reuse reduces dependency on natural water cycles, it also introduces uncertainties and potential risks, including supply reliability and public acceptance. Therefore, while water reuse policies offer long-term economic and environmental benefits, their implementation requires upfront financial commitments, strategic risk management, and sustained governmental and public support.

11.2. Reflection on the Used approach

The modeling approach adopted in this study, centered on dynamic partial equilibrium (DPE), provides a structured and insightful framework for analyzing water reuse policies within the Dutch water sector. Although much of the literature such as Cagno et al., 2022 assumes a single price elasticity for the entire water sector, this model improves accuracy by segmenting customers into three distinct sectors—households, industry, and agriculture—allowing it to capture sector-specific demand dynamics and their responses to different policy scenarios. The ability to model each sector's water demand separately ensures that economic and behavioral differences among users are accounted for, which is particularly crucial given that each sector exhibits distinct price sensitivities, infrastructure needs, and regulatory constraints. Household consumers, for instance, exhibit relatively inelastic demand, whereas agricultural users are more responsive to price fluctuations and regulatory incentives and industries are non-sensitive at all. This differentiation allows for a more precise assessment of how water reuse strategies impact each segment and, by extension, the entire water economy.

A major strength of the approach lies in its capacity to incorporate the economy of scale when modeling the cost structure of water reuse. Unlike Cagno et. al. Cagno et al., 2022 which used static cost assessments that assume constant pricing structures, the model acknowledges that the unit cost of water reuse declines as capacity increases (and vice versa), reflecting real-world operational efficiencies. Large-scale centralized reuse facilities benefit from reduced per-unit treatment, making them more economically viable compared to smaller, decentralized alternatives. This feature of the model is particularly relevant in evaluating the cost-effectiveness of different policy pathways, enabling a nuanced understanding of how scale influences financial feasibility and long-term sustainability.

Another key strength of the model is its ability to factor in external economic forces, particularly the effects of energy and material inflation on both urban water supply and water reuse costs, while most of studies such asCagno et al., 2022 considered fixed cost for urban and reused water. Given the energy-intensive nature of water treatment, rising energy prices directly influence the cost dynamics of water production and reuse. Additionally, inflationary pressures on materials such as chemicals, piping, and filtration further complicate the financial landscape for water sector investments. By embedding these macroeconomic factors into the analysis, the model ensures that its projections remain robust against economic uncertainties, providing policymakers with a resilient tool for scenario planning.

However, while the DPE model excels in economic analysis, its limitations must be acknowledged. The approach primarily focuses on economic interactions and pricing mechanisms, making it less suitable for capturing the intricate social and behavioral dynamics associated with water reuse adoption. Public perception, institutional inertia, and policy compliance are critical factors that influence the success of water reuse programs, yet these elements are only indirectly considered in the economic modeling framework. Unlike agent-based models (ABM), which can simulate individual decision-making behaviors, the DPE model relies on aggregate economic relationships, limiting its ability to predict adoption barriers at a granular level.

Most of the equations in this study are derived from historical data. While the relationships and parameters used are statistically significant, the limited number of observations—primarily due to restricted data availability—introduces a degree of inaccuracy in the dynamic modeling process. This constraint affects the robustness of certain estimations and may limit the model's ability to fully capture long-term trends and emerging patterns in water demand and reuse adoption. Expanding the dataset through improved data collection and integration of real-time monitoring systems could enhance the accuracy and predictive capabilities of the model.

Given the impact of technological advancements, the DPE model has limitations in accurately predicting long-term future trends. Innovations in water treatment and reuse technologies can significantly influence the costs associated with both urban water supply and wastewater reuse. As treatment efficiency improves and operational costs decrease, the economic feasibility of reuse systems may shift, which the current model does not fully capture. Incorporating technology-driven cost reductions and future advancements into the modeling framework would enhance its ability to provide more accurate long-term projections.

Additionally, while the model effectively simulates price and demand interactions, it does not optimize policy incentives in the way that multi-criteria decision analysis (MCDA) or computable general equilibrium (CGE) models might. Financial incentives such as subsidies, tax breaks, and pricing structures are integral to encouraging water reuse adoption, yet their detailed mechanisms are not explicitly incorporated into the equilibrium framework. As a result, while the model provides a strong basis for assessing the feasibility of water reuse policies, further refinement—such as integrating a financial optimization layer—could enhance its applicability for policy formulation.

Another notable limitation is the lack of regional and local considerations in the modeling approach. While the model effectively captures macroeconomic trends and sector-wide interactions, it does not explicitly account for local variations in water policies, infrastructure constraints, or geographic differences in water availability. These factors can play a significant role in determining the feasibility and efficiency of water reuse strategies, especially in a country like the Netherlands, where regional disparities in water management practices exist. Future research could benefit from incorporating geospatial modeling or regionalized economic assessments to enhance the precision of policy recommendations.

Despite these limitations, the dynamic partial equilibrium approach remains a powerful tool for evaluating the economic sustainability of water reuse policies. Its capacity to model sector-specific demand relationships, incorporate economies of scale, and adjust for inflationary pressures provides a realistic and adaptable framework for decision-makers. By complementing this approach with additional methodologies that capture behavioral, regulatory, and regional dynamics, future research can further refine the model's predictive capabilities and strengthen its policy relevance. Ultimately, the findings of this study contribute to a deeper understanding of how water reuse can be strategically integrated into the Dutch water sector, fostering a more resilient and circular water economy.

11.3. Further Research Avenue

Many aspects of this study can be refined through further research. First, relaxing some of the key uncertainty in this study could provide valuable extensions to the model. One critical concern is the uncertainty in the cost of water reuse. Future research could explore this aspect in more depth by incorporating dynamic pricing mechanisms that account for fluctuations in energy costs, material inflation, and economic growth. A more flexible cost model would allow for a better understanding of how these factors interact and influence the feasibility of water reuse strategies over time.

Another key area for refinement lies in the modeling of water demand. While this study has separately examined demand in household, industrial, and agricultural sectors, introducing more complex demand function could provide a more realistic representation of consumer behavior. This enhancement would enable a more detailed understanding of how changes in relevant parameter affect water demand, offering insights into potential shifts in water consumption patterns under varying policy conditions.

Further research could also expand the spatial granularity of the analysis by incorporating regional and local variations. The current study primarily examines macroeconomic trends, yet water reuse feasibility is highly dependent on geographic factors such as infrastructure availability, local regulations, and water scarcity levels. A more detailed regional analysis could provide policymakers with tailored recommendations that consider location-specific constraints and opportunities.

In addition, technological advancements in water treatment and recovery should be more dynamically integrated into future models. As innovations in filtration, desalination, and energy-efficient treatment continue to evolve, techno-economic modeling could provide valuable insights into how these technologies affect cost structures and operational efficiencies. A forward-looking approach would help policymakers and industry stakeholders assess the long-term sustainability of different reuse strategies.

Beyond economic and technological considerations, incorporating behavioral and institutional factors could further enhance the model's applicability. Public perception and regulatory acceptance are critical determinants of water reuse adoption, yet these elements are only indirectly addressed in this study. Future research could employ agent-based modeling (ABM) or survey-based methods to examine how consumer attitudes, governance frameworks, and institutional incentives shape the success of water reuse initiatives.

Finally, additional sensitivity analyses could further refine the findings of this study. Expanding the range of tested parameters and policy scenarios could reveal which factors most significantly impact the effectiveness of reuse strategies. A deeper exploration of policy combinations could also provide more comprehensive insights into how different interventions interact, potentially uncovering synergies or unintended consequences that might not be apparent when policies are analyzed in isolation.

By addressing these areas, future research can build upon the foundation established in this study, enhancing both the precision and policy relevance of water reuse modeling. A more comprehensive approach that integrates economic, technological, behavioral, and spatial dimensions will help ensure that water reuse strategies are not only theoretically viable but also practically implementable within diverse regulatory and economic landscapes.

12 Conclusion

In this chapter the conclusions of this study are presented. In the first two sections the sub-research questions and the main research question are revisited. In the third and fourth section the societal and scientific contributions are discussed and in the fifth and final section, recommendation for policy makers are suggested.

12.1. Revisiting Sub-Research Questions

The first sub-research question of this study is:

Sub-Research Question 1

”How can the interactions and behaviors of actors within the water system, as well as the financial aspects of water reuse, be formulated based on established policies and organizational frameworks?”

To address this sub-research question, a comprehensive investigation was conducted to understand the intricate interactions between various stakeholders in the Dutch water sector. This research involved analyzing the roles and behaviors of key actors, including households, industries, and agricultural users, as well as policymakers, regulatory bodies, and water utilities. The study mapped out the decision-making processes and dependencies among these agents, revealing how policy interventions and economic mechanisms influence water demand and allocation.

One of the key challenges in this analysis was the complexity of the Dutch water tariff system, which varies across sectors and regions. To make this system more analytically tractable, the diverse pricing structures were consolidated into a single price index, allowing for a more streamlined and consistent modeling approach. This index captures the essential financial dynamics of water use while enabling comparative analysis across different user categories.

Finally, historical data on water consumption patterns were gathered and systematically analyzed to derive demand functions for each customer segment and water type. These demand functions integrate critical factors such as price elasticity, income elasticity, economic growth, and environmental influences, providing a robust predictive framework for assessing the impact of policy changes and economic fluctuations in the water sector. This sub-research question has been answered in chapter 4 and 5.

Sub-Research Question 2

”How can strategies and policies be integrated into the DPE framework and implemented within computational tools such as MATLAB?”

The second sub-research question focuses on the practical implementation of the developed model.

Specifically, it addresses how the Dynamic Partial Equilibrium (DPE) model is constructed and utilized to simulate water demand, cost structures, and policy impacts within the Dutch water sector.

The DPE model is built upon the demand functions derived in the first research phase, combined with cost functions governing urban and reused water production. The cost function for urban water is based on historical data collected from the Netherlands, capturing key economic dependencies such as energy inflation, material costs, and operational expenses. In contrast, the cost function for water reuse is primarily sourced from existing literature, due to limited real-world data availability.

For implementation, the model is developed in MATLAB. The DPE model consists of multiple interlinked modules:

- Partial Equilibrium Module: This core component ensures that water demand and cost functions reach equilibrium for each modeled scenario.
- Baseline Prediction Module: Simulates water system behavior in the absence of water reuse, serving as a reference point for comparative analysis.
- Centralized Reuse Module: Models scenarios where water reuse is managed through large-scale, centrally controlled infrastructure.
- Decentralized Reuse Module: Simulates scenarios where reuse is distributed across multiple local actors, allowing for comparisons in efficiency, cost, and policy impact.

In addition to the main model, supplementary scripts have been developed for data analysis and visualization, enabling a clearer interpretation of model outputs. This sub-research question has been answered in chapter 5 and 6.

Sub-Research Question 3

"How can the impact of various strategies be measured using the model?"

To answer this question, an experimental framework has been designed to analyze the most rational strategies for facilitating the adoption of water reuse. The study defines two primary policy approaches: centralized and decentralized water reuse. Model parameters have been systematically defined, and their values have been carefully selected based on historical data and literature, ensuring a realistic representation of different policy scenarios.

Sub-Research Question 4

"How can different strategies be compared to one another using the model?"

To systematically compare the impact of various policies and strategies, key stakeholders within the water sector have been identified, along with their respective Key Performance Indicators (KPIs). These KPIs provide a quantitative framework to evaluate the effectiveness of different water reuse strategies across multiple dimensions, such as economic feasibility and environmental impact.

For each scenario, the defined KPIs are systematically measured and compared to assess the relative performance of different policy interventions. However, because certain KPIs (such as freshwater saving) vary significantly depending on the scale and implementation capacity of reuse projects, a normalized index called the Freshwater Saving Rate has been introduced. This index allows for an objective comparison of water-saving policies across different scales and scenarios, ensuring that strategies are evaluated on a proportional basis rather than absolute values.

12.2. Revisiting the Research Question

The main research question that guided the development of this study is:

Main Research Question

"How can policies and water reuse strategies, tailored to the local characteristics of water systems, be designed to make water reuse an economically viable alternative to freshwater?"

Most of the insights gained from this study are covered in the answers to the sub-research questions and can be summarized in two key points.

The first point is that both centralized and decentralized water reuse strategies can be effective in making water reuse an economically viable alternative to freshwater, but they operate through fundamentally different mechanisms. Centralized reuse benefits from economies of scale, making it cost-efficient for large-scale applications. However, it requires high initial investments, regulatory coordination, and public acceptance, which can slow down implementation. On the other hand, decentralized reuse provides flexibility and resilience by allowing local actors to implement reuse solutions tailored to their needs. However, decentralized systems face higher operational costs and require incentive structures to be financially attractive.

The second point is that financial mechanisms and pricing strategies play a crucial role in determining the feasibility of water reuse. For instance, an encourage/punishment strategy from water boards for wastewater treatment costs can be a strong driver for decentralized water reuse, even at the household level. On the other hand, introducing extra taxes or tariffs on urban water prices does not significantly affect non-sensitive consumers, such as industries, which remain less responsive to price-based incentives for adopting water reuse. The final answer to this question is that a well-balanced combination of regulatory policies, financial incentives, and tailored reuse technology is essential to ensure the economic viability of water reuse, making it a competitive and sustainable alternative to freshwater consumption.

Water scarcity and the growing imbalance between supply and demand necessitate a fundamental shift in water resource management. This study presents a framework for assessing the economic viability of water reuse strategies in the Netherlands, demonstrating that reuse approaches can serve as effective alternatives to freshwater extraction under specific conditions. By quantifying the impacts of reuse policies and identifying key barriers such as investment costs, regulatory challenges, and public perception, the findings contribute to the broader discourse on sustainable water management. Beyond the Dutch context, the insights from this study have broader implications for global water sustainability. Many regions worldwide face similar challenges due to climate change, population growth, and urbanization. This research provides a transferable framework that can be adapted to different geographical and economic contexts, offering valuable guidance for policymakers and stakeholders in water-scarce regions.

Water reuse is increasingly recognized as a key component of circular economy strategies, aligning with global sustainability initiatives such as the European Green Deal and the United Nations Sustainable Development Goals (SDGs). In particular, this research supports SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production) by demonstrating how treated wastewater can be reintegrated into economic activities, reducing reliance on freshwater sources and minimizing environmental impact. The findings underscore the urgent need to transition towards circular water management. As climate change intensifies and economic pressures escalate, inaction will exacerbate water crises and heighten vulnerabilities in both urban and rural water systems. To ensure long-term water security, collaboration among governments, industries, and research institutions is essential in developing scalable, cost-effective water reuse solutions.

12.3. Sceintific Contribution

This study contributes to the scientific debate on the economic viability of water reuse as an alternative solution for water scarcity by addressing key gaps in the understanding of financial and policy mechanisms shaping water reuse adoption. The contributions of this research can be summarized in three main points:

Firstly, it provides the most recent economic parameters of the Dutch water sector, offering an updated and data-driven foundation for modeling water demand, cost structures, and financial feasibility in the context of water reuse. This ensures that economic assessments align with current market conditions, regulatory frameworks, and price dynamics.

Secondly, it introduces a framework for incorporating external economic factors, such as inflation, economies of scale, and operational costs, into water reuse implementation. By integrating these dynamic economic dependencies, the study moves beyond static cost assessments, enabling a more realistic and adaptive evaluation of how financial fluctuations impact water reuse policies and investments over time.

Finally, the study provides insights into the economic and structural differences between centralized and decentralized water reuse strategies. This comparative analysis supports a more strategic and tailored policy approach to integrating water reuse into future water management frameworks.

12.4. Societal Contribution

This study provides insights into water reuse as a viable solution to the clean water crisis, a pressing societal challenge, particularly in regions facing growing water stress. By analyzing economic feasibility and policy mechanisms, it supports sustainable water management and promotes resource efficiency, ensuring alignment between environmental sustainability and economic practicality.

Taking a holistic approach, this study considers the environment as a primary stakeholder, emphasizing that access to clean water must be both economically viable and ecologically responsible. Additionally, it treats price as a social parameter, aiming to prevent water inequality by identifying policies that ensure fair access to water resources.

Furthermore, it acknowledges the importance of social acceptance in water reuse adoption, focusing on strategies that align with public perception. By prioritizing non-sensitive applications for water reuse, the study explores policies that enhance feasibility without compromising public trust, ensuring a realistic and effective transition toward circular water use.

12.5. Recommendation for policymakers

As the Netherlands faces de facto level 2 water shortage, policymakers are actively seeking long-term solutions to secure water availability. Water reuse presents a sustainable and viable alternative to freshwater consumption, but its success depends on policy adjustments that actively promote and incentivize its adoption. Without changes in financial mechanisms, regulatory frameworks, and public engagement strategies, water reuse will remain an underutilized resource rather than a mainstream solution.

One of the key challenges is that current policies do not support the economic feasibility of water reuse. For reuse to become viable, a fundamental policy shift is needed to integrate it into the national water management framework. This includes acknowledging reuse as a primary water source, rather than just an alternative, and implementing financial mechanisms that make it competitive with freshwater use. Additionally, long-term regulatory stability is crucial to encourage investment in water reuse infrastructure.

While centralized reuse currently faces social resistance, this should not prevent its gradual implementation. Instead of direct reuse for potable purposes, initial efforts should focus on non-sensitive applications where public acceptance is higher. Examples include groundwater recharge, which helps secure long-term freshwater availability, and using reclaimed water for heating and cooling systems in buildings and industries. These applications allow for a stepwise introduction of reuse, demonstrating its benefits and building public confidence while avoiding major societal opposition.

A key finding of this study is that incentives from the wastewater sector can be highly effective in promoting reuse adoption. Currently, wastewater tariffs for businesses are contamination-based, which has successfully encouraged high-pollutant industries to implement pre-treatment measures. However, for households, wastewater tariffs remain generalized, offering little incentive for individual reuse efforts. A more targeted approach would be to link wastewater tariffs to total water consumption, which would encourage households to reduce their wastewater output through reuse, particularly for low-sensitivity applications such as toilet flushing and irrigation. Additionally, introducing a sustainability index—similar to an energy label—that measures household water efficiency could further drive adoption, especially if it is linked to mortgage interest rates as an incentive for water-efficient home design. Moreover, a gradual increase in wastewater treatment costs combined with discounts for households and businesses that implement reuse could further encourage adoption.

Beyond economic policies, investment in research and development is necessary to support the technological and socio-economic aspects of water reuse. Policymakers should allocate grants and funding for research on water treatment technologies, ensuring that reuse solutions become more efficient and cost-effective over time. Additionally, real-time contamination monitoring is essential, as reuse lacks the natural buffers present in conventional freshwater sources. Developing online monitoring systems for water quality would enhance safety and public trust in reuse technologies, making large-scale adoption more feasible.

Overall, a combination of regulatory changes, financial incentives, and investment in research is necessary to make water reuse an economically and socially viable alternative in the Netherlands. By gradually introducing reuse through non-sensitive applications, refining wastewater tariff structures, and supporting technological advancements, policymakers can ensure that reuse becomes a key component of sustainable water management in the coming decades.

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Part V

Appendix

A

Appendix A: Results of Centralized Reuse Policy for Industry and Agriculture Sectors

This section presents and discusses the outcomes of a centralized water reuse policy that were not covered in the main text, with a focus on the economic and technical considerations influencing its feasibility, particularly in the industrial and agricultural sectors. The findings highlight sector-specific dynamics in response to water reuse policies, including demand shifts, pricing effects, and the implications for freshwater conservation.

Centralized Water Reuse: Demand and Price

A similar pattern to what was discussed in Chapter 9 is observable in both the industrial and agricultural sectors, as illustrated in Figures A.1 and A.2. These figures present the projected impacts of implementing water reuse policies, taking into account sector-specific demand characteristics and price sensitivities. The number and capacity of reuse plants in these sectors have been determined based on their baseline water demands, as summarized in Table 9.1.

Historical data indicate that the industrial sector exhibits relatively low price sensitivity for water. Consequently, even when substantial reuse capacity leads to lower water prices (as shown in Figure 9.2d), total industrial demand remains largely unchanged. This suggests that while price reductions may benefit industrial users, they do not necessarily encourage increased water consumption, thereby maintaining the intended water savings.

By contrast, agricultural water use is more sensitive to price fluctuations. In scenarios with high reuse capacity—where increased supply leads to lower water prices—agricultural demand for tap water rises, potentially undermining the effectiveness of water reuse measures. This effect, known as the rebound effect, occurs when cost savings lead to increased resource consumption, counteracting conservation efforts.

Figure A.3 further explores the interplay between reuse capacity, price elasticity, and total demand in the industrial sector. The three subfigures present total demand and freshwater savings under varying reuse capacities and different levels of price elasticity. As price elasticity increases, meaning industries become more responsive to price changes, the decline in water prices due to expanded reuse infrastructure results in higher industrial water consumption. This effect reduces the net effectiveness of reuse policies.

Additionally, price elasticity is influenced by various external factors, such as regulatory frameworks, technological advancements, and the availability of alternative water sources. If industries adapt to lower water prices by becoming more price-sensitive, the challenge of balancing reuse benefits and

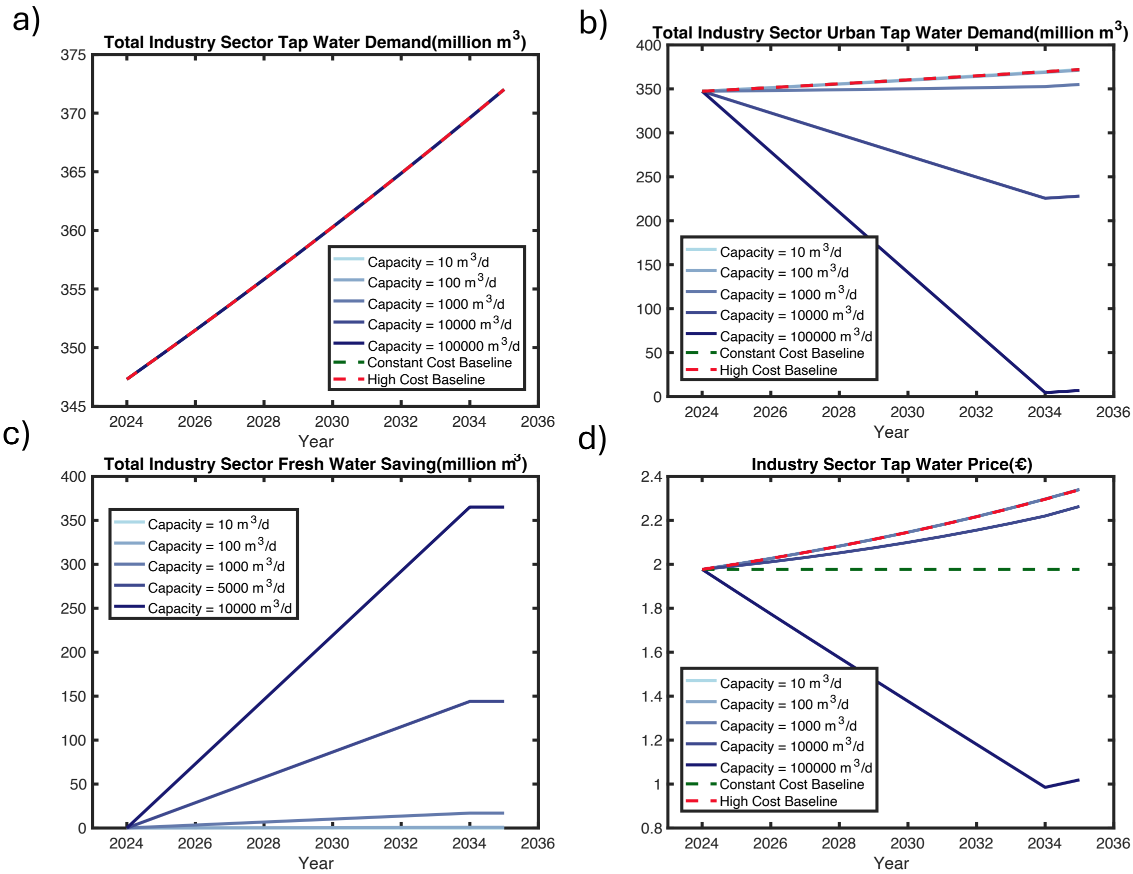

Figure A.1: Water demand and price as a result of the centralized reuse policy for the industrial sector.

overall water conservation becomes more complex.

Economic and Technical Considerations for Reuse Facilities

The feasibility and effectiveness of centralized reuse policies depend on both economic and technical factors, particularly the capital and operational costs of reuse facilities. Figure A.4 illustrates the relationship between the proportion of reuse water in the overall supply mix and the corresponding volume of freshwater conserved, plotted against the initial investment required for each reuse facility.

The exponential relationship between reuse share and upfront capital expenditures suggests that large-scale facilities are essential for significant water resource sustainability impacts. Larger reuse systems benefit from economies of scale, as they spread fixed costs—such as treatment infrastructure and distribution pipelines—over a greater volume of water, resulting in lower per-unit costs.

Consequently, small-scale reuse initiatives, while beneficial at a local or niche level, are unlikely to substantially reduce the broader pressure on natural freshwater resources across the country. This underscores the importance of strategic investment in centralized reuse infrastructure, ensuring that economies of scale can be leveraged to maximize cost efficiency and sustainability outcomes.

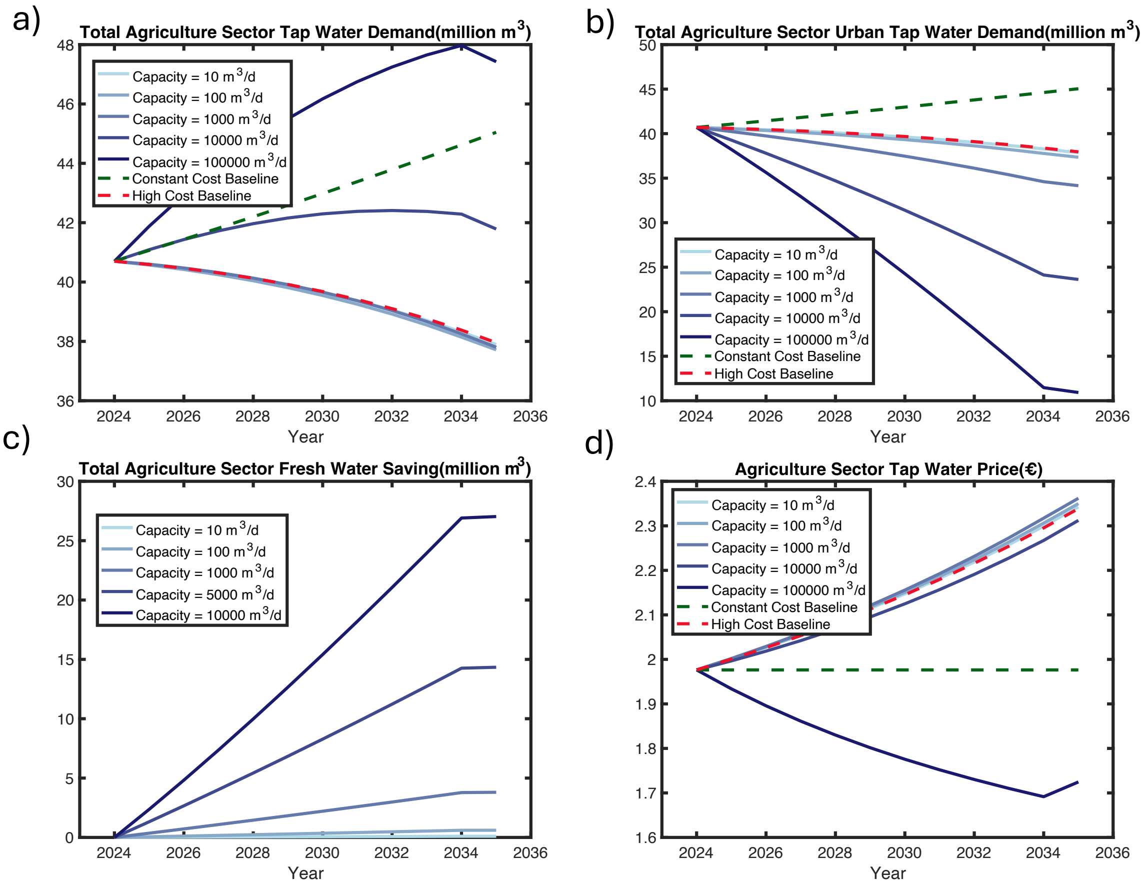

Figure A.2: Water demand and price as a result of the centralized reuse policy for the agricultural sector.

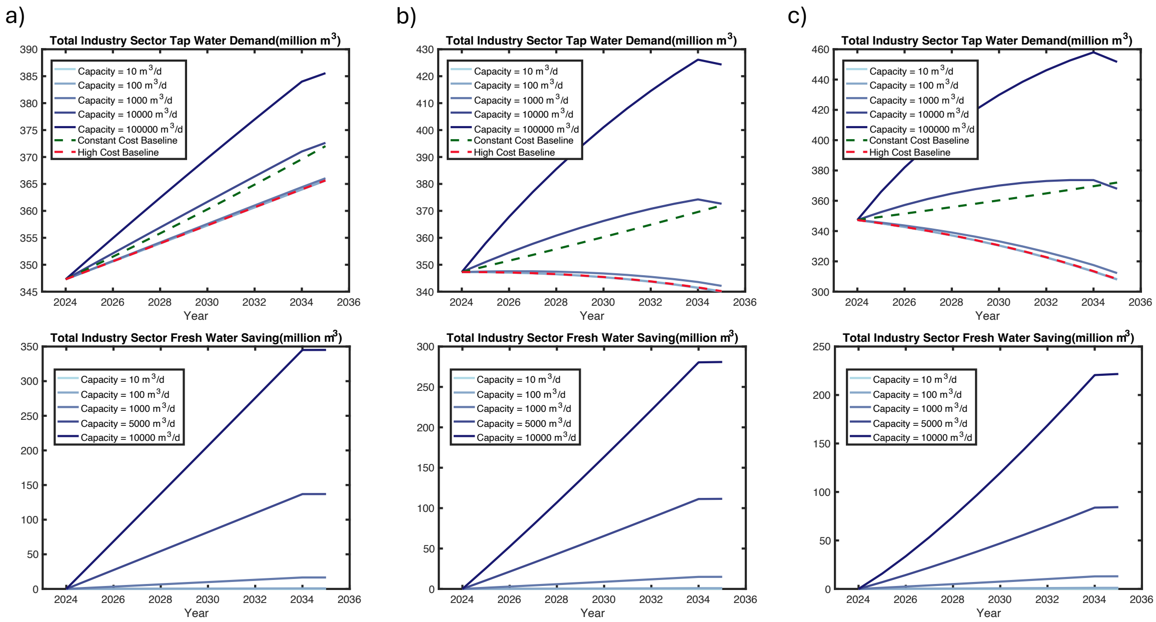

Figure A.3: Total demand and freshwater savings in the industrial sector for different price elasticity values: a) $\beta_{ind} = -0.1$, b) $\beta_{ind} = -0.5$, c) $\beta_{ind} = -1$.

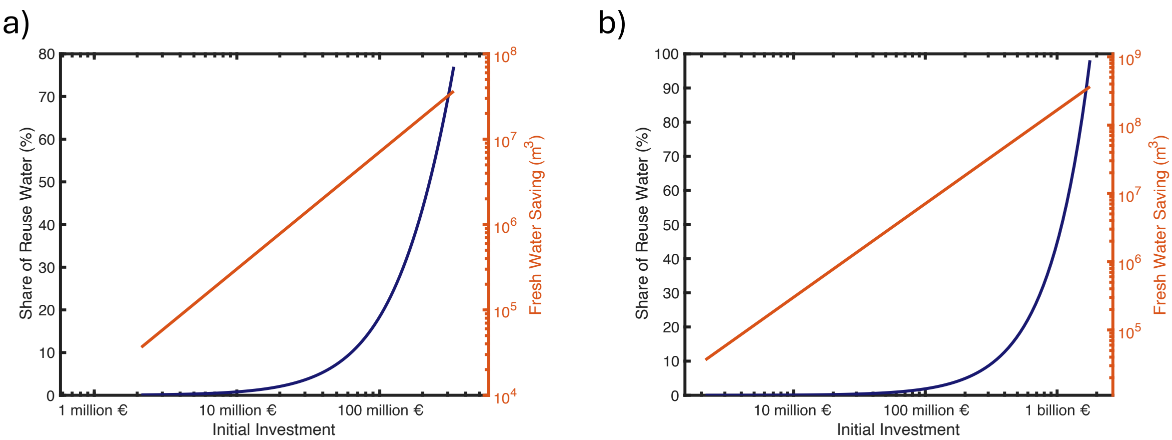

Figure A.4: Share of reuse water and freshwater saving versus initial investment for a) industry sector and b) agriculture sector customer with reuse facility suitable for MQWW-HQW

B

Appendix B: Results of Decentralized Reuse Policy for Industry and Agriculture Sectors

This section presents and discusses the outcomes of a decentralized water reuse policy that were not covered in the main text, with a focus on the economic and technical considerations influencing its feasibility, particularly in the industrial and agricultural sectors. The findings highlight sector-specific dynamics in response to water reuse policies, including the impact of water board policies on wastewater treatment and collection (WTC) costs, as well as pricing effects associated with reuse implementation.

Decentralized Water Reuse: Water Bill

Figures B.1, B.2, and B.3 illustrate the projected water bills for industrial and agricultural customers under different decentralized reuse scenarios. These figures consider three different reuse facility configurations: LQWW-HQW, MQWW-HQW, and HQWW-LQW, across various reuse shares.

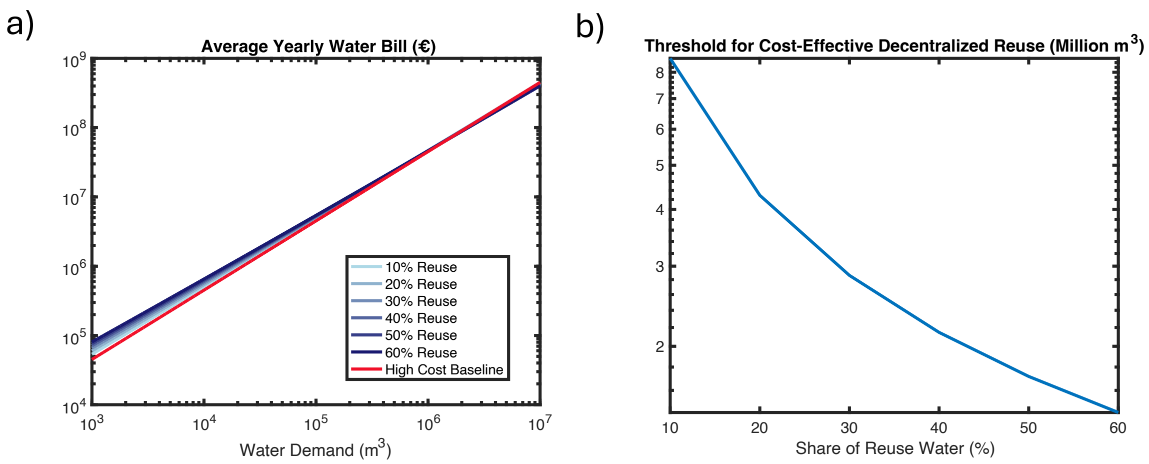

Figure B.1: Average yearly water bill for a business customer with varying shares of reused water for potable applications, using LQWW-HQW reuse facilities.

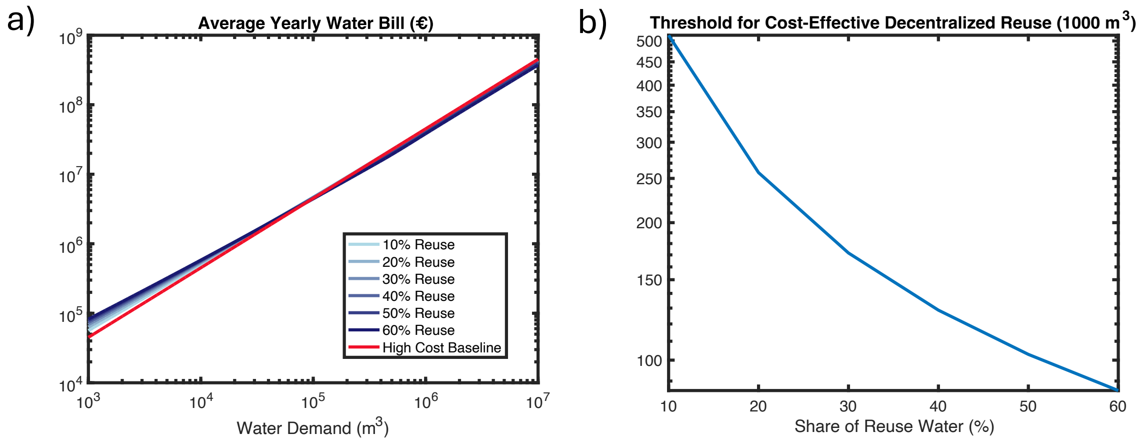

Figure B.2: Average yearly water bill for a business customer with varying shares of reused water for potable applications, using MQWW-HQW reuse facilities.

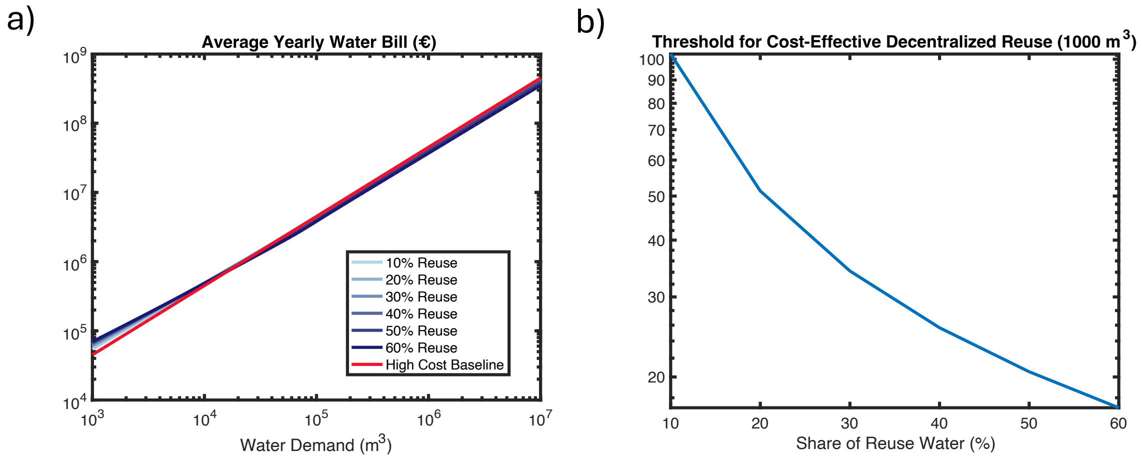

Figure B.3: Average yearly water bill for a business customer with varying shares of reused water for potable applications, using HQWW-LQW reuse facilities.

Similar to the household sector, the financial viability of reuse in the business sector improves as the share of reused water increases. Larger-scale reuse facilities reduce per-unit costs, making reuse increasingly beneficial for businesses. Moreover, businesses implementing water reuse strategies can gain additional financial advantages by utilizing byproducts from the treatment process, such as nutrients or biogas, which further enhance the economic feasibility of decentralized reuse.

Decentralized Water Reuse: Freshwater Saving

From an environmental perspective, the effectiveness of a decentralized water reuse scheme in conserving freshwater depends on two primary factors: the number of customers adopting reuse technologies and their respective reuse capacities. Given these variables, this section focuses on analyzing the freshwater saving rate—the proportion of total water demand replaced by reused water—rather than absolute freshwater savings.

Figure B.4 illustrates the freshwater saving rate for the agricultural sector as a function of implemented reuse facility capacity. In comparison to the household sector, agriculture exhibits a higher price elasticity, which leads to a more pronounced rebound effect. However, this rebound effect only becomes significant at reuse capacities much higher than those required for financial viability. Furthermore, the rebound effect is only observed in reuse facility configurations where the cost of reuse water drops below the price of urban water.

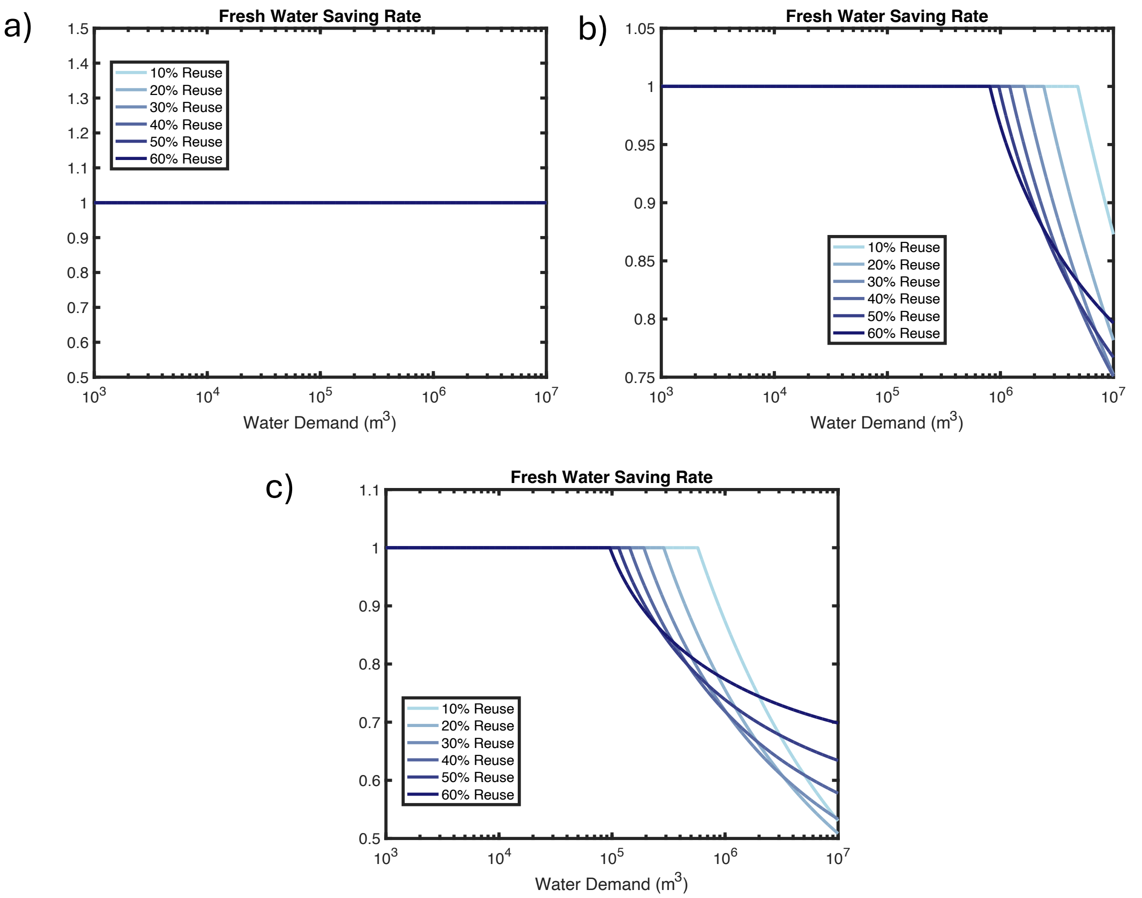

Figure B.4: Freshwater saving rate versus capacity and share of reuse facilities of a)LQWW-HQW b)MQWW-HQW and c)HQWW-LQW

C

Appendix C: Data used for Chapter 5

Demand data from CBS

Table C.1: Water Demand (million m^3)

Year	Tap Water			Ground Water	
	Household	Industries	Agriculture	Industries	Agriculture
2003	815.4	323.6	57.6	215.7	141.7
2004	796.2	317.1	49.9	216.8	55.3
2005	790.5	314.0	47.6	181.8	54.8
2006	800.7	315.9	46.5	180.1	92.0
2007	789.4	318.8	46.0	175.0	49.3
2008	788.4	323.3	44.3	173.8	51.6
2009	788.1	326.0	47.2	180.9	73.4
2010	786.2	333.8	43.8	141.1	93.2
2011	781.8	332.3	42.7	143.8	88.6
2012	783.0	320.3	39.3	139.1	46.7
2013	785.3	329.2	41.0	145.0	83.0
2014	783.3	321.7	41.9	145.1	60.8
2015	793.7	319.8	42.7	147.3	77.0
2016	805.3	326.1	43.6	147.6	56.4
2017	808.3	320.1	48.4	134.1	97.0
2018	837.2	329.0	48.9	136.3	225.3
2019	818.4	335.4	43.8	131.6	198.8
2020	855.3	331.5	41.9	113.8	214.2
2021	811.6	342.7	40.6	112.5	62.6

Tap Water Price from Vewin

Table C.2: Water Pricing and Usage Data

Year	Avg. Price HH	Total Avg. Price	Avg. Tax	Total Avg. Exc.	HH Use	B Use	B. Avg. Price	CPI	Re HH Price	Re B. Price
2011	1.50	1.56	0.21	1.35	781.8	379.9	1.041	0.79	2.17	1.59
2012	1.38	1.45	0.21	1.24	783.0	365.4	0.940	0.81	1.97	1.43
2013	1.40	1.47	0.21	1.26	785.3	374.9	0.967	0.82	1.97	1.44
2014	1.42	1.61	0.35	1.26	783.3	368.1	0.920	0.82	2.16	1.55
2015	1.40	1.61	0.35	1.26	794.0	366.2	0.957	0.82	2.12	1.58
2016	1.374	1.60	0.35	1.25	805.3	373.9	0.983	0.83	2.09	1.61
2017	1.37	1.60	0.36	1.24	808.3	372.8	0.958	0.84	2.07	1.57
2018	1.33	1.53	0.35	1.18	837.2	383.4	0.852	0.85	1.98	1.42
2019	1.29	1.59	0.40	1.19	818.4	385.7	0.978	0.86	1.96	1.60
2020	1.31	1.61	0.41	1.20	855.3	380.4	0.953	0.87	1.97	1.56
2021	1.35	1.67	0.42	1.25	811.6	390.4	1.042	0.89	1.98	1.63

Delfland Tariff

Table C.3: Water-related Property, Resident, Land, and Pollution Data

Year	Property	Resident	Land	Wastewater/Pollution
2009	0.0001612	89.84	171.7	65.06
2010	0.0001639	98.37	181.29	71.81
2011	0.0001787	105.14	177.63	78.34
2012	0.000204	113.4	147.41	85.14
2013	0.000205	116.69	205.86	89.4
2014	0.000246	113.51	180.88	92.08
2015	0.00027	116.16	183.85	94.38
2016	0.000274	117.9	179.28	94.45
2017	0.000273	119.67	180.8	93.5
2018	0.000264	121.47	176.34	93.5
2019	0.000251	123.29	178.18	93.5
2020	0.000233	123.29	178.18	93.5
2021	0.000198	123.29	178.18	93.5

Cost of Water Production from Dunea

Table C.4: Financial and Sales Data (2019-2023)

Category	2019	2020	2021	2022	2023
Cost of raw material (€1000)	3,158	3,941	3,972	4,913	6,222
Energy cost (€1000)	3,952	4,395	5,893	8,447	13,395
Subcontracted work (€1000)	8,432	9,351	10,011	9,954	11,285
Wage (€1000)	35,032	36,878	38,715	41,917	43,275
Depreciation (€1000)	31,035	30,806	30,608	31,133	32,416
Total (€1000)	130,829	135,496	134,279	132,789	149,167
Sale (1000 m^3)	73,750	76,606	75,459	74,019	73,658

Groundwater Tax from CBS

Table C.5: Ground Water Tax (2003-2021)

Year	All (€)	Agriculture (€)	Industries (€)	Water Companies (€)
2003	33,000,000.00	3,000,000.00	21,000,000.00	9,000,000.00
2004	34,000,000.00	4,000,000.00	21,000,000.00	9,000,000.00
2005	36,000,000.00	4,000,000.00	23,000,000.00	9,000,000.00
2006	35,000,000.00	4,000,000.00	22,000,000.00	9,000,000.00
2007	35,000,000.00	4,000,000.00	21,000,000.00	10,000,000.00
2008	20,000,000.00	4,000,000.00	6,000,000.00	10,000,000.00
2009	17,000,000.00	3,000,000.00	6,000,000.00	8,000,000.00
2010	15,000,000.00	3,000,000.00	5,000,000.00	7,000,000.00
2011	15,000,000.00	4,000,000.00	5,000,000.00	6,000,000.00
2012	14,000,000.00	-	6,000,000.00	8,000,000.00
2013	10,000,000.00	(1,000,000.00)	4,000,000.00	7,000,000.00
2014	22,000,000.00	1,000,000.00	9,000,000.00	12,000,000.00
2015	14,000,000.00	-	5,000,000.00	9,000,000.00
2016	20,000,000.00	-	7,000,000.00	13,000,000.00
2017	15,000,000.00	(1,000,000.00)	6,000,000.00	10,000,000.00
2018	13,000,000.00	1,000,000.00	5,000,000.00	7,000,000.00
2019	14,000,000.00	-	4,000,000.00	10,000,000.00
2020	15,000,000.00	-	4,000,000.00	11,000,000.00
2021	15,000,000.00	2,000,000.00	3,000,000.00	10,000,000.00

Level of Precipitation from CBS

Table C.6: Environmental Condition: Total Rainfall (2003-2021)

Year	Total Rain (mm per year)
2003	648
2004	910
2005	873
2006	867
2007	1,033
2008	943
2009	833
2010	901
2011	962
2012	973
2013	934
2014	952
2015	818.31
2016	784.76
2017	858.58
2018	619.89
2019	808.91
2020	777.91
2021	866.27

Economic Value from CBS

Table C.7: Economic Value (2011-2021)

Year	GDP (€)	Avg. Income (€)	Avg. Disposable Income (€)	Population	CPI
2011	675 077 000 000	54 552.00	25 600.00	16 660 000	95.74
2012	668 121 000 000	54 735.00	25 800.00	16 730 000	97.71
2013	667 252 000 000	54 898.00	25 900.00	16 780 000	98.97
2014	676 749 000 000	54 604.00	27 300.00	16 830 000	99.60
2015	690 008 000 000	55 267.00	27 100.00	16 900 000	100.00
2016	705 131 000 000	55 490.00	28 200.00	16 980 000	100.25
2017	725 657 000 000	55 096.00	29 200.00	17 080 000	101.62
2018	742 789 000 000	54 497.00	29 500.00	17 180 000	103.01
2019	757 315 000 000	54 116.00	31 600.00	17 280 000	104.64
2020	727 885 000 000	55 533.00	32 100.00	17 410 000	105.94
2021	772 954 000 000	54 754.00	33 600.00	17 480 000	108.55

D

Appendix D: Explanation of Signs and Colors in Qualitative Assessment

To effectively translate quantitative results into qualitative assessments, a structured system of signs and colors has been employed. This system ensures clarity in conveying the relative impact of different scenarios on various stakeholders. Below is a detailed explanation of the methodology used for assigning signs and colors.

Sign System

The assessment relies on a system of plus (+) and minus (-) signs to indicate positive and negative impacts, respectively.

- Positive Impact (+): Scenarios and policies that benefit a stakeholder are marked with one or more plus signs.
  - ”++” (Strong Positive Impact): The scenario significantly benefits the stakeholder.
  - ”+” (Moderate Positive Impact): The scenario has a mildly beneficial effect.
- Negative Impact (-): Scenarios and policies that impose a burden on a stakeholder are assigned one or more minus signs.
  - ”–” (Strong Negative Impact): The scenario significantly disadvantages the stakeholder.
  - ”-” (Moderate Negative Impact): The scenario has a mild negative effect.
- Neutral Impact (-+): When a scenario neither positively nor negatively affects a stakeholder, it is assigned a neutral symbol (-+).

Color System

The color coding visually reinforces the sign system to improve interpretability:

- Green Shades (Positive Impact):
  - Sharp Green: Positive impact (++).
  - Pale Green: Low positive impact (+).
- Red Shades (Negative Impact):
  - Dark Red: Strong negative impact (—).
  - Light Red: Negative impact (–).
  - Orange: Low negative impact (-)

- Yellow (Neutral Impact): Used for scenarios that do not cause a significant positive or negative effect (-+).

Application of the System – Example Case

For example for the centralized reuse scenario, a table has been compiled to translate quantitative results into a qualitative model. This analysis considers various stakeholders and their corresponding key performance indicators (KPIs), examining the impact of different water reuse capacities on each stakeholder and their respective KPIs. One of the stakeholders is environment and a KPI related to it is freshwater saving rate, meaning the amount of freshwater saved per amount of water reused.

Freshwater saving rate:

- At low reuse capacities, the impact is more pronounced since all reused water directly reduces freshwater consumption. This is represented by two plus signs (++) and a sharp green color.
- At moderate capacities, the effect is still positive but less significant, marked with a single plus sign (+) and a pale green color.
- At high capacities, a rebound effect occurs, reducing the freshwater saving rate below that of the moderate capacity scenario. As a result, the high-capacity scenario is associated with a negative impact, denoted by a minus sign (-) and an orange shade.

By employing this qualitative assessment approach, readers of this study can easily interpret the relative effects of different scenarios and policies through clear signs and intuitive color coding. This method enhances transparency while ensuring consistency with the underlying quantitative data.