Master Thesis

A water-energy nexus approach to improve the climate resilience of the city of Leeuwarden

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Before you lies the thesis, which concludes the period of studying the Master Environmental Energy Management at the University of Twente. With this thesis, I demonstrate that I can conduct a thorough Master research, in which I link my theoretical knowledge and research skills to an actual situation at the municipality of Leeuwarden. I am very grateful to the organization for the opportunity they gave me to participate in the water-savings project and happy to have developed myself in the heart of the water technology capital. In particular, I would like to thank Peter Luimstra for the assignment and support during the writing process.

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I hope that this research has contributed to accelerating the water transition in Leeuwarden.

Abstract

Decision-makers face challenges due to the increasing demand for water and energy driven by climate change and urbanization. Especially in urban water management, local decision-makers should develop strategies to adapt to more frequent and intense rainfall, saltwater intrusion, and periods of droughts. To do so, the actors should gain a better understanding of these challenges and, in doing so, improve their climate resilience. In the Netherlands, the city of Leeuwarden, a forerunner in water technology, is coping with these challenges. Although the drinking water supply in the Netherlands has proved robust during the dry summers of recent years, the future availability of sufficient, high-quality freshwater is no longer a matter of course. Therefore, the Municipality of Leeuwarden and the Vitens drinking water company have the ambition to reduce drinking water consumption by 5% in 2030 compared to 2019 and formed a partnership with key stakeholders to counter the impacts of these challenges, seeking ways to reduce the domestic water use towards increasing climate resilience and water scarcity. This calls for a methodology and comparison tool to assess the most cost-effective and appropriate strategies for Leeuwarden. In this research, an analytical framework was formed based on the literature on water-energy nexus, water governance, water security, and water-saving technologies, providing a step by step approach to comparing water-saving solutions. To incorporate all sustainability criteria, and because of its inevitable interdependence, the energy in water use is included, allowing for a nexus perspective. This research provides a technology assessment, showing insights into the criteria for comparing and selecting water-saving technologies in the current situation, and is applied to rainwater harvesting, greywater reuse and warm water reduction. A Technology Assessment Model was developed to provide structural guidance through the process of choosing alternatives. The model was applied to the city of Leeuwarden based on its water supply, use, and disposal. This research considers technological, social, economic, political, and ecological criteria, which greatly influence the water system. Several drinking water experts were involved in the research, who provided input for selecting the assessment criteria and assigning weights of importance to each criterion. The outcome is a clear prioritization based on the Analytical Hierarchy Process tool. The assessment concludes that the rainwater harvesting technology receives the highest prioritization in the current situation. It is therefore recommended for the Municipality of Leeuwarden to support the adaption of rainwater harvesting systems. Possibilities on changing the perception of the community on the value of water, incorporated in the price of water, should also be included in the water-saving project to increase awareness. Since water-saving positively influences energy use and saving energy provides an extra incentive, future projects should also incorporate energy-related objectives.

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1. Introduction

Over the previous decades, global demand and consumption for water and energy have increased drastically due to many factors such as industrialization, population increase, urbanization, and climate change, posing severe challenges at all governance levels, from local to global. It is predicted that the consumption of fresh water and energy in the world will increase by half in 2050 compared with 2015 (Ferroukhi, 2015). This will lead to massive pressure on existing water and energy systems because of the supply shortage in most countries. Furthermore, the environmental crisis triggered by excessive water and energy use is now the most prominent global risk (Waughray, 2011; Ding, 2020). Water and energy security are among the most important issues of sustainable development. More importantly, these systems mutually affect each other (Ding, 2020).

It is essential not only to mitigate climate change by increasing the use of renewable energy resources, reducing the emission of CO2, and increasing energy efficiency, but also to adapt to more intense rainfall, rising sea levels, higher river discharges, saltwater intrusion, and periods of droughts and heatwaves. These phenomena are embedded in deep uncertainty, so decision-makers should adopt strategies using an adaptive approach (Hallegatte, 2009). In such an approach, actors should better understand the climate change impacts and optimize the response to these impacts, which improves the climate resilience of a system under variable conditions (van Buuren, 2015).

Urban areas have a high population density and depend on their hinterland to supply natural resources. In addition, the high density of people and economic activities in urban areas concentrates risks (Hoekstra, 2018). Besides that, efforts to foster climate change must go hand in hand with efforts to promote urban development. It is fundamental to follow dynamics such as the growing urban population, ageing water infrastructure, and the equity of climate change effects to be able to understand the interconnections between land, development, density, and emerging profiles of risk and vulnerability (Özerol, 2020; Brown A. D., 2012; Leichenko, 2011). This puts much pressure on urban water management, but it also implies that cities have the highest potential to reduce these pressures (Koop, 2015). Nevertheless, many cities lack the capacity to cope with the more frequent climate extremes that put overwhelming pressure on urban water resources. When considering urban water security and climate change resilience, cities must withstand a broader range of shocks and stresses to be prepared for climate change (Brown A. D., 2012). Water security and climate change resilience are emerging concepts that add value to the urban water management discourse and complement the dominant integrated water resources management (IWRM) paradigm (Bakker, 2013; van Ginkel, 2018).

Even though water is abundant in some countries, it might still be a challenge to have enough freshwater of sufficient quality available for domestic use due to droughts or water pollution. As is the case Europe, which is not an arid continent and water is relatively abundant (European Commission, 2010). However, large areas face water scarcity; 17% of European river basin areas are in severe water stress, affecting at least 11% of the European population. It is forecasted that by the year 2070, 34-36% of the river basins will be facing severe water stress, further exacerbated by economic and social development (Commission of the European Communities, 2007; European Commission, 2010). Water scarcity is experienced most acute in the south but by no means limited to the Mediterranean region. In the northern regions, the overall water availability might increase but decrease during the summer leading to drought events (Bressers, 2016; Urquijo Reguera, 2016). Tackling the impacts of climate change is a particularly crucial challenge for water management, intensifying the intersectoral competition for water (Rajendra, 2015). The slowly cumulating effects of human-caused distortions foster water degradation, endangering water quality, water availability, the health of the ecosystem and biodiversity, as well as jeopardizing the delivery of ecosystem services (Patterson, 2013; Markowska, 2020).

1.1. Empirical Background

The Netherlands is located in a low-lying delta of four rivers, and therefore it has a long tradition of water management. Water management has historically been a government responsibility. The Article 21 of the Dutch Constitution states that it is the authorities' responsibility to ensure that the land is habitable and to protect and improve the environment (Wettenbank, 2021). This duty led to the formulation of water legislation and regulations aimed at reducing flood risks from the sea and rivers and adequate land drainage for agricultural purposes. The Dutch water management system is polycentric, meaning that several different government agencies are involved. The state defines the general rules and responsibilities are shared by the Ministry of Infrastructure and Water Management, the Ministry of Agriculture, Nature and Food Quality, and the Ministry of the Interior and Kingdom Relations (van Rijswick, 2012; Rijksoverheid, 2021).

Nowadays, the country faces water stress, which occurs with more frequency, intensity, and variability in river runoffs and water quality. There is sufficient annual rainfall, but in periods of drought, there are regional water shortages of tens of millions of cubic meters () (VEWIN, Unie van Waterschappen, 2021). After the extreme rainfall in the summer of 2016 in the southeast of the country, resulting in flooding, the summers of 2018 and 2019 and the spring of 2020 followed with significant water shortages for nature and agriculture, the groundwater levels dropped deeply, and watercourses became nearly dry. The drought led to water shortages and deteriorated water quality (Beleidstafel Droogte, 2019). Therefore, freshwater availability for domestic water supply must be considered. The occurrence of droughts or low-quality surface water sometimes constrains the ability to supply municipal water to households. The current forecasts show a worrying trend: the precipitation deficit has increased in recent years and is expected to grow further in the coming years. In short, water scarcity is increasing even more now that the demand for freshwater is also increasing (Gilissen, 2019). Between 1920 and 1990, the annual municipal freshwater use per capita increased from 17 m^3 to 70 m^3. If total water use increases, more energy is needed to supply freshwater, treat wastewater, and heat the water (Gerbens-Leenes, 2016). This leads to several policy-related questions, including the question of to what extent the current system of freshwater supplies is sufficient to cope with future water scarcity. Many cities have analysed water security at the regional level, although several have pointed out the lack of evaluation and implementation of water security measures. Recent studies have not captured the whole picture, and there is still no consensus on how to define and execute an evaluation of the state and dynamics of urban water security (Aboelnga, 2019).

In recent years, the province of Friesland has profiled itself firmly as a development region for companies and knowledge institutions in the water sector. Its capital, the city of Leeuwarden, is coping with challenges that arise from the pressure on urban water management. Once situated at the former

Middelsea, Leeuwarden, the capital of the province of Friesland, has been battling water for centuries. In the meantime, the city counts more than 100.000 inhabitants (Oozo.nl, 2020), and the role of the water has changed. Leeuwarden faces droughts and has to take strategic actions to maintain water security (RIZA, 2005). Since Leeuwarden bears the title ´City of Water Technology´, many experts and entrepreneurs are attracted, and numerous companies work together in the sector (Gemeenteraad Leeuwarden, 2010). The aim is to make Friesland the most promising region in the field of a sustainable circular economy by 2025 (de Graaff, 2019). New socio-economic paradigms such as the circular economy call upon better use and reuse of natural resources, including water (Romano, 2019). A balance is sought between economic, ecological, and social goals. In this way, the municipality of Leeuwarden aims to contribute to the national government's ambition to have a climate-resilient, competitive, circular delta by 2050 (Rijksoverheid, 2016; Rijksoverheid, 2021). To realise the transition, the municipality has drawn up a vision with stakeholders, such as the Friesland Circular Association, Innovation Pact Fryslân, Omrin, knowledge institutions and companies. Together they want to implement measures towards a climate-proof and resilient future (de Graaff, 2019). The municipality of Leeuwarden has indicated in its sustainability program that it wants to realize a climate-proof and climate-neutral society and thus create a sustainable and competitive economy. They aspire to be frontrunners in several topics, such as energy and water transition, circular economy, and climate adaptation. In doing so, they want to keep connecting with knowledge and innovation, economic structure enhancement, and employment opportunities, focusing on water technology, sustainability, and energy (de Graaff, 2019; Gemeente Leeuwarden, 2018). The municipality also links these actions to the UN Sustainable Development Goals (SDGs) and aims to contribute to multiple SDGs related to climate, energy, water and cities (Gemeente Leeuwarden, 2018).

The recent drought events have prioritized water scarcity, and in line with climate adaptation, the aim to become a resilient, competitive, and circular delta and to guide the energy and water transition efficiently, the Department of Economic Affairs of the municipality of Leeuwarden set up a stakeholder participation project to reduce domestic consumption (Boersma, N., Luimstra, P., Personal Communication, 2021) and enhance water security and climate resilience towards a climate-neutral society. Based on previous and ongoing water projects, the municipality aims to achieve the reduction through close collaboration with project developers, such as Bouwgroep Dijkstra Draisma, and knowledge institutions, such as the Centre of Water Technologies and Wetsus, using three water-saving technologies (Mous, 2021):

1. *Reducing warm water usage*
2. *Harvesting and reusing rainwater*
3. *Treating and reusing wastewater*

To reduce water demand on-site, there should be attempted to increase the efficiency of water use and profit of these alternate sources of water, which were considered useless before (Bazargan, 2018). This research distinguishes four types of water, i.e., blue, green, grey and black. Rainwater as alternate source, is considered green water, and can be used through rainwater harvesting technologies for collecting and storing rainwater for commercial, domestic, and industrial applications. (Alim, 2020). Rainwater harvesting is a common practice; however, it has recently regained popularity in many urban areas due to its ability to meet non-potable water demands, e.g., gardening, laundry, and car washing, and by that; reducing the use of potable water for non-potable purposes (Rahman, 2017). After analysing implemented cases in Werrington, Australia, Alim et al. (2020) conclude that rainwater harvesting is particularly good to apply in regions with drought events and steady rainfall (Alim, 2020). The other source of supply is greywater; this water has not met sources with high levels of contamination, e.g., sewage or food waste. Greywater is already used for facilities as a bath, sink or shower. By finding the proper quality of water to particular water need, this greywater can replace the drinking water in applications that do not need water of this quality, e.g., toilets and irrigation (Bazargan, 2018). In the case of bath or shower use, the water is heated and usually drained immediately, losing considerable amounts of energy. Applying systems that can reuse this heated water for purposes that require warm water will save water and increase energy efficiency. The other sources are blue water, referring to the consumed volumes of surface or groundwater, and black water, water that has been used for toilet flushing (Mekonnen M. H., 2011; Cheng, 2009; Wang, 2006)

1.2. Problem Statement

The problems of water scarcity and climate change in cities are immense, underscoring the importance of addressing governance issues that hinder adaptation (Koetsier, 2017). These challenges are often approached in a fragmented way since there is no dedicated framework for assessing the sustainability of urban water management (van Leeuwen, 2012). Existing indicator frameworks are either too general or specific to evaluate Integrated Urban Water Management (IUWM). IUWM is better approached locally, where civil society's position and expertise can be maximized (van Leeuwen, 2012).

At the local level, the municipality, as part of the collaboration, wants to reduce water use to improve climate resilience and water security. Following Adger (2005), to improve climate resilience, the degree to which this complex adaptive system is capable of self-organization should improve (Adger, 2005). To enhance water security, an integrative understanding of urban water management should be achieved (van Ginkel, 2018). The water sector trends regarding increasing demand and population growth are not due to any single entity, technology or event. These trends that emerge from the complex interconnections are called a ´system effect´. These complex sustainability issues can be tackled by system thinking (Bosscheart, 2019; Romano, 2019). Applying systems-based approaches can reduce institutional fragmentation while improving coordination and coherence across different sectors (Romano, 2019). Therefore, the water reduction goal of the municipality of Leeuwarden should be approached holistically, including the interrelations of water consumption with other sectors, in particular energy.

The water-energy nexus shows the connections between the demand for and use of energy and water, presenting strong parallels between the growing water crises and conflicts over energy sources (Mekonnen M. G.-L., 2015; Gerbens-Leenes, 2016). In the energy system, water is used for energy production, transportation, and usage. More than 90% of global electricity production facilities are dependent on water (Duan, 2017). On the other hand, activities in the water system, such as water extraction, treatment, transportation, and desalination, use much energy as well (Thiede, 2016). Given this mutual relationship, increasing energy efficiency can reduce the pressure on water resources, and improving water efficiency can lessen the consumption of energy (Li, 2019). Therefore, energy use in the water sector has received attention in the Netherlands. Several studies have considered energy use and have given an in-depth overview of Dutch households' usage. However, they have not explicitly specified the energy used for freshwater use (Gerbens-Leenes, 2016).

The research in the water-energy nexus has made significant progress in the past few years. Many modelling approaches, such as the input-output analysis, life cycle assessment, econometric analysis and other optimization models, are developed. However, as Ding et al. (2020) and Dai et al. (2018) show in extensive literature reviews, several knowledge gaps remain to be addressed. First, the studies so far mainly focus on macroscopic data, which aim to assess water-energy nexus at urban, urban-agglomeration or national levels, often involving analyses of resource availability and forecasts (Dai J. W., 2018). Second, the existing models include large-scale and uncertain data. Third, the methods to assess water governance are scarce and mostly lack an integral or scientific foundation. The information and knowledge bases are weak, providing a limited base for decision support and action (van de Meene, 2011). Therefore, the microscopic environment (including individual behaviours), such as residents, neighbourhoods, companies and sectors, should be investigated. Emerging technologies and methodologies should be studied to analyse multilevel data and dynamic large-scale data for analytic models and form an integrated framework. The aim is to provide specific and refined findings for policy implementation and improve the efficiency of the water and energy sectors (Ding, 2020). For the specific case of Leeuwarden, to reduce the domestic water consumption holistically, measurable criteria from the water and energy system should be analysed to understand the dynamics, improve the efficiency and, by that, help improve the resilience and water security of the city.

1.3. Research Objectives

There is an existing problem in which the research is given a place, referred to as the project context. Initially, this is very broad and complex, but a section is demarcated for the research that can be handled in the available time. The result is a well-defined problem, where an actual contribution to the solution is possible. This is formulated as a contribution to the goal to be achieved and forms the research objective.

With the municipality of Leeuwarden as initiator, a group of organizations and institutions, i.e., the Municipality of Leeuwarden, Vitens, the province of Friesland, Wetsus, and the Centre of Expertise Water Technology, which all have to do with providing high-quality clean drinking water in Leeuwarden, decided to join forces in a new partnership. This partnership aims to reduce household water consumption in Leeuwarden by 5% by the year 2030. This percentage stems, the strategic determinations of the water supplier Vitens and is to prevent the problems that arise with regard to water scarcity. In recent years, much research has been done into increasing climate resilience and water security. This has shown that understanding the entire, holistic situation surrounding domestic water use is necessary because many different variables and actors influence this consumption. An important factor is the inclusion of the relationship between water and energy. A better understanding of the background and interrelations of this mutual relationship will promote efficient water use, especially through the allocation of the right technologies, and thus will reduce the ultimate water consumption.

Based on the knowledge gaps identified in the previous section, the research has two objectives:

1) to assess water and energy requirements related to Dutch household water supply, use, and disposal for all freshwater chain components, including energy use in the household for water heating.

2) to provide a robust estimate of the total energy consumption associated with municipal water demand in the Netherlands by including energy for water use.

1.4. Research Questions

To reach the research objectives, the following main question is formulated:

> ***Which technologies help to reduce the domestic water consumption of Leeuwarden under different scenarios, taking into account the interrelations of water and energy?***

To answer the main question, the research will provide answers to the following three sub-questions:

1. *What are the elements of a diagnostic model for identifying the relationships between water and energy consumption and the water efficiency of households in Leeuwarden?*
2. *What outcome does the application of the model give with regards to the domestic water and energy use in Leeuwarden?*
3. *To what extent do different water-saving technologies improve the domestic water and energy efficiency of households in Leeuwarden?*

1.5. Thesis Outline

Chapter 2 provides the used research methodology, including the research strategy as well as the data collection and analysis. In chapter 3, a technology assessment model is developed to answer the first sub-question. For the second and third central question, the model is confronted with the research object: the city of Leeuwarden. Chapter 4 presents the results based on the application of the model and a comparison of the three technologies. Chapter 5 concludes the thesis, and finally, chapter 6 describes the recommendations to the municipality of Leeuwarden regarding the best water-saving technology.

2. Methods

In this chapter, a distinction is made between a conceptual design and a research technical design. The conceptual design shows what is being investigated, and the technical design describes how this is being investigated. The nature of the research is described first in the conceptual design. After this, the research goal is formulated, followed by a visualization of this goal and the steps to be taken for this based on the research model. Finally, research questions have been formulated, divided into central questions and sub-questions. The research technical design describes how this is done and included the research strategy.

2.1. Nature of the Research

The research problem described in section 1.2 has been recognized and acknowledged by the municipality. The problem has been brought to the attention of the stakeholders, after which a collaboration of stakeholders is formed to reduce the amount of domestic water used in Leeuwarden. That means the problem-analytical phase has been gone through. Therefore, in the next phase in the intervention cycle, the background and the causes of the identified problem should be examined. So, the chosen instrument to tackle the practice-oriented research is to use a diagnostic analysis. The problem is so complex that the existing theory and practical knowledge are insufficient to clearly indicate which of the many possible factors now influence the identified problem. Concerning the nature, this research concerns diagnostic, practice-oriented research. In this situation, it is essential to find out which factors influence domestic water use (Verschuren, 2015). Relevant assessment criteria have been distilled to form a model and used to diagnose the research object. The significant individual elements of the problem have been analysed, after which they have been systematically recombined to develop effective recommendations for the particular set of conditions in the case of Leeuwarden.

2.2. Research Framework

As section 1.3 shows, the research objectives are set; now, it is important to draw up a plan of action; how can these intended objectives be achieved? In this case, the situation in the city of Leeuwarden forms the research object and is looked at with a certain perspective. In a sense, this research perspective forms the lens with which the object is viewed. A research model has been set up to create insight and overview of the various actions and the dynamics within the research. The schematic representation of the research framework is given in Figure 1, after which the steps taken are explained.

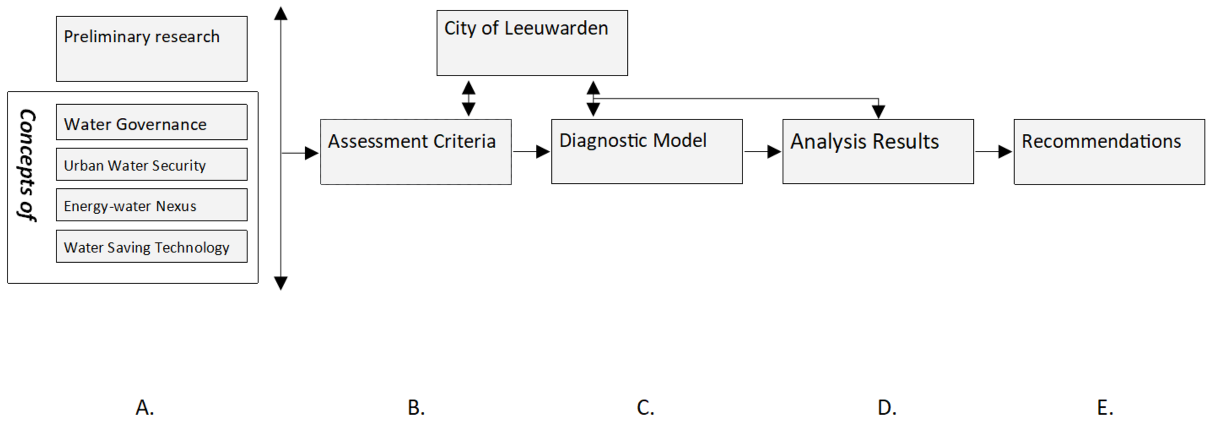

Figure 1 Research Framework

The steps that were taken in this research project are formulated as follows:

A. Conduct preliminary research by examining documentation and discussing with stakeholders and specialists, and review the scientific and grey literature on relevant concepts and methods.

B. Develop the diagnostic model based on the preliminary research and literature review.

C. Apply the diagnostic model by using the collected data

D. Analyse the data to reach results that emerge from comparing the three technologies.

E. Provide recommendations for the municipality to improve climate resilience through a water-energy nexus approach.

The research questions are linked to the different steps of the research framework. The first question relates to the diagnostic model. The second question relates to passage (C) from the research model, the analysis of the collected data about the research objects. The third question relates to passage (D), in which the results of the analyses of each of the research objects are compared.

2.3. Research Strategy

The purpose of the research is known and so are the research questions. Now it is necessary to look at how these questions can be answered so that reliable conclusions can be drawn from the results. A research strategy includes all coherent decisions about how the research is carried out. This implementation refers to the collection of relevant material and the processing of this material into valid answers. Within the research, an attempt is made to gain a thorough and integral insight into the situation regarding the water use in Leeuwarden. The water use in Leeuwarden is examined by considering the core concepts: qualitative versus quantitative research, breadth versus depth, and empirical versus desk research; it was decided to go for the case study as a research strategy. All the characteristics of the situation are revealed, the interrelations of these characteristics have been looked into as well as their impacts (Verschuren, 2015).

In this research, the research object is investigated holistically to obtain an integral picture of the research object as a whole. It is essential to know which aspects of water and energy are related and what their impact is. The aim of the project is an optimization in which a specific change is pursued. Suppose one does not have a clear picture of the relationships between different facets of water and energy on water use. In that case, one cannot correctly estimate the consequences of a change.

In order to obtain a holistic picture of a research object, the research uses a quantitative method of data collection in combination with the use of qualitative methods and open methods of data collection. A combination of multiple data sources and collection methods is used, in this case: group interviews, individual interviews and the interpretation of data files. Using this triangulation method ensures that no useful data is overlooked, which is preferred in research with multiple people involved.

2.3.1 Data Collection

In this section, an overview is given of the data sources and data collection methods. First, it is indicated how these sources can provide relevant information and thus contribute to the research. Subsequently, the relevant objects were determined for each sub-question, along with the types of information required for the objects. It indicates how many sources there are and what access method is used; an overview is created in Table 1.

Table 1 Overview of the data sources and collection methods

	Sub-Question	Information required	Sources of Data	Kinds of data required	Data collection method
Generating the Assessment model	1. What are the elements of a diagnostic model for identifying the relationships between water and energy consumption and the water efficiency of households in Leeuwarden?	Model framework Requirements, assessment criteria	Documentation	Concepts of Water-Energy Nexus (criteria and indicators)	Document review
			Documentation	Concepts of Water/Energy transition (criteria and indicators)	Document review
			Documentation	Concepts of Urban Water Management (criteria and indicators)	Document review
		Internal Indicators on how the supply, use, and disposal (treatment) looks like	Documentation	Concepts of Domestic Use (criteria and indicators)	Document review
			Documentation		Document review
			Media	Data files on Energy and Water usage	Document review
			Persons	Experts ▪ Insight in criteria for supply ▪ Insight in criteria for use ▪ Insight in criteria for disposal ▪ Insight in criteria for water-saving technologies	Semi-structured interviews, ´face-to-face´ interviews.
		External Indicators that influence supply, use, and disposal	Documentation	Policy documents	Content Analysis
			Media	Data files on social and demographic factors	Content Analysis
Applying the Assessment model	2. Based on the assessment of the situation in Leeuwarden, what outcome does the application of the model give with regards to water and energy use?	Where and to what extent	Media	Data files on the outcome of the model	Content Analysis
			Persons	Residential behaviour of water and energy use	Content Analysis
		Where and how do water and energy interact in water use, supply and disposal.	Persons	Experts	Focus Group
	3. To what extent do different water-saving technologies improve the domestic water and energy efficiency of households in Leeuwarden?	External indicators that influence the water use to be able to make the distinction between scenarios	Documentation	Results of the Analysis	Content Analysis
		And internal indicators that show which reduction technology fits best	Documentation	Results of the Analysis	Content Analysis

Research material

An overall picture is given of what the plan for generating the required research material looks like. For each sub-question, an explanation is given below: the research units and the data and knowledge sources are selected and specified. It also indicates how to ensure reliability.

Research Question 1: *What are the elements of a diagnostic model for identifying the relationships between water and energy consumption and the water efficiency of households in Leeuwarden?*

The research relating to the first sub-question consists of a qualitative and a quantitative part. The qualitative part focuses on gaining in-depth knowledge from the theory to establish a fixed model that can be used to solve similar problems. In addition, qualitative in combination with quantitative research is used in the preliminary research to get a clear picture of the current situation. This step-by-step plan can be specifically aimed at overlapping the gap in the literature and addressing the situation at hand.

Qualitative research

The qualitative part consists of a literature review about the efficiency of water and energy use. For this purpose, various publications related to urban water management and the water-energy nexus were reviewed. The internet is used to find out which concepts are relevant concerning domestic water use, the efficiency of energy and water and how these theories are related. Google Scholar, Scopus, Deepdyve, ScienceDirect and Emerald Insight are used to search scientific publications. The publications were searched based on the following search terms: *water-energy nexus, climate resilience, water scarcity, water efficiency, energy efficiency and water technologies*. Useful articles will also be searched for based on the references given in the publications. Attention is paid to the number of times the article is cited: a minimum citation is required.

In addition, semi-structured interviews were conducted (Table 2). This stimulated the interviewee to elaborate on the subject and thus provide insight into current actions and underlying motives. These interviews were conducted to identify relevant criteria to assess the research object and the possible water-saving technologies. The interviews started at the municipal level because this body signifies the executive board's interest in the city hall. Besides that, it oversees the application of municipal funds and the administration of property. This interview with the coordinator and strategic advisor of economic affairs helped to identify the key stakeholders. The interviews with the informants aimed to collect contextual data, e.g., knowledge of sources for information, relationships between agencies. Therefore, the questions were formed based on the characteristics of the respondent. Concerning the interviews with the experts, the questions were more specific, and an interview guide was set up (Appendix A. Interview Guides). These questions were asked to determine the perception of the experts on the water scarcity problem and the link between the water and energy transition, actions taken, institutions responsible, how decisions are influenced and their views on, and relevant criteria for, water-saving technologies. When the interview was over, the respondent was asked about other actors that might be valuable for the research, which then was contacted for requesting an interview. Interviews were enriched based on the information obtained from previous interviews and lasted about 45-60 minutes. Usually, semi-structured interviews are done face-to-face, as Verschuren et al. (2015) suggest, but due to the Covid-19 measures, this was not feasible, and digital sources like Microsoft Teams were used instead.

Table 2 Experts involved in the research

Code	***Organization***	***Position***	***Interview date***	***Information used for sub-question***
[1]	Municipality of Leeuwarden	Coordinator and strategic advisor economic affairs	24-04-2021	1, 2, 3.
[2]	Municipality of Amsterdam	Policy advisor	26-06-2021	2.
[3]	Vitens	Business development manager	06-05-2021	1, 2, 3.
[4]	MijnWaterfabriek	Owner	24-06-2021	2, 3.
[5]	Upfall Shower Systems	Sales manager	23-06-2021	2, 3.
[6]	Zwanenburg	Project developer	01-07-2021	2.
[7]	Wetterskip Fryslân	Senior policy advisor water chain	26-05-2021	2.
[8]	Hydraloop	CEO	30-06-2021	2, 3.
[9]	Centre of Expertise Water Technologies	Business Developer	26-05-2021	2, 3.
[10]	Rainblock	Partner	29-06-2021	2, 3.
[11]	Water2Keep	CEO	30-06-2021	2, 3.
[12]	Vewin	Senior policy officer, project leader Benchmark & Statistics	14-06-2021	1, 2.
[13]	Vereniging Circulair Friesland	Business Developer	30-06-2021	1, 2, 3.

Quantitative research

Databases of the water supplier ´Vitens´ were used to obtain information about internal variables that indicate how the domestic water supply, use and looks like in different residential areas, including energy use. Databases of the municipality of Leeuwarden have been consulted to find external variables that influence water use, such as the demographic and social aspects of the residents. And databases of the waterboard have been consulted for the water and energy use in the disposal and treatment.

Research Question 2: *What outcome does the application of the model give with regards to the domestic water and energy use in Leeuwarden?*

The problem statement shows that to maintain the water security and climate resistance of Leeuwarden, the focus must be on reducing the domestic water demand. The literature indicates that this is done holistically, which is why the energy factor has been added to the formula. In this step, the variables that provide insight into the efficient use of water in households based on the water-energy nexus are linked to the research object, the city of Leeuwarden, as a whole.

Quantitative research

The quantitative part mainly consists of analysing data from different forms of media. Databases consisting of historical and real-time data related to the water efficiency of the residential area have been analysed, looking specifically at the relationship between the variables of water and energy, whether they are in synergy, show a trade-off or conflict with each other.

Qualitative research

A focus group was used to increase reach and accelerate the creation of ideas and possible follow-up actions. This group of experts was brought together once every month between April and July 2021 to discuss findings, questions and solutions, and has provided an insight into the multilevel participation and coordination of water governance stakeholders. These experts are also part of the project group set up to achieve the target of reducing household water consumption by 5%. In addition, various research institutes have been approached to take part in the research group. As a researcher and permanent participant in the project, the support base grew significantly, and the willingness to cooperate with it. Access to and reliability of information therefore increased.

Research Question 3: *To what extent do different water-saving technologies improve the domestic water and energy efficiency of households in Leeuwarden?*

Based on the semi-structured interviews conducted to answer research question 1, experts were selected to be interviewed to form criteria for the assessment of water-saving technologies. Given the complex nature of the water security problem, professionals were sought to provide varying angles on the issue. For this research question, the experts in water technologies were contacted again, this time to establish a hierarchy between the criteria. To gauge the perceptions of the experts on the criteria, a questionnaire was used. This questionnaire was made in google forms and consisted of 48 closed questions. The questions were pair-wise comparisons between each criterion on which the respondent could judge the importance and influence, using the Saaty scale of 9 points, elaborated on in Chapter 4. To reduce the inconsistencies and bias, the goal of the weighing was explained during the interview, and the experts were asked to answer the questionnaire directly after the interview. The outcome of the questionnaires was processed in an Excel worksheet and then inserted into the expert choice software ´Comparion´. The software provides the possibility to include participants. This was done by sending them a link with which they could access the online project and check their input and adjust possible inconsistencies, ensuring the judgements of the respondents were correctly translated.

2.3.2. Data Validation

To be able to ensure data is validated, different aspects were taken into account regarding the interviewees, e.g., years of experience, job function, researchers from the knowledge institutions of CEW and Wetsus have provided an objective perspective, the results of the interviews are shown to the interviewee, and results have been overlooked or confirmed by a third party (triangulation). Besides that, the validity of the data generated by the focus group is ensured by including all relevant stakeholders, direct feedback during the meeting, and the researcher shared his role in and structure of the meetings beforehand.

2.3.3. Ethics Statement

This research respects the ethical standards of the Research Ethics Policy of the University of Twente. Before conducting the interviews, approval has been received from the Ethics Committee. The following principles, drawn up by the Ethics Committee, were kept as guidelines through the process of obtaining information when human participants were involved (BMS Ethics Committee, 2021):

- Researchers respect the dignity of humans and their environment and strive to minimise harm by avoiding exploitation, treating participants and their communities with respect and care, and protecting those with diminished autonomy.
- The researcher will adopt an ethical attitude and will be able to account for it.
- The researcher will make sure that the research conducted will be scientifically valid.

This means for the research that the interviewees were provided with an informed consent form (Appendix B) to approve before the start of the interview. The interviewees were informed in advance about the procedure, and it was made clear that the interviewee is allowed to stop the interview at any time. The anonymity of the interviewees is preserved, and confidential information was not shared.

3. Theoretical Framework

The theoretical framework provides an overview of the interaction of concepts and the scientific background for creating the technology assessment model. The levels of the framework shown in Figure 2 are based on various concepts in the literature. The framework resembles the broad concepts mentioned in 2.3.1. and how they can be used as an environment for a set of indicators that assess the water-energy nexus and water-saving technologies for households. The selected indicators will be specified to develop concrete policy recommendations regarding the choice for water-saving technologies. By forming this model, the research question: “What are the elements of a diagnostic model for identifying the relationships between the water and energy consumption and the water efficiency of households in Leeuwarden?” will be answered.

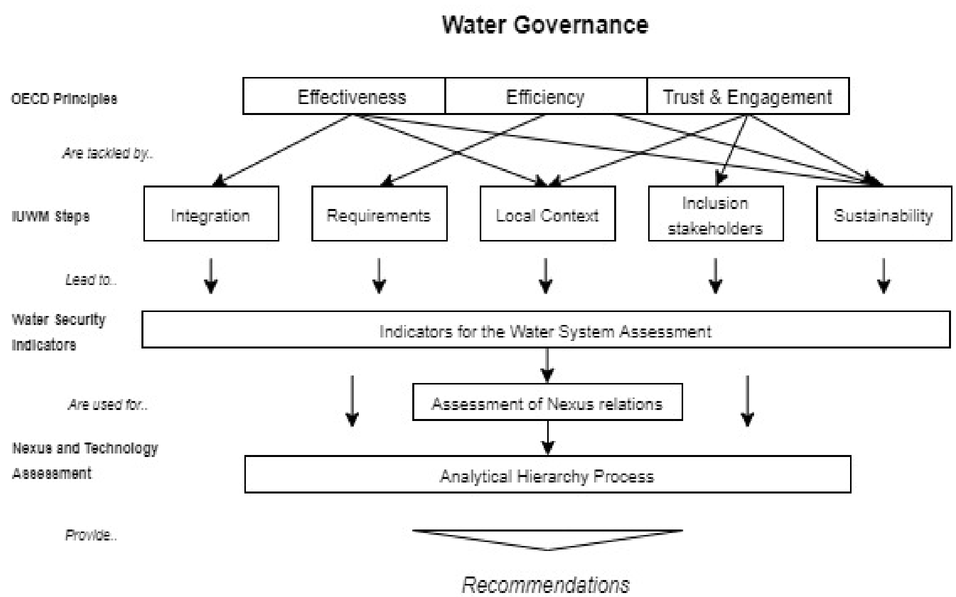

Figure 2 Theoretical Framework

The framework is specified into the technology assessment model as shown in Figure 3, which consists of 3 practical steps that will lead to insight into Leeuwarden's situation and provide a base for recommendations that will lead to achieving the research objective. The technology assessment model shows three phases in the assessment process; the definition, measurement, and analysis phase. The first three steps in the define phase give merely a realization of the situation at hand: what is the current state of the problem, what is the objective, and what stakeholders are involved. Besides that, it is used to scope to recognise issues and problems and to set priorities, defining the scale, a scenario in time, components involved, and a review of data availability. At the end of the design phase, the goal is to have established a set of indicators to quantify the urban water security of Leeuwarden (Dai J. W., 2017). The measurement phase includes all the factors that are of relevance for the assessment. Step 2 has three elements; step 2.1 involves the criteria to understand the environment in which the assessed technologies will be implemented, step 2.2 involves the criteria that should be obtained to be able to make a distinction between the assessed technologies. The third element involves the perception of stakeholders providing an understanding of the interrelations between criteria and their relative importance within the water chain. This is not a step that should be taken, but a source of information that should be used. At the end of the measurement phase, an index of well-understood criteria is presented as well as the basic requirements to apply them effectively. It serves as the input for the Analysis Phase. This phase represents the assessment and comparison of the technologies, guided by step 3. To be able to give proper recommendations, decisions must be made. Considering the complexity of water management activities, a multi-criteria decision analysis (MCDA) tool, namely the Analytical Hierarchy Process (AHP), which is mainly applied because of its good understandability, broad applicability and is accessible to couple with other analytical systems (Paul, 2020; Fukasawa, 2020). The outcome will show a prioritization of technological alternatives transparently, after which a cost-benefit analysis (CBA) is conducted.

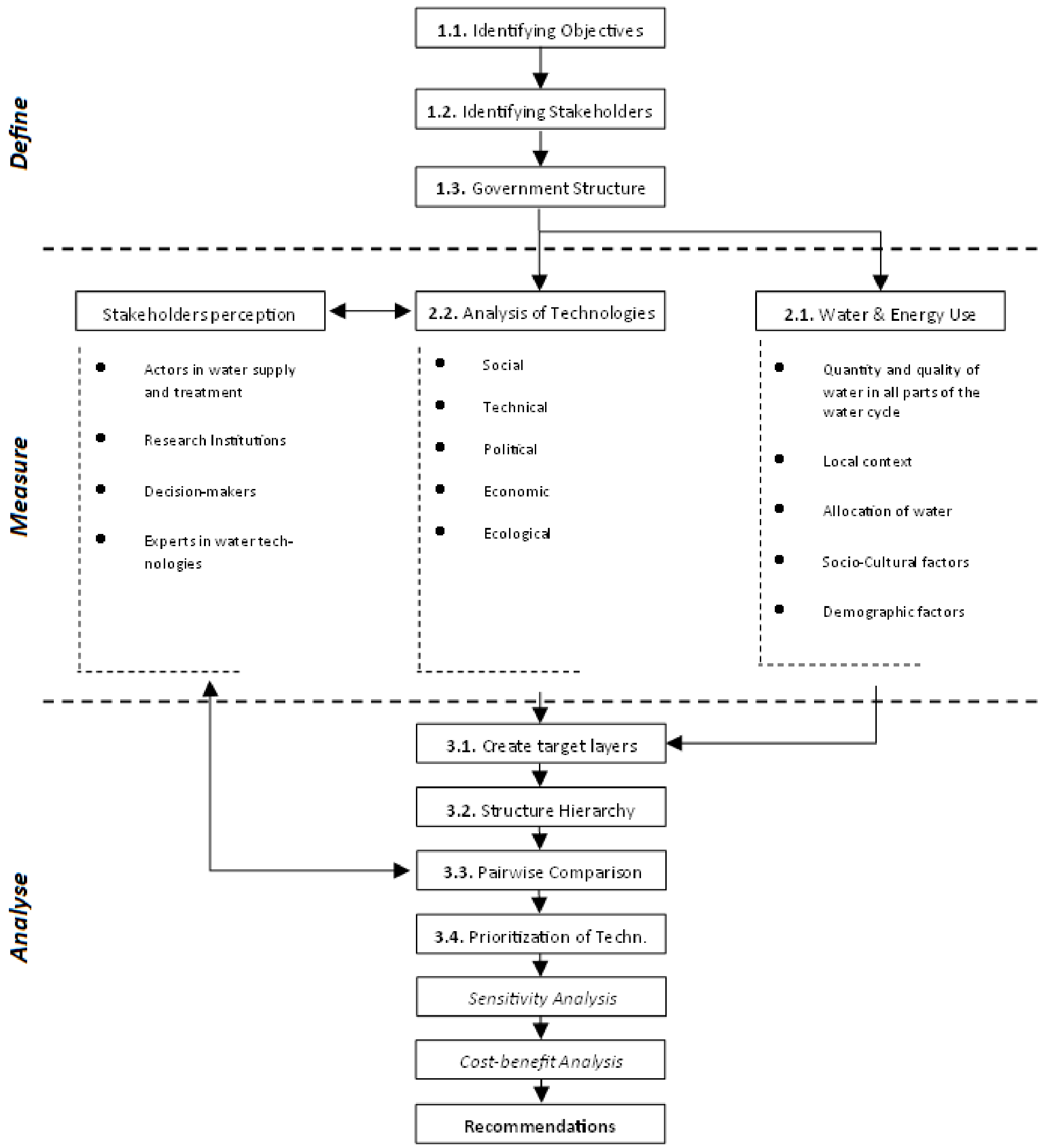

Figure 3 Technology Assessment Model

3.1. Definition Phase: Objectives and Stakeholders

This phase consists of three steps: setting the objectives, identifying the stakeholders, and describing the government structure. Completing these steps forms the research foundation will provide a base of knowledge to start with the measurement phase.

3.1.1. Step 1.1: Setting the objectives

A clear objective and scope are required for defining a strategy for conducting the assessment and making sound decisions during the assessment process. It is also crucial to think about the aspects of governance the analysis should focus on since water governance, like other sectors, is intertwined with a society's overall governance and political economy (UNDP, 2015). In this case, the objective is a 5% reduction of the water used by households in Leeuwarden with the criteria of considering the effect of energy on water use and the effectiveness of proper water-saving technologies to increase water security. Spatial and temporal scales determine the scope of the research; the spatial scale refers to the defined geographical area of Leeuwarden, the inhabitants of these neighbourhoods and all its used water resources. The temporal scale is set to be able to catch the dynamics of the water used.

3.1.2. Step 1.2: Identifying the Stakeholders

It is essential to include the perspective of decision-makers in a technology assessment to enhance the extent of support that can influence the management to implement projects in the form of economic resources and leverage (Taboada-Gonzales, 2014). Commonly, an assessment process is embedded into specific policy processes. This can be used for a multitude of themes, including influencing policy, increasing advocacy and accountability, and providing the data needed to make proper financial decisions. The way the evaluation is conducted is just as significant as the actual findings in achieving these goals. When a decentralized water system is implemented, the water system requires a series of changes in the relations between the informal and formal water management institutes (UNDP, 2015). The current centralized systems are managed by private and public companies that are subject to government control. Decentralised systems are managed by communities or individuals, mainly families or neighbourhoods. This leads to a shift in the power held over the water cycle. The top-down approach is replaced by a multi-level governance model that increases the number of actors and renews their relations (Domenech, 2011; Aboelnga, 2019). Therefore, it is critical to understand who the stakeholders are, their interests, and their relative power and sphere of influence to ensure a successful process. Insight in this type of data will engage stakeholders (Domenech, 2011; Krozer, 2010).

3.1.3. Step 1.3: Describing the Governance Structure

As Dutch urban water governance is a shared responsibility across multiple levels, distinctions should be made; central governments play a central role in policymaking and regulation. Local governments participate actively in water functions such as drinking water supply and drainage (Romano, 2019). Therefore, roles and responsibilities should be mapped. Many of the adopted water policies contain similar goals and features, e.g., better coordination of decision-making or decentralization. On paper, these policies seem sound, but many encounter problems in the formation and functioning of these structures. The following barriers in water governance to adopting policy interventions are identified: fragmented responsibilities, lack of legislative mandate, lack of institutional capacity, insufficient funds, uncertainties in performance and cost, and lack of incentives for the market (Allison, 2008; Bressy, 2014). To improve the effectiveness of policy interventions in their local context, it is important to assess the governance of water resources and identify where changes are needed and what action can support these. The OECD provides twelve principles, which can be linked to three key elements of government intervention; trust and engagement, effectiveness, and efficiency. These form the structure to allow practical management tools (OECD, 2020). The analytical assessment supporting these principles is to produce design data that represents a structured process identifying gaps and possible bridges; A successful design identifies critical failures (Bressers, 2016; Backman, 2005; Romano, 2019).

3.2. Measurement Phase: Principles and Indicators

As the first phase is finished, the project's environment (the circumstances), and the governance structure identified, the shift is made to the measurement phase. In this research, the Integrated Urban Water Management (IUWM) principles indicate what to measure in the situation in Leeuwarden.The terms "water governance" and "water management," and by that Integrated Water Resource Management (IWRM), are used interchangeably. However, water governance and water management are interrelated issues in the sense that effective governance structures are intended to allow for practical management tools (Tortajada, 2010; UNDP, 2015). According to the Global Water Partnership, water governance should be regarded as creating the structure in which IWRM can be implemented (UNDP, 2015).

The increase of water governance challenges has culminated in the rise of IWRM (van den Brandeler, 2019). IWRM is defined as "a process that promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare equitably without compromising the sustainability of vital ecosystems" (Global Water Partnership, 2020, p. 1). As Maheepala et al. (2010) state, the IWRM addresses water distribution at the river basin level. Besides that, in terms of good water governance, it has been taken over by the majority of the global water community (Johannessen, 2017; Maheepala, 2010). However, the IWRM application has been criticised for failing to offer practical solutions to the problems, complexities, and uncertainties inherent in water management. (Aboelnga, 2019). IWRM has been further advanced to Integrated Urban Water Management (IUWM), which manages water supply, wastewater, and storm water in urban areas within the IWRM process's boundary conditions (Maheepala, 2010). The main driver for adopting IUWM is to provide sustainable urban water services to the community, which improves the water system´s outcomes and human welfare (Grace Mitchell, 2006; Makropoulos, 2008).

According to the IUWM literature, specific processes should be constructed and managed so that the system is as efficient as possible, minimizing the negative impact as far as is practically feasible (Maheepala, 2010). Within urban water systems, taking an integrated approach is one of the significant advantages, providing the ability to increase available opportunities to develop more sustainable systems or scale-up. The primary goal of IUWM is to promote multifunctionality in urban water services to improve the system's outcomes. Mitchell (2006) identifies five principles that are crucial to capture the obtained information of the measurement phase (Grace Mitchell, 2006):

- Integration
- Consider all requirements
- Local context

- Stakeholders
- Sustainability

Within these five principles, the whole urban water cycle is considered, including the social, economic, political, and specific environmental factors that influence the water system's performance. The water system contains processes in the water cycle, e.g., drinking water production, storage and distribution, and the collection, treatment and discharge of wastewater (Liu J. D., 2018), in this research specified to supply, use and disposal. Water reduction projects analysed by Mitchell (2006) show that when IUWM concepts are implemented successfully, significant reductions in the impact on the total water cycle and reduction in water use can be achieved (Grace Mitchell, 2006). Given the previous context, a better comprehension of resilience in urban water management, as well as the thresholds, and an understanding of what permits the transition towards climate adaptation, will lead to the further development of IUWM and adaptive water management (Johannessen, 2017).

Urban water security and climate resilience

In addressing climate change adaptation in urban areas, the concept of resilience has become increasingly prominent (Özerol, 2020). The study of resilience in the face of large-scale physical and climatic change is becoming significant. However, although the physical variables are well-defined, the concept of resilience remains a hazy concept. It has come to mean both mitigation and adaptation in recent years, terms that are often used interchangeably or in tandem (“adaptation-mitigation”). However, mitigation and adaptation could be placed in opposition to one another: The first refers to the capacity to conduct business as usual, while the second rejects the ‘business as usual’ norm and acknowledges new realities (Ching, 2016; Johannessen, 2017).

In this research, climate resilience will be looked at in a more general sense where there is referred more specifically to a multiscale system. A system with the capacity for learning and adaptation when ecological, political, social, or economic factors untenable the current system. Moreover, it “reflects the degree to which a complex adaptive system is capable of self-organization,” that is, “the capacity of linked social-ecological systems to absorb recurrent disturbances to retain essential structures, processes, and feedbacks, and the degree to which the system can build capacity for learning and adaptation” (2005, p.1036) (Adger, 2005). Key concepts discussed are water-energy transitions and transformation, permitting and restricting factors and thresholds (Johannessen, 2017). Participation at the local level is particularly crucial for implementing water management practices that are sustainable, equitable, and resilient over time.

Urban water resilience is a critical element for water security. Over time, many different definitions for water security have been developed, and some focus on a broad understanding. Garrick et al. (2014) define water security as an acceptable level of water risk, where Brears et al. (2017) pose a narrower framing and define water security as only matching supply and demand (Brears, 2017; Garrick, 2014). An integrative understanding of water security is adopted in this research which addresses urban water management’s commonplace concerns; either too little, too much, or too dirty (van Ginkel, 2018). As it is a significant concern, van Ginkel et al. (2018) state that systems thinking should help understand the mechanisms that influence the long-term water security of a city. Short-term, localized, and single-sector decisions often result in poor system efficiency and are more easily avoided. Another one is providing water security through the diversification of sources, i.e., increasing supply and efficient demand management, in other words, using less (van Ginkel, 2018). Several studies have highlighted the absence of local assessments of protection and implementation of water security actions (Srinivasan, 2017). In order to effectively resolve urban water issues and offer decision-makers comprehensive policy instruments and strategies to achieve urban water protection, these actions should represent the significant variation in the dynamics of water security at the local level (Allan, 2018). The water security indicators will specify how to measure and have been selected using three criteria; 1) relevance for technology purposes, 2) relevance for assessing the water-energy nexus at the household level, and 3) the availability of tools to measure or scale them for practical use and understand the contextual situation.

3.2.1. Step 2.1: Water Security Indicators

The identification of criteria is a technical process based on empirical research, theory and common sense. As can be seen in the theoretical framework, there are many concepts for screening criteria related to water resources and technology assessment (Perez, 2015; Romano, 2019). Based on these concepts, the holistic perspective, and the results of the analysis of interviews with experts, there can be concluded that water resources and technology assessment is based on criteria from the dimensions of the political environment, the socio-cultural, demographic, ecological, and economic factors and the assessment criteria based on the characteristics of the water-saving technologies *[Interviewee 9 and 13]*. The indicators that adequately cover the aforementioned criteria should be suitable to measure the resilience of water resources and the technology readiness level of the neighbourhoods (Zhou, 2018; Ling, 2021; Balkema, 2002). Sets of indicators are derived from these dimensions, linked to the integrated urban water management literature provided by Grace Mitchell, and divided into the first three principles, i.e., the consideration of all parts of the water cycle, of all requirements and the local context. The criteria based on the characteristics of the technologies are kept apart.

A. Consider all parts of the water cycle, and recognize them as an integrated system.

The problems related to climate change adaptation are complex; they can only be tackled by system thinking (Bosscheart, 2019; Romano, 2019; Liu J. M., 2015). System thinking can reduce institutional fragmentation while improving coordination and coherence across different policies (Romano, 2019). That is why it is essential to first understand the water cycle, the volumes included, and its capacity before adjusting the process *[Interviewee 13]*.

To understand how the body of water and its resources work; the quantity of water is specified into its availability, consumption, and reliability. The availability, **¡Error! No se encuentra el origen de la referencia.**, a key indicator for measuring water stress and diversity, indicate the domestic water resources used. Water consumption is paramount to measure, to be able to consume it most rationally *[Interviewee 10 and 13]*. Besides that, in this research, the dependency on the energy system is focused on and therefore, it is important to measure the energy efficiency in water supply and use *[Interviewee 3]*. Ensuring access to water and sanitation for all is a basic human right and fundamental to achieving SDG 6 (United Nations, 2021), but these services are well managed in the Netherlands.

Table 3 Criteria to consider the whole water system

Dimensions	Indicators	Variables	Units
Water quantity	Availability	Total water resources/Total population	m3/capita/year
	Diversity	Reused wastewater/production of wastewater	% /total
		Contribution of alternative water sources	%/total
		Contribution of alternative energy sources	%/total
	Consumption	Authorized consumption/Total population	L/capita/day
	Reliability	Non-revenue water	%/total
		Metered water	%/total
		Energy efficiency in the network	%/total
	Disposal	Volumes of water disposed of/Total population	L/capita/day
Water Quality	Quality of water supplied	The proportion of samples meeting local standards	%/total
	Quality of water used	Wasted streams from households	Types
	Quality of water after treatment	Effluent of WWTP	Standards

The storm water and sewage system are crucial to the urban water system's resiliency. Storm water runoff is demarcated as runoff generated from all grey infrastructure surfaces, while rooftop rainwater is generally identical with the rainwater collected from rooftops *[Interviewee 10]*. The generation of storm water runoff increases substantially because the urban grey infrastructure seals the soil, reducing infiltration and groundwater recharge (Hatt, 2006) *[Interviewee 10 and 11]*. To capture this water from the source is a more efficient way of discharge; therefore, the potential volumes per location should be considered. Besides, insight into these volumes is crucial to be able to implement certain water technologies efficiently, and therefore the annual rainfall is included (Inman, 2006).

B. Consider all requirements for water, both anthropogenic and ecological.

It is essential to mention how the water is treated since the high agricultural standards of the Dutch government have influenced the way we look at water and how this has influenced the environment and water use. This research will not analyze these criteria profoundly, but it is crucial for understanding the context in which changes must be made *[Interviewee 9]*.

Everchanging consumption patterns, environmental deprivation, local politics, and climate change have made water a commonplace topic in the anthropological literature (Rasmussen, 2015). Besides, residents in the Netherlands are surrounded by water, and confronted with rainfall all year long, which makes it difficult to make them aware of the need for water saving *[Interviewee 3]*. The value of water needs a pivot since people in the Netherlands see it as a disturbance that should get rid of quickly. Even Rijkswaterstaat describes water management as all activities that are necessary for the safe discharge of water. Over time the water has shaped the Dutch national identity. The Netherlands, due to its geography, has been in a constant struggle to protect the land from flooding and reclaim space from the sea. To be able to cope with these struggles, perseverance, ingenuity and cooperation were required. Especially the cooperation resulted in an egalitarian society and democratic institutions, the oldest being the water boards (Mostert, 2020; Kullberg, 2019).

C. Consider the local context, accounting for environmental, social, cultural, and economic perspectives.

Domestic water consumption is dependent on demographic factors, e.g., the size of the family in the house, age, levels of education, the lot size of properties, and income (Inman, 2006; Renwick, 2000; Taboada-Gonzales, 2014). Attention must be paid to social and economic activities' potential and actual role since decentralized structures shift the financial weight from the public sector to users. Consequently, they favor cost recovery, of which residents are often not completely informed and unaware of the financial benefits (Domenech, 2011) *[Interviewee 4, 7 and 11]*. Therefore, energy, water and sanitation tariffs are included, see Table 4.

Features of the hydro-social cycle are likely to change during conversion to decentralized water management. In Dutch urban areas, water is permitted to enter the house after it has been purified or treated and is then quickly removed after use; therefore, the consumers are not aware of their water use *[Interviewee 9 and 11]*. In local strategies, the alienation of water consumers is less likely since the collection, storage and distribution of water are more visible (Domenech, 2011; Brown R. W., 2009). It is therefore expected that water conservation attitudes would become more entrenched in resident's daily life. Being able to shift the residents towards these kinds of practices requires understanding, awareness and appreciation of the environment and water (Willis, 2011; Hassel, 2007; Fan, 2013; Pahl-Wostl, 2008)*[Interviewee 10 and 11]*. Vewin (Association of water companies in the Netherlands) highlights the importance of cultural background in water use, which will be included (van Thiel, 2017)*[Interviewee 10 and 12]*.

Table 4 Criteria to consider all requirements for water

Dimensions	**Indicators**	**Variables**	**Units**
Environment	Energy in Water Supply	Energy in Transportation, distribution	kWh/m3
	Energy in Water use	Energy use in different appliances	kWh/m3
	Energy in Water disposal	Energy in treatment	kWh/m3
	Energy in Water-saving technologies		kWh/m3
	Average annual precipitation		mm/year
	Average annual temperature		°C
Socio-Cultural	Attitudes	Towards putting effort in reusing water	1-9
	Awareness	In use and impact	1-9
Economic	Water tariffs	Water tariff per m3	€/m3
	Energy tariffs	Energy tariff per m3	€/m3
	Treatment tariffs	Treatment tariff per m3	€/m3
	Affordability	Water and Wastewater Services (WWS)/income	%
	Operation and maintenance cost recovery	Operating expenditure/operating revenue	%

3.2.2. Step 2.2: Criteria based on the characteristics of the water-saving technologies.

For each technology, i.e., water reuse, rainwater harvesting and warm water reduction technologies, five main criteria are established: social, technical, political, ecological and economic, see *Table 5*.

As explained in part C, the social context is of relevance, but to help the adaptation, environmental awareness needs to be turned into the acceptance of technologies. To be able to compare the different technologies, it is essential to know the technical characteristics. Stakeholders have underlined that there is no clear overview of available technologies or how they could be beneficial *[Interviewee 3]*. Moreover, the technical aspects form major barriers in adopting technologies because of its required space and adjustments to the building for installation *[Interviewee 4 and 13]*. Besides that, these barriers bring extra costs *[Interviewee 4, 6 and 13]*. The political environment is included for understanding the external legislation and regulation that influence water reduction, as there are often subsidies for water-saving *[Interviewee 4]*. To measure the positive impact the technology has on the environment, the capacity of water and energy savings is taken into account since they often work in synergy when water is saved *[Interviewee 5]*. It is essential to understand that water use at the household level is based on the fit-for-purpose principle, which assumes that water has many qualities, while not all water facilities in the household require the same level of quality (Wong, 2009). In the Netherlands, potable water is used to meet all domestic demands, regardless of the small percentage strictly requiring the use of high-quality water (to drink). A large part of the demand could be fed with decentralized, local sources, often of lower quality than the potable piped water (Domenech, 2011; Brown R. W., 2009) *[Interviewee 8]*.

Table 5 Criteria based on the characteristics of water-saving technologies

Criteria	Sub-Criteria	Description
Social	Community acceptance	Acceptance of technologies and environmental awareness
Technical	Space not intruding in the live space	Required space for installation
	Operating knowledge	Knowledge to use the technology
	Lifetime	The time the technology can work
	Applicable to multiple households	One installation can be coupled to multiple households
Political	Legislative/regulatory aspects	Legal support for the installation of equipment (e.g. subsidies)
	Approval of decision makers	Extent of support and knowledge of technologies
Economic	Installation costs	Acquisition costs of equipment and installation of technologies
	Maintenance costs	Additional annual costs
Ecological	Reuse for high quality water necessities	Effluent can be turned into drinking water
	Volume of water saved	Effluent can be used for toilets, washing machines, and outdoor use
	Impact on energy use	Energy is saved by using less water

3.3. Analysis Phase: AHP and CBA

In this section, the AHP is described. The data of the water security indicators form the input for the Analytical Hierarchy Process (AHP) to make multicriteria decisions and examine alternative solutions. In this way, the multidimensional scaling problem is transformed into a one-dimensional scale problem (Klemann Raminelli, 2019). Eventually, a cost-benefit analysis (CBA) is done to link the outcome with the economic criteria.

3.3.1. Analytical Hierarchy Process

To manage the water system properly, the stakeholders should understand the complexity of water resilience in their relevant context and the water-energy relations between the multiple criteria (Ling, 2021; Ashley, 2008). Multi-criteria decision analysis is used to identify the most preferred option of water-saving technology for decision-makers and deal with multiple and often conflicting data. This will help by providing a standardized method to guide a logical and coherent decision-making process (Finkbeiner, 2010). It allows for the analytical comparison of multiple alternatives from different predetermined quantitative or qualitative criteria relevant to the decision-making process (Esmail, 2018; Fukasawa, 2020; Mutikanga, 2011). Applying MCDA has the benefit that it can assess alternative interventions to reduce the domestic water demand and include estimates of energy required by water appliances, assessing the energy-water nexus at the household level (Dai J. W., 2018).

The AHP is one of the most widely used multi-criteria methods for analysing a finite number of alternatives (Saaty, 1990). AHP is a multi-criteria method based on a hierarchical structure and an aggregation process, with the ability to handle different kinds of parameters, including numerical, qualitative, and empirical data and subjective evaluations (Opher, 2018). It is a non-probabilistic method, which is formulated following a hierarchical structure and an additive preference model. Within the AHP, each criterion and criteria is judged to determine their importance towards the alternatives. This is done by pairwise comparisons based on a scale of one to nine. To preserve consistency in the rank of alternatives, the eigenvector entries need to be divided by the largest amount among them. Saaty (2006) refers to rank reversal and preservation on multi-criteria when ranking alternatives in terms of alternative independence. Rank reversal in relative measurements occurs in practice due to the number and quality of the other alternatives. Thus, dependent alternatives cannot be included in the multicriteria setting because they would make an alternative dependent on another. Moreover, the weight normalization method could influence the ranking of the alternatives depending on the characteristics of the new alternative (e.g. the new alternative is dominant for one of the criteria), where normalization is carried by their sum (distribute mode) or idealize by dividing by the weight of the largest alternative (Contreras, 2008).

The process involves four main sub-steps to solve the decision problem for the most applicable water reduction technology: 1) Define the problem 2) Structure the decision hierarchy 3) Construct pairwise comparison matrices 4) Prioritize and choose technology.

3.3.2. Step 3.1: Define the problem

The first step, the target layer, decomposes the decision problem into a hierarchy of goals, criteria, sub-criteria and alternatives as interconnected elements (Wu, 2011; Wei, 2017; Contreras, 2008). After considering the water resilience and security literature in the former step, the criteria have been formed, but in this phase, the sub-criteria are added, using the input of stakeholders through a quick survey (Klemann Raminelli, 2019; Thungngern, 2017).

3.3.3. Step 3.2: Structure the decision hierarchy

In this step, the hierarchy is formed, showing how the criteria influence the objective. The model should be constructed from stakeholders' perspectives. In this research, this is achieved using semi-structured interviews with experts and a literature review of relevant concepts, as elaborated in section 2.3.1.

3.3.4. Step 3.3: Construct pairwise comparison matrices.

This phase, the rule layer in the process, consists of weighing. Each criterion needs to be weighted using preferred judgements or perceptions of the stakeholders, i.e., experts in water supply and treatment, actors from knowledge institutions, and decision-makers on the relative importance of each criterion. The judgement is made using Saaty´s semantic scale, see Table 6, so pairwise comparisons can be formed (Wei, 2017; Ivanco, 2017). Then each of the alternatives for water-saving technology, i.e., rainwater harvesting, grey water reuse, and warm water reduction, are pairwise compared to each criterion with the same scale. This will help aggregate indicators into a composite index for each option for water-saving technologies (Gherghel, 2020). This is integrated into the Expert Choice software, which is used to facilitate the application of the AHP. The shortcut pairwise comparison is built on the statement that if criterion A is (x) times better than criterion B and criterion B is (y) times better than criterion C, then criterion A is (x.y) times better than criterion C. The comparison of A to C is, therefore, not required (Taboada-Gonzales, 2014). Each comparison determines the direction and degree of importance between two criteria or indicators (Ling, 2021; Bottero, 2011).

Table 6 Saaty´s semantic scale

Scale	Numerical Rating	Reciprocal
Extremely importance	9	1/9
Very to extremely strongly importance	8	1/8
Very strongly importance	7	1/7
Strongly to very strongly importance	6	1/6
Strongly importance	5	1/5
Moderately to strongly importance	4	1/4
Moderately importance	3	1/3
Equally to moderately importance	2	1/2
Equally importance	1	1

Once the judgement of pairwise comparisons is collected, the weights can be acquired by either calculating the eigenvectors of the matrix or the geometric mean of each row, which provides similar results (Wei, 2017; Ivanco, 2017). To be able to use the data, the consistency of each criterion in the matrix is evaluated. Each comparison between the criteria is subjective; therefore, the AHP tolerates a surplus in inconsistency in process, measured by the consistency index (CI) and random consistency index (RI). If this surplus is higher than the required CI>0.1, then the comparisons should be re-examined. The consistency of the decisions made can be estimated using the equation presented below. The principal eigenvalue obtained from the priority matrix is λ max, and n is the size of the comparison matrix. The random consistency index (RI) can be calculated when pairwise comparison matrices of various sizes are created, depending on matrix size (n).

$$CI = \frac{\lambda max - n}{n - 1}$$

If this is done, a square matrix (which is an $n.n$ matrix) can be formed () showing the value of the input of all comparisons $A[a_{ij}]$, based on the equation: $a_{ij} = 1/a_{ij}$ (Thungngern, 2017).

Table 7 Example Pairwise Comparison Matrix

A =

Matrix comparison	C1	C2	C3
C1	1	3	5
C2	1/3	1	1/7
C3	1/5	7	1

3.3.5. Step 3.4: Prioritize and choose technology

After the pairwise comparisons of the criteria have been developed, they are linked to the relative judgements of each alternative for water-saving technology towards the same criteria. They result in an overall prioritization of alternatives, providing insight into the best applicable water-saving technology (Wei, 2017; Wu, 2011). A sensitivity analysis is performed to determine the robustness of the outcome, which shows the need to consider an alternative technology (Taboada-Gonzales, 2014; Contreras, 2008).

3.3.6. Cost-Benefit Analysis

To better understand the prioritization of costs and benefits by potential end-users in this context, Dominguez et al. propose a benefit-cost ratio assessment of the outcome of the AHP (Dominguez, 2017; Eggiman, 2017; Zang, 2021). As the AHP gives a synthesis of the opportunities and benefits of each alternative, it can be misleading to add costs in the assessment. Therefore, a new hierarchical structure is formed, with the criteria influencing costs, which will prioritise the least costly alternatives. Besides that, the fifth IUWM principle describes that cost recovery is an important performance indicator of a sustainable, well-managed water solution (Taboada-Gonzales, 2014; Hajani, 2014; Ortiz, 2007).

4. Results

This chapter starts with presenting the results based on the confrontation of the model to the research object; the current situation in Leeuwarden. The second section gives insights into the water supply, use and disposal, energy use, and interlinkages. The third and last section analyses the best fitting water-saving technologies to reduce domestic water use. The steps of the previously developed technology assessment model provide the structure for this chapter.

4.1. Diagnostic Model of Domestic Water and Energy Consumption in Leeuwarden

This section answers the second sub-question: *Based on the assessment of the neighbourhoods in Leeuwarden, what outcome does the application of the model give with regards to domestic water and energy use?*

4.1.1. Step 1.1: Setting the objectives

The functional unit of this research is the supply, use, reuse, and reclamation (disposal) of the water consumed at an urban scale. Based on the Vewin Water Supply and Drinking Water Statistics, the drinking water consumption is divided into the following three sub-uses:

1. The household use, the total use for domestic use. Depending on the drinking water company, this is:

- the total use of all connections registered as domestic connection;
- the total use of all connections that use less than 300 $m^3/year$ (also referred to as small-scale use);
- the total use of the type of connection for households (determined by the calibre of the water meter).

2. Non-domestic use: the full use of all non-domestic connections. This use is related to both small business, agricultural and recreational activities (which typically use less than 10,000 $m^3/year$), and large business, mostly industrial activities (which typically use more than 10,000 $m^3/year$).

3. Non-revenue water: the difference between the amount of drinking water supplied to the distribution network and the drinking water settled with the customers; the sum of the other two partial uses. The difference is mainly caused by distribution and blowdown losses, extinguishing water and measurement errors.

The objective of the project is to reach a 5% reduction in domestic water use. In accordance with the goal of the project ´Water-saving Leeuwarden´, system boundaries are limited to the foreground subsystems only: household use, potable water supply (including non-revenue), wastewater and greywater conveyance and treatment, and reclaimed wastewater reuse.

4.1.2. Step 1.2: Identifying the stakeholders

The water system in Leeuwarden is governed by allocated governmental bodies, although water-related projects increasingly include the input of local research institutes or private companies. Where local water resources, such as runoff water and wastewater, used to be treated as nuisances, the flows are more appreciated as valuable resources. Leeuwarden also promotes itself as the water capital of the Netherlands and aims to be in the frontline of urban water resilience, recognizing the importance of local solutions. They want to set a collective learning environment and play a guiding role in the promotion of decentralized technologies

Regarding the water-saving project, key stakeholders play different roles. The leading body is the Municipality of Leeuwarden, which is interested in facilitating a successful shift towards a more water-secure city to deal with risks and uncertainties. They are accountable for the project's success and communicate the project status concerning project status, e.g., scope change, milestone monitoring, to all stakeholders. The executive sponsor is Vitens, providing resources and support and is accountable for success. In this case, Vitens formed the project's objective: a water reduction of 5% before 2030, and included project members. Vitens also provided the project coordinator, which ensures that the project delivers the expected results. They steer the project's direction to be able to form a presentable policy plan for a more resilient Leeuwarden. The Centre of Expertise Water Technology, Wetsus and VCF (Vereniging Circulair Friesland), are the project members and provide information. They work together with NHL Stenden and Van Hall Larenstein students to extract information from residents concerning water using behaviour via interviews and questionnaires. Residents function merely as a source of information, and are not actively involved. The members analyse the information and report back on the outcome to Vitens and the Municipality. The municipality then approaches local organizations and entrepreneurs to find a solution for the situation at hand.

4.1.3. Step 1.3: Governance Structure

The Dutch water system is structured linearly; this means that the water is supplied, used, and treated, after which the effluent and the rainwater are pumped back into the surface waters (Van Tuijn, 2018). Therefore, urban water governance is a shared responsibility and makes it essential to map roles and responsibilities over multiple government levels clearly. Water management in the Netherlands has attended to the commonplace concerns: either too little, too much or too dirty water. There is a slight shift towards efficient demand management, using less to improve water security and climate reliance. There is increasing insight into water availability, and concrete measures needed to prevent freshwater shortages have been combined in the Delta Plan on Freshwater (Deltaprogramma, 2021).

In the Dutch polycentric water system, the overarching law for water management is the Water Act, which mainly regulates the management of water systems, including flood defences, surface water and groundwater bodies. The Act aims to prevent or limit flooding, flooding and water scarcity, the protection and improvement of the quality of water systems, and the fulfilment of social functions by water systems (Overheid.nl, 2021). The following responsibilities for water management are laid down within the Water Act:

- The national government, the Ministry of Infrastructure and Water Management, is responsible for the national policy framework and strategic goals for water management in the Netherlands and measures of a national character.
- The province is responsible for translating this into a regional policy framework and for strategic goals at a regional level. In addition, the province has operational tasks for part of groundwater management. The province is not a water manager within the meaning of the Water Act.
- The water manager (the water boards for the regional water systems and the central government for the main water system) is responsible for operational water management and have a duty of care for the purification of urban wastewater. The water manager establishes the conditions for achieving the strategic objectives of water management, determines the concrete measures and implements them.
- Municipalities have a duty of care for the collection via the sewerage [1] of urban wastewater and rainwater and groundwater 8 (art. 3.5, Water act); this is directly linked to the waterboards duty of care for the purification of urban wastewater. However, the municipality´s duty is regulated in the Environmental Management Act. (Sanders Zeilstra van Speandonck, 2009; Rijksoverheid, 2021), the way in which a municipality fulfils these duties of care is stated in the municipal sewerage plan (Gemeentelijk Riolerings Plan, GRP), in which they are obliged to elaborate the care for rainwater. A municipality can also make rules for rainwater and groundwater in a municipal ordinance *[Interviewee 7]*.

Chapter 3 of the Water Act regulates the organization of water management in the Netherlands. Including the (inter-administrative) supervision by a higher authority by the provinces and the central government. Regarding water management, they also supervise municipalities via the Spatial Planning Act because

[1] In practice, a transfer point between the municipality and the water board is used as the boundary between the public wastewater sewer and the treatment plant.

water management and use of space are inextricably linked. The provinces and the national government have been given the power to lay down general rules (Rijkswaterstaat, 2021).

Dutch legislation on water supply, use and disposal

The Decree on the discharge of wastewater from households (Ddwh) regulates all discharges from private households. The Environmental Management Act, the Soil Protection Act and the Water Act form the basis for this decision. The Ddwh regulates all discharge situations that may arise in a private household, both in urban and rural areas. At the same time, the Wastewater Discharge Regulations for households is in effect. It contains three requirements: Scope of the Household Wastewater Discharge Decree, customization, and duty of care (Rijkswaterstaat, 2021).

The scope of the Household Wastewater Discharge Decree contains all the rules for discharges from private households and refer to all types of wastewater released by private households, i.e., waste water from the use of the toilet, kitchen, bathroom; the domestic waste water, from outside activities and the run-off rainwater. The Environmental Management act is the basis for the rules for discharges into sewer systems (indirect discharges). The Soil Protection Act is the basis for the rules for direct discharges on or into the soil. The Water Act is the basis for the rules for direct discharges into surface water. As soon as activities are no longer of a domestic nature, the Decree on the discharge of wastewater from households does not apply. It is possible that customization of the general rules is sometimes necessary but should be reported to the municipality.

The decree of Duty of care does not lay down any concrete regulations for the discharge of most wastewater flows from households. Wastewater usually can be discharged into the sewer without restrictions. Based on article 4, a ban applies to discharges that cause damage to the sewerage system and water treatment (Overheid.nl, 2021; Sweco, Gemeente Leeuwarden, 2019). Based on the duty of care, one may expect that users discharge the wastewater into the correct sewage system;

- the domestic wastewater in the municipal wastewater sewer
- the rainwater on the municipal rainwater system

The municipality cannot make it mandatory for households with a custom-made regulation that the rainwater runoff must be disconnected from the wastewater sewer. However, the municipality can oblige this based on a new regulation for rainwater and groundwater supported by the municipal sewerage plan (Sweco, Gemeente Leeuwarden, 2019).

In the case of new construction projects to be completed, in order to obtain a permit, the Spatial Planning Act makes it mandatory to weigh up the consequences for water (consumption) via the water test and its associated water section (de waterparagraaf) *[Interviewees 2 and 6]*. These instruments allow water management interests to be considered explicitly and balanced when drawing up spatial plans and decisions. Consisting of 1) the obligation to initiators of spatial plans to involve the water manager at an early stage in the planning and 2) the obligation to initiators of spatial plans to account for in their proposal *[Interviewee 4 and 11]*. The latter is usually done in the water section of the relevant plan (Rijkswaterstaat, 2020).

4.1.4. Step 2.1. | Water Security Indicators

This section presents perceived water security indicators. First, the local context is described, after which the national and local domestic water supply, use, and disposal (treatment) is elaborated. Eventually, the energy in water supply, use and disposal, and its interlinkages are discussed.

Local Context

The study was carried out over several neighbourhoods in Leeuwarden. Leeuwarden lies in the north of the Netherlands, close to the Waddenzee and at two meters below sea level. The region's annual precipitation ranges from 825 to 875 mm, based on data from 1991-2020, with an annual average temperature of 12.4^{0}C. The population of Leeuwarden counts 93,395 residents, and the population grows each year by 3%, based on data from 2013-2020 (AlleCijfers.nl, 2021; Cbs.nl, 2021). With 48,260 houses with an average roof surface of $60m^2$ (European Environment Agency, 2013) the catchment storm water amount or roof drainage is $1.969 \cdot 10^3\ m^3$ water ($Q_c = A \times r \times p$[2]). In Figure 4, the annual precipitation in Leeuwarden is shown for the year 2018, which was one of the driest years in the last 100 years in the Netherlands (knmi.nl, 2018; OpenInfo.com, 2021).

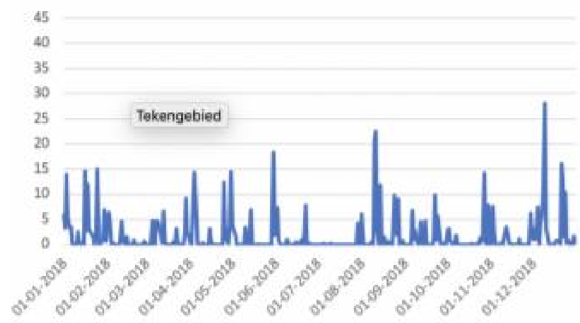

Figure 4 Annual precipitation of Leeuwarden in 2018

Water supply

In the Netherlands, the national drinking water supply is put under pressure by future developments, such as the increasing drinking water demand rates. However, it still meets the SDG6 target of safely managed drinking water services and treated wastewater (van Engelenburg, Sustainability characteristics of drinking water supply in the Netherlands, 2021). On the other hand, the more specific SDG6 targets, which consider the impact on water-related ecosystems, water pollution, or water shortage, are not met (Van den Brink, 2016; Kools, 2019). The drinking water supplied in the Netherlands comes for 55% from groundwater resources, which strongly depend on hydro-chemical characteristics, showing pressure on the water quality due to nitrates, pesticides, historical contamination and salinization (Baggelaar, 2017). Nearly half of the abstraction areas are affected, and due to traces of new pollutants, groundwater quality will further deteriorate (Teuling, 2018). Therefore, it is expected that future abstractions will not comply with the quality standards set in the Water Framework Directive.

In 2019, all Dutch drinking water companies together produced and supplied about 1.2 billion m^3 of drinking water. Vitens, Brabant Water and Evides accounted for the most significant part of this production with 366, 192 and 170 billion litres, respectively. Within the Vitens area, which supplies the provinces of Friesland, Flevoland, Overijssel and Gelderland, has an average daily supply of 965.000 m^3 per day, although during the extreme drought periods of 2018, the average volume of the summer supply increased by 27% and with a maximum of 43% (van Engelenburg, Sustainability characteristics of drinking water supply in the Netherlands, 2021). The infrastructure of the drinking water supply is designed with

[2] Q_c = Catchment storm water amount, A = Catchment´s area, r = Run-off coefficient (0,8 for inclined roof), and p = annual precipitation (Taboada-Gonzales, 2014)

overcapacity to meet the regular demand peaks. However, the flexibility to more extreme peaks for a more extended period is limited *[Interviewee 3]*.

The drinking water for Leeuwarden, which is divided into ten sub-sectors, is supplied by Vitens. The city is located in a mixing area, which means that the water is supplied by two pumping stations, namely Spannenburg and Noord-Bergum *[Interviewee 3]*. Based on the hourly values of the drinking water supply for the years 2019 and 2020, it can be stated that an average of 6.727.068 m^3 was supplied to the ten sub-sectors[3].

Water use

This sub-section provides information about national and local water demand and its trends; besides, it gives an insight into the division of in-house water use and its costs. The annual water demand was 818,4 million m^3 in 2020 (Cbs.nl, 2021). Household use is by far the largest share of use; in 2016, this comprised 69.5% of the total drinking water consumption (VEWIN, Unie van Waterschappen, 2021). Household use is the largest share of users, with 69.5% of the total in 2016. Determined by the total use of all connections registered as domestic connections (based on registered connections < 300 m^3 and on the water meter). The household level is essential for property ownership, such as garden, dishwasher and water-saving shower head. Besides that, the individual level is relevant, especially for personal usage, such as the number of showers and toilet flushes per day.

From the 1990s until 2016, domestic water consumption decreased by at least 10%, see **¡Error! No se encuentra el origen de la referencia.**. This saving was mainly due to more efficient washing machines and toilets. The cessation of the growth in household use from the early 1990s – despite the continuing growth in the number of inhabitants – is mainly caused by: 1) households becoming saturated with water-using facilities (especially showers and washing machines) and 2) the advancing technical water-savings, such as through more efficient toilets (smaller cisterns, flush interrupters) and more efficient washing machines. However, 2013 was a turning point, after which the total yearly drinking demand started to grow again. The Delta scenario for the Netherlands project a drinking water demand increase of 10% to 35% in 2050, compared to 2015. This increase can be fitted to the increase in demand in the Vitens area for 2013-2019, see Figure 5. Besides that, climate change has its impact; the drought and heat in 2018 and 2019. Vewin's research report shows that the temperature has gradually risen by 0.5C over three years, showing a proportional increase in water use for drinking, irrigation and showering. This trend, combined with the increasing popularity of the rainfall shower (Google trends, 2021), has a significant impact.

As of 2019 data, the household water consumption amounts to 130 litres pppd (Cbs.nl, 2021). The report of Vewin shows the division of the water use over the different facilities used in the household; this is done over the water use of 2016, which was then 119,2 pppd, see Figure 5. The use per time in litres in this overview is determined by recalculating the results per partial use. The following information about the water use in households comes from the Vewin report and the interview with interviewee [3].

[3] Negative readings caused by sensor errors have been taken into account.

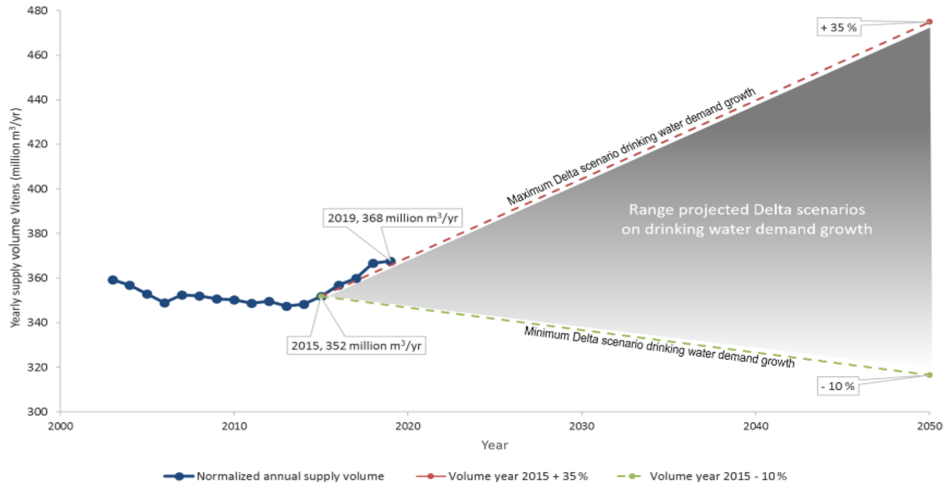

Figure 5 Water use and projected annual domestic water demand

Table 8 shows that the facilities that use the most water are the shower (49,2L/41,3%), the toilet (34,6L/29%) and the washing machine (14,1L/11,8%) (Vewin, 2020). They are responsible for 82.1% of the in-house water use, so in the further assessment of the water use, there will be mainly focused on the use of these facilities. A distinction is made in the water use of people of different ages, gender, ethnic background, and education.

Table 8 Domestic water use per appliance

Lpppd[4]	**1995**	**2004**	**2007**	**2010**	**2013**	**2016**
Bath	9,0	2,8	2,5	2,8	1,8	1,9
Shower	38,3	43,7	49,8	48,6	51,4	49,2
Sink	4,2	5,1	5,3	5,0	5,2	5,2
Toilet	42,0	35,8	37,1	33,7	33,8	34,6
Clothing wash (hand)	2,1	1,5	1,7	1,1	1,4	1,3
Clothing wash (machine)	25,5	18,0	15,5	14,3	14,3	14,1
Dishes (hand)	4,9	3,9	3,8	3,1	3,6	3,5
Food preparation	2,0	1,8	1,7	1,4	1,0	1,3
Drinking water	1,5	1,6	1,8	1,8	1,0	1,3
Rest	6,7	6,4	5,3	5,3	3,4	4,5
Total	**137,1**	**123,8**	**127,5**	**120,1**	**118,9**	**119,2**

Concerning age, 45 to 54-year-old people consume the most water (120.5 litres), representing 24% of the residents in Leeuwarden. Young people aged 13-17 years used the least water in 2016 (93.9 litres). Although the elderly, i.e., the people over 65 years old, come very close to the average on a total level, the water use pattern in this group is very different from the average pattern. The elderly use the most

[4] Liter per person per day

water to flush the toilet, while in the other age groups, the most water is used when using the shower (see Table 9).

Table 9 Water use by age (litres per person per day, person level)

Years	*0-12*	*13-17*	*18-24*	*25-34*	*35-44*	*45-54*	*55-64*	*64+*	Average
Shower	47,1	51,7	64,2	60,7	54,4	58,4	42,6	32,7	49,2
Toilet	24,9	26,1	29,0	33,0	31,8	37,5	37,1	44,9	34,6
Washing Machine	11,2	10,2	12,4	14,0	12,7	15,5	17,3	16,6	14,1
Other facilities	…	…	…	…	…	…	…	…	…
Total of water use	112,4	105,0	126,1	128,1	118,7	134,3	118,3	121,3	119,2

Immigrants use 163.3 litres of water per person per day, compared to 104.8 by natives (56% more). While the average water consumption has decreased by 11.9 litres compared to the previous measurement in 2013, this difference is only marginally due to ethnic minorities *[Interviewee 3]*. Compared to the 2013 measurement, ethnic minorities consume an average of 2.8 litres less. The difference can be explained by the fact that immigrants shower more often (1.2 times a day vs 0.70 times a day respectively) and take longer showers (9 minutes vs 7 minutes respectively) than natives. In addition, immigrants use a relatively large amount of water with hand washing, but this is offset by relatively low use utilizing the washing machine (see Table 10).

Table 10 Water use by ethnicity (litres per person per day, person level)

	Immigrant	Native	Average
Shower	104,0	47,7	49,2
Toilet	38,9	34,2	34,6
Washing Machine	10,2	14,3	14,1
Other facilities	…	…	…
Total of water use	183,5	116,5	119,2

Water consumption is by far the highest in the lower wealth classes[5]. Compared to the other classes, this class consumes much more water when showering (+17.5 litres more than the average of the other classes). Furthermore, this class also uses more water for toilet flushing (+13.1 litres more than the average of the other classes). This use can be explained by the higher average frequency of toilet flushing (an average of 8 times a day for the lower class and six times a day for the other wealth classes). Concerning showering, the difference is not explained by the frequency of showering but mainly by the length of showering. Higher wealth classes take a much shorter shower on average (approximately 6 minutes and 43 seconds) than lower wealth classes (approximately 8 minutes and 43 seconds). A difference of 2 minutes between the highest and the lowest wealth class, (see Table 11).

[5] The distinction is based on the classification by wealth class is a classification based on education and profession of the main breadwinner.

Table 11 Water use by wealth class (litres per person per day, person level)

	Higher	Middle	Lower	Average
Shower	42,0	50,2	66,7	49,2
Toilet	35,7	31,6	48,7	34,6
Washing Machine	12,5	14,9	14,0	14,1
Other facilities	…	…	…	…
Total of water use	110,9	112,9	162,9	119,2

In the Netherlands, there is a fixed rate per connection plus a variable volumetric charge per m^3 (no block tariffs). In the Vitens area, the fixed rate is € 45.78 per year (including 9% VAT), and the variable charge is € 0.70 per m^3 of drinking water (2021). For an average 4-person household this equals a variable charge of €190 per year. Based on the Water Framework Directive principles, the prices resemble a 100% cost-recovery and are used by Vitens for merely operating and capital expenditure and environmental charges and taxes (European Environment Agency, 2013).

Water disposal (wastewater treatment)

As the law states, three water flows are considered: urban (grey and black) wastewater, rainwater and groundwater. After the water has been used, it is discharged through the sewage system to a waste water treatment plant (WWTP). Rainwater and domestic wastewater often end up in the same sewer pipe, which the mix is also considered urban wastewater. The WWTP in Leeuwarden has an average influent of 36.000 m^3 per day, the water is purified and then returned to the surface water. As long as the precipitation does not come into contact with pollution, the water remains clean and can be introduced directly into the soil or surface water (Sweco, Gemeente Leeuwarden, 2019). It is essential that people process the water that falls on their plot themselves or ensure proper drainage with separate sewerage, supported by legislation *[Interviewee 7]*. Promoting a reduction in the influent seems contradictory for the wastewater treatment process, but this is due to the maximum production capacity of the water treatment system. The water treatment facility in Leeuwarden has a capacity of 100,000 purification units; one purification unit is, on average, $50m^3$ wastewater, the total wastewater of one person per year[6]. Rainwater and 'clean' wastewater, which do not need to be purified, unnecessarily burden the hydraulic capacity (8000 m^3 per hour) of the system. This burden has to do with the purification process; the water that enters the purification is purified for concentration; 90% of each unit is purified. If this unit is dirtier and therefore more concentrated, more waste is removed *[Interviewee 7]*. Less volumes, therefore, put less pressure on the process, making it more efficient and cheaper to treat. In practice, solving these problems leads to high costs. The government charges the costs for this to the citizen through the sewerage levy and purification levy. Work is being done on decentralized applications, but water system infrastructure is built in the Netherlands for the long term and has existing sunk-in investments creating path dependencies, which is why the system is cumbersome and difficult to change.

[6] A purification levy is claimed on this, being 3 purification units per household of 60 euros each.

4.2. Interlinkages of Domestic Water and Energy Use in Leeuwarden

This section provides an insight into the energy used in water supply, use and disposal (treatment) in the situation of Leeuwarden.

Energy in water supply

The energy used for the production and distribution of the Vitens area is monitored, but the two pumping stations for Leeuwarden are not monitored separately. To create a picture of the energy needed, Vitens advised calculating with the specific energy consumption for the whole of Friesland, being 0.6085 kWh/m^3. Multiplying this number with the supplied water gives a total amount of 4093MWh energy used. In the future, climate change developments will result in a more energy-intensive process to produce drinking water (van Engelenburg, 2021).

Energy in water use

As the Netherlands is a water abundant country, the energy demand for warm tap water use for households is about eight times more than the energy used to supply or treat the domestic water (Frijns, 2013; Ibrahim, 2021). Where energy use in buildings is continuously decreasing in segments like heating, ventilation and air-conditioning, and lighting, the share of energy used for domestic hot water heatings increasing (Pomianowski, 2020). As legislation on indoor space conditioning becomes stricter, the energy demand for heating domestic hot water is overlooked (Zwanenburg) (Knight, 2007; Marszal, 2011). Many water experts see similarities of the water transition with the energy transition. Where the water transition is still in its early days, the energy transition has already matured. The period in which the energy transition gained speed was the period that it became financially attractive. Besides that, the awareness of global warming is high among the people resulting in the willingness to participate *[Interviewee 3]*.

The average energy consumption in Leeuwarden is 2171 kWh, and the average natural gas consumption is 1300 m^3 (AlleCijfers.nl, 2021). For showering, laundry, and cooking purposes, a substantial amount of energy is added to water through heating. Analyses of European cases estimate that 20-35% of energy need is dedicated to heating hot water, and in zero-energy buildings, this percentage goes up to 40-50% (Bohm, 2013; Frijns, 2013). As it is rarely done in Europe, domestic hot water in the Netherlands is rarely explicitly considered but mostly associated with other parts of the energy balance; for the billing, no distinction is made between indoor space heating or domestic water heating. Besides that, in electrical hot water production, the total energy consumption is available from metering devices. It appears that it is hard for clients and design engineers to implement and appreciate the benefits of measures for more efficient heating of water since there is limited knowledge and no nudges *[Interviewee 3]*. The energy needed to heat up the domestic water can be categorized into three groups, i.e., end-use, distribution (circulation), and storage/conversion (Pomianowski, 2020; Frijns, 2013).

Energy in wastewater treatment

Although the energy losses from buildings have decreased, the thermal losses linked to consumed hot water that flows into the sewers have an increasing share, which embeds a potential in heat recovery from wastewater in Dutch households. The average temperature leaving a house is 27°C, linking that to the amount of water used, the potential heat in this water is 0,87 kWh/home/day, with a drop of 5°C (Capodaglio, 2019). With 48.000 homes in Leeuwarden, that yields 15.242 MWh/year of total theoretical heat potential to be recovered. Wastewater as a heat source has a large thermal capacity, high thermal conductivity, as it contains nutrients and energy (Pomianowski, 2020). In the municipal sewer plan (Gemeentelijk Rioleringsplan), the municipality aims to implement heat recovery installations; besides that, the waste water is exploited at the water treatment plant (Sweco, Gemeente Leeuwarden, 2019)*[Interviewee 7]*.

At the treatment plant, this energy potential is only partially recovered, and at the same time, the treatment process costs substantial amounts of energy. The average energy use for wastewater treatment is 26.6 kWh/population equivalent [7] removed, which means that the average energy use of the plant in Leeuwarden is about 6200 MWh/year. At this plant, various projects are underway within the water board to extract energy from the water, mainly based on raw materials that can be extracted and sludge[8] treatment. The phosphates, for example, are bound to sludge, incinerated and return to the combustion ashes and can thus be recovered. Energy production is mainly done because of the revenue model that is linked to this *[Interviewee7]*. Besides that, sludge digestion is done, as it is common practice in the Netherlands producing biogas. This biogas is converted in a combined heat and power system to electricity and heat. This heat is used in the area to heat the facility and other nearby institutions; in doing so, the WWTP of Leeuwarden aims to be energy neutral in 2025 *[Interviewee 7]*.

As the Wastewater Treatment Directive and Water Framework Directive put higher standards on the effluent of supplied and treated water, including the extraction of hormones and dangerous substances, the processes will require more advanced and 10% more energy-intensive treatment processes in the near future (Frijns, 2013).

4.2.2. Step 2.2 | Criteria based on the characteristics of the water-saving technologies

This section elaborates on the domestic water-saving technologies of rainwater harvesting, wastewater reuse, and warm water reduction. A number of technologies can be applied for greywater treatment varying in both complexity and performance. This research focuses on small decentralized systems that allow for more “fit-for-purpose” use with more flexibility in process selection and matching end uses (Chong, 2013; Brown V. J., 2010). An overview of the technologies is presented in

[7] Population equivalent = 378 Litres per capita per day.

[8] Sludge is a product of the treatment process consisting of dead bacteria.

Table 12, after which they are further explained.

Table 12 Overview of the three water-saving technologies

Criteria	Rainwater harvesting	Greywater Reuse	Warm water reduction
Social	Low contact reclaimed water. Less convenient, by limitations for potable use.	Medium/low contact with the reclaimed. Less convenience since it does not provide potable water.	High contact with reclaimed water. Convenient, provides potable water.
Technical	Slightly intruding *[Interviewee 4]*. The lifetime is 50 years, and it can be clustered *[Interviewee 4].*	Highly intruding when installed. When installed the maintenance, costs are €120 a year. It has a lifetime of 30 years. Grey water systems can be clustered. *[Interviewee 8]*	Not intruding., the system can be installed easily. It has low maintenance. Every ten years, a pump needs to be revised (100 euro´s), and the lifetime is 25 years. *[Interviewee 5]*
Political	Subsidy for: 1) Disconnecting the downspout from the sewer (€5 per m^2, max. €500). 2) Rain barrels (€25 per barrel, max. 2 units). 3) RW system (max. €2500). 4) Rainwater storage fence (€200 per unit, max. €1000). Resident is responsible for their own rainwater drainage *[Interviewee 7]*.	Subsidy for water reuse system (max. 2500). The water recycling system must comply with NEN EN 16941-2:2020 (quality certificate).	Subsidy for water reuse system (max. 2500). The water recycling system must comply with NEN EN 16941-2:2020(quality certificate).
Economic	Acquisition costs: ~ €2000 *[Interviewee 4]*	Acquisition costs: ~ €5000 *[Interviewee 8]*	Acquisition costs: ~ €4000 *[Interviewee 5]*
Ecological	Use is principally for water use of low quality. On average, 5000L. litres can be saved/reused. No energy is saved *[Interviewee 4]*.	The saved water can be used for a variety of (low to medium water quality) appliances. Capacity of reused water is 500 litres per household per day. Saves about 400 kWh a year.	High quality use. Can save up to 400 litres per household per day. Saves about 700 m^3 of gas per year (7815 kWh). *[Interviewee 5]*

Greywater reuse

In this research, two types of the most conventional grey water systems are included: The Home Eco Grey water system and the Hydraloop H300. The ´HOME Eco grey water system´ consists of a complete system with storage tanks, control, a bioreactor and a membrane station and has a capacity of 300L/day. The water captured by this system can be used for toilet flushing, cleaning, washing clothes and irrigation purposes and saves up to 50% of the total water use. In a situation of 4-person household, in which the Hydraloop reuses the water from the shower and bath, an average of 180 litres per day can be saved, which adds up to 65.000 litres per year (Valkieser, 2020). The Hydraloop consists of a complete, smart and integrated system, with a capacity of 530L/day *[Interviewee 8]*. It can recycle greywater from the shower, bath, air-conditioning, and washing machine, used for toilet use and washing clothes. With add-ons, the water can be used for irrigation and the pool as well. The system is user friendly, providing an app that gives insight into the available water to reuse *[Interviewee 8]*. Although, it is very intrusive when installed since the plumbing needs to be altered. Besides the water-saving, the greywater reuse systems save on the energy bill; since the recaptured water already has a higher temperature, there is no energy lost in heating it, which saves about 400 kWh a year.

Rainwater harvesting

In this research, the most conventional rainwater system is included, namely the Home Pro system. It consists of a rainwater tank with a built-in filter and quiet inflow, charge pump and pressure line, rainwater station with fully automatic drinking water replenishment, expansion vessel. That's why the installation can be intruding, depending on the size, since a tank (3000 -20.000L) needs to be installed to store the water for reuse (a moderate garden has a storage capacity of 5000 litres). Besides that, some additional pipes and pumps are needed. In the situation of Leeuwarden, calculating with the precipitation rates of 2018 and an average storage tank of 5000 litres, there is enough capacity for indoor water use throughout the year, expect for 36 days during the summer. During these days tap water is needed. When water is available, this can be used for toilet flushing, cleaning, washing clothes and irrigation purposes and saves up to 40% of the total water use, which means a reduction about 50.000 litres for a 4-person household (Valkieser, 2020). The system can be expanded with extra filters to improve the quality and make it appropriate for showering and drinking. Reclaimed water quality is subject to the same regulations to enable domestic non-potable reuse. With rainwater harvesting, no energy is saved; the installation needs a small amount of energy for pumping the water *[Interviewees 4 and 8]*.

Warm water reduction

The warm water reduction technology that is included in this assessment is the Upfall shower system. The Upfall shower system is a complete installation that captures the shower water in a reservoir pumps it up through a filter and UV light. A warm tap water is added and redirected towards the shower head. The system can be installed quickly, the water meets the water quality standards (which one), and the integrated system is user friendly because of its display providing all the necessary information. This system saves about 95% of the water used for showering, with means that it saves up to 180 litres per day in a 4-person household, about 66.000 litres per year. Besides that, it uses water that is already heated, which saves 30% on the annual energy use, lowering the EPC value (energy coefficient, measuring the energy that is used per square meter) of a house *[Interviewee 5]*. Which makes it interesting for new construction, since they need to build houses that comply with a minimal EPC value.

4.3. Comparison of Water-saving Technologies

This section answers the third sub-question: *To what extent do different water-saving technologies improve the domestic water and energy efficiency of households in Leeuwarden?*

4.3.1. Step 3.1 | Define the target layer

The AHP will be applied in order to find the best alternative for water-saving technologies. The three alternatives are: rainwater harvesting, greywater reuse and the warm water reduction

4.3.2. Step 3.2 | Structure the decision hierarchy

The hierarchical tree shown in Figure 6 comprises six groups (the set of criteria within the dotted square with each of their sub-criteria); there are at least two elements (criteria) in each group. Within each group, a two-step comparison was phrased using the Comparion software for all possible combinations. The first question is about which of the two has a more significant influence on the other criteria, and the second question is about to what extent this criterion has a more significant influence on the other one. For the total assessment of the hierarchy as presented in Figure 6, 18 sets of questions with 64 questions were required. The respondents were confronted with these questions in interviews in which the verbal judgements of relative importance were converted into Saaty´s scale of numerical values. For every set of more than two elements, the AHP-OS tool automatically calculated the consistency ratio (CR) in Excel worksheets. Because the respondents provided input for selecting relevant criteria, they understood the hierarchy very well, which led to low inconsistency. When the inconsistency was above the permitted 0.1, the AHP-OS tool and the software provide insight into the inconsistency, so it was immediately evident. Therefore, the expert could reconsider the comparison on the spot when necessary (Goepel, 2018).

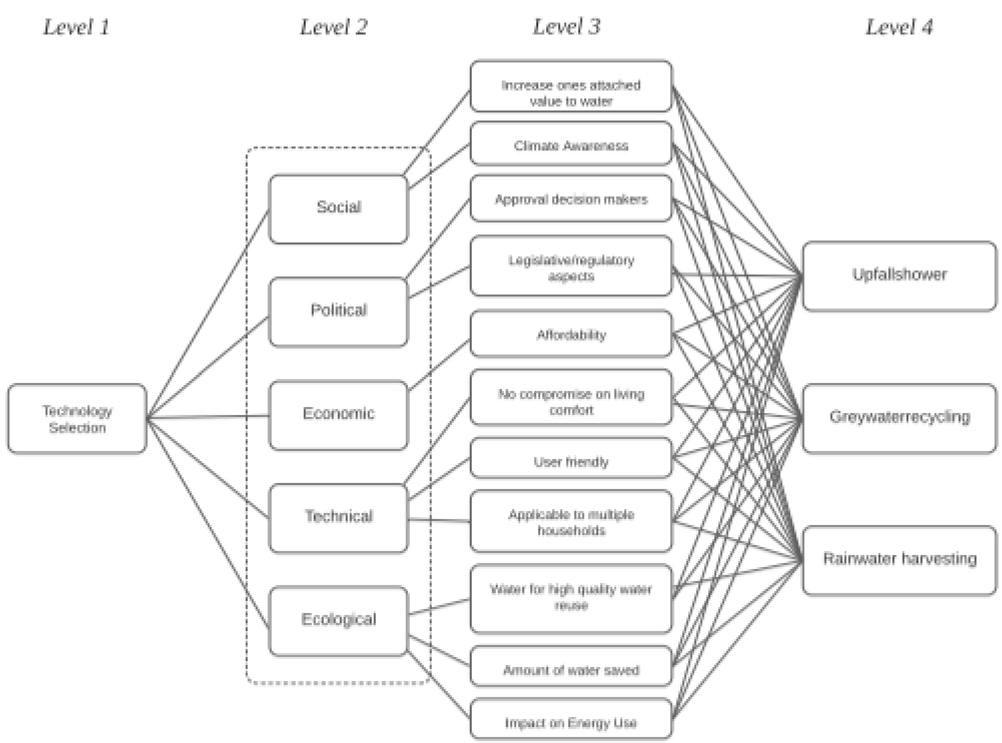

Figure 6 The hierarchical tree for AHP

4.3.3. Step 3.3 | Construct pairwise comparison matrixes

The outcome of the expert judgements was inserted into Excel worksheets and automatically turned into a reciprocal matrix, as is shown in Table 13. This matrix shows the pairwise comparison of all criteria with respect to each other. The criteria have been assessed based on each set of criteria with a shared parent node and the calculated vector of all relative overall weights of the indicators, see Figure 7.

Table 13 Pairwise Comparison Matrix

	1	2	3	4	5	6	7	8	9	10	11	12
1	1	6.00	7.00	8.00	6.00	4.00	2.00	3.00	3.00	5.00	4.00	4.00
2	0.17	1	2.00	3.00	2.00	0.20	0.20	0.25	0.25	0.33	0.33	0.20
3	0.14	0.50	1	3.00	2.00	0.17	0.17	0.20	0.20	0.25	0.33	0.25
4	0.12	0.33	0.33	1	0.33	0.14	0.17	0.20	0.20	0.20	0.25	0.20
5	0.17	0.50	0.50	3.00	1	0.17	0.14	0.25	0.20	0.17	0.25	0.20
6	0.25	5.00	6.00	7.00	6.00	1	0.50	4.00	3.00	4.00	4.00	2.00
7	0.50	5.00	6.00	6.00	7.00	2.00	1	4.00	3.00	4.00	4.00	3.00
8	0.33	4.00	5.00	5.00	4.00	0.25	0.25	1	0.25	0.50	2.00	0.25
9	0.33	4.00	5.00	5.00	5.00	0.33	0.33	4.00	1	3.00	5.00	3.00
10	0.20	3.00	4.00	5.00	6.00	0.25	0.25	2.00	0.33	1	2.00	0.33
11	0.25	3.00	3.00	4.00	4.00	0.25	0.25	0.50	0.20	0.50	1	0.25
12	0.25	5.00	4.00	5.00	5.00	0.50	0.33	4.00	0.33	3.00	4.00	1

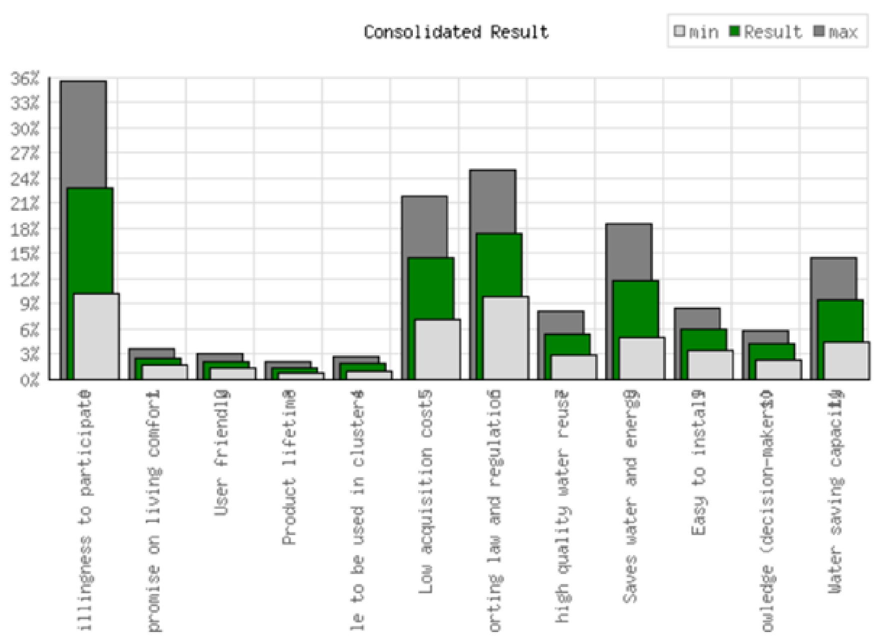

Figure 7 Relative weights per indicator

4.3.4. Step 3.4 | Evaluate outcome

The data was inserted and analysed in the software, in which the criteria and its judgements of pairwise comparisons are linked to the three alternatives. For each criterion, a pairwise comparison is made between the alternatives by the researcher based on the information gained from the semi-structured interviews with the water technology experts. In this case, the consistency was kept on a CI of 0.05, which is within limits. Besides that, the consensus between inputs was calculated in the range of 0-100%. The maximum standard deviation was 13%, implying that there was a high consensus between decision-makers. The software compares the criteria and relation to the alternatives and makes a prioritization, see Figure 8. The prioritization shows that the rainwater harvesting is most effective to apply (with a percentage of 46.07%) after that the warm water reduction (33.24%) and eventually the grey water reuse (20.59%).

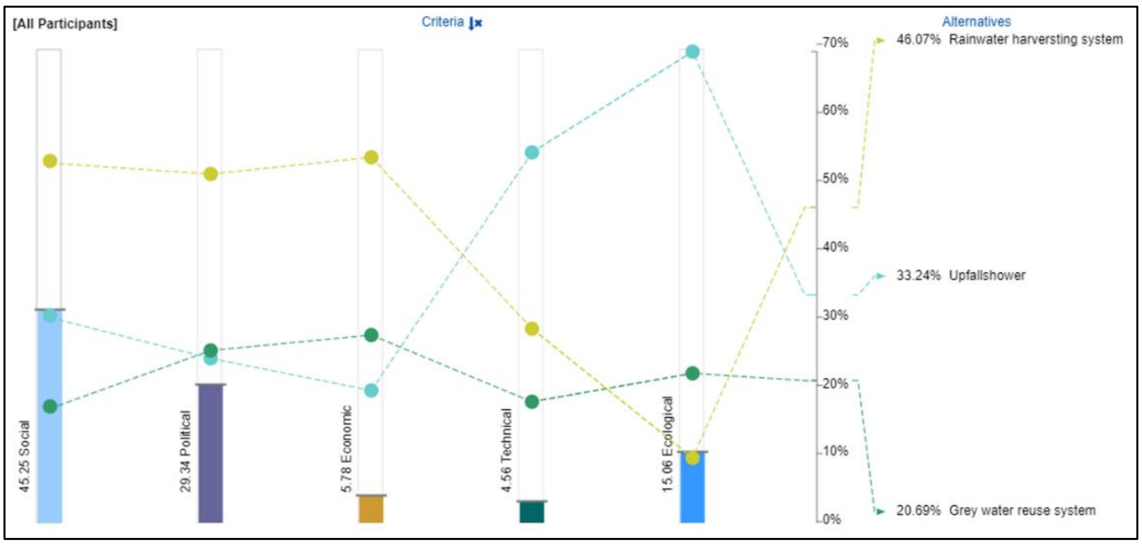

Figure 8 Prioritized outcome AHP

Sensitivity Analysis

As the model prescribes, the following sensitivity analysis has been conducted to assess the robustness of the outcome and whether an alternative technology should be considered. Of the five level-one indicators, a sensitivity analysis is shown in Figure 9.

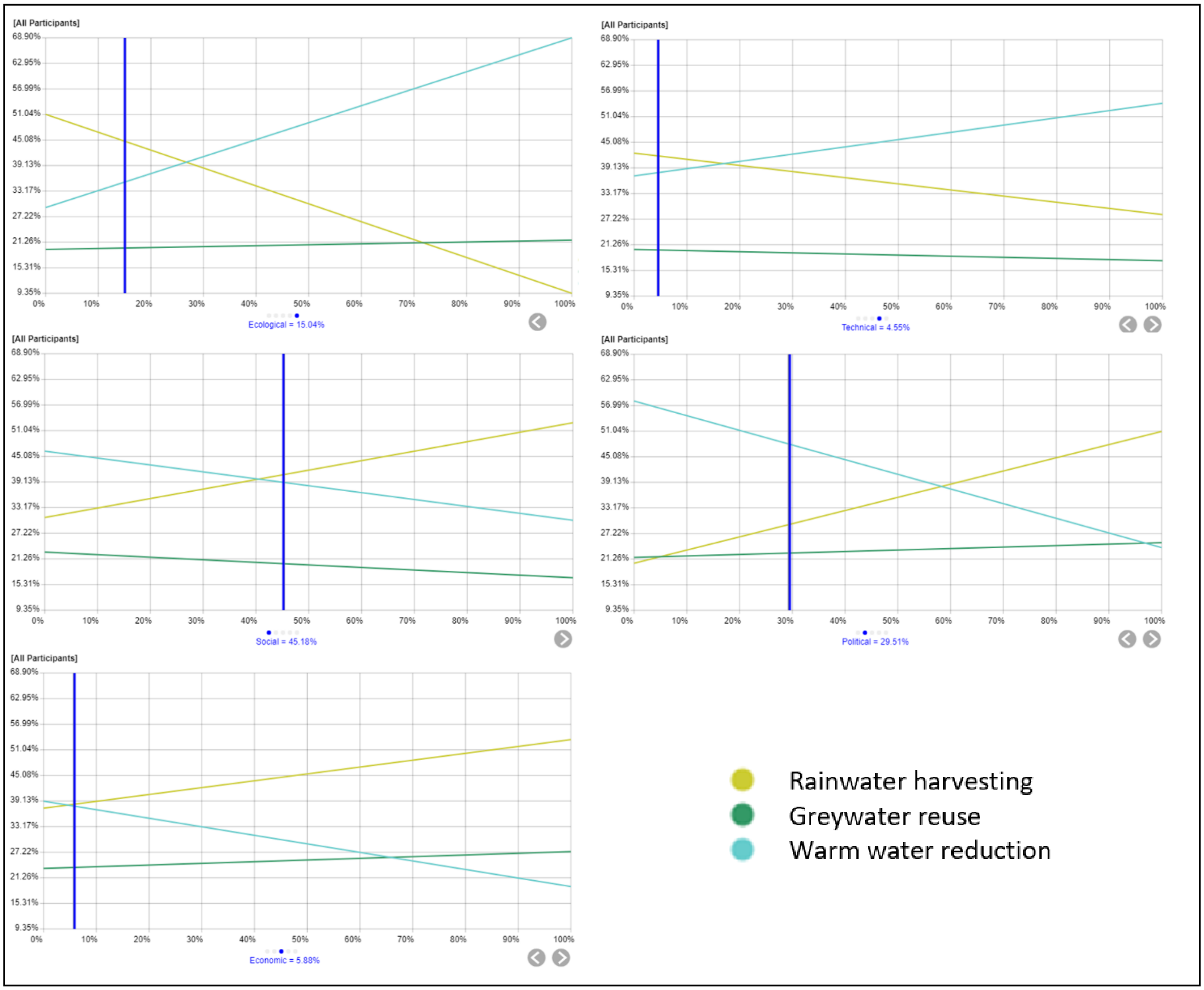

Figure 9 Sensitivity Analysis

The sensitivity analysis results show what happens with the priority of alternative technologies when weights per criteria are changed. There can be seen that when the weight of the social and economic criteria decreases and the weight of ecological and technical criteria increases, the warm water reduction alternative should be considered by decision-makers. In all cases, the sensitivity analysis shows that greywater reuse is not the best fitting alternative for water-saving purposes in the existing situation of Leeuwarden.

4.3.5. Cost-Benefit Analysis

In this section, the objective is to examine which water-saving alternatives would be the least costly. The criteria included in this analysis are installation cost, acquisition cost, life cycle maintenance costs, and the reduction of costs through water and energy savings (Figure 10) (Babalola, 2020; Mohamadian, 2011).

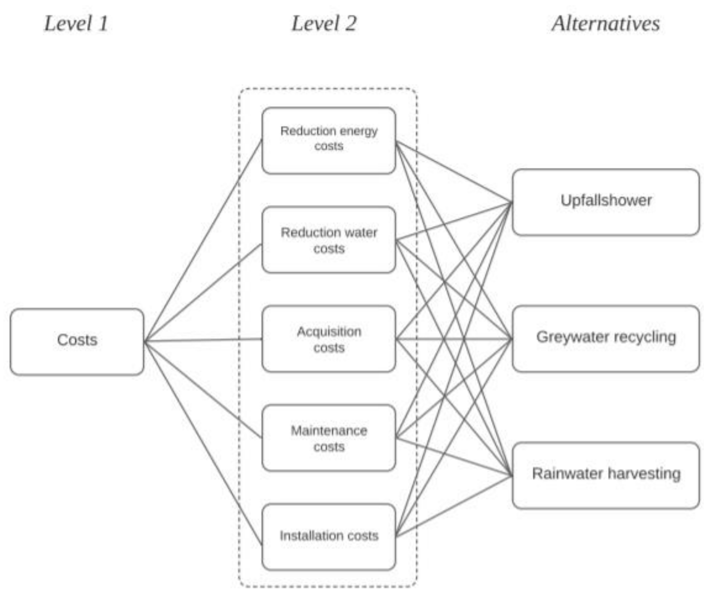

Figure 10 Hierarchy structure for the cost analysis

On the author's judgement, based on Saaty´s scale (1-9), a weight is given to each criterion. After which pairwise comparisons are drawn up, using the software of ExpertChoice. Eventually, a synthesis of all criteria is formed, showing the prioritization of the alternatives concerning costs. As shown in Figure 11, rainwater harvesting is the most cost-effective solution.

Figure 11 Synthesis for all criteria in cost with their relative weights

5. Conclusions

Water-related problems due to climate change and water scarcity are incredibly complicated and need a holistic approach to solve them effectively. To resolve these problems and work towards a climate-resilient and water-secure city, water and energy requirements in household water supply, use and disposal have been assessed, and a robust estimate of energy use in the water cycle is given, which forms the objective of the research. Chapter 3, presents the technology assessment model, identifying clearly the key elements for water and energy consumption in Leeuwarden, providing a better understanding of resilience in urban water management, answering sub-question 1. Chapter 4, presents the outcome of the model, answering sub-question 2, and shows insight in the water use and the energy use involved in each element of the water system. For this research, the water system in the urban area of Leeuwarden was analyzed by different criteria, which gave insight into the supply, use, and disposal of domestic water. Three different appliances are responsible for 80% of the 130 L of water used pppd: the shower (49.2%), the toilet (34.6%), and the washing machine (14.1%). Trends show that the popularity of comfort showers is rising, and therefore the prognosis is that the water demand will only increase. The city is supplied with $1.969 \cdot 10^3\ m^3$ of runoff water each year, but because of the Dutch state of mind concerning water governance, this water is drained quickly, which gives an unnecessary high pressure on the capacity of the WWTP. The energy part in water heating is increasing, which shows that energy optimisation is not sufficient. Upcoming demands will need a new integrated method of the water cycle as a whole.

The last section of chapter 4, answers sub-question 3, and presents the technology assessment, resulting in a prioritization of best water saving technologies. Three different water-saving technologies, i.e., rainwater harvesting, greywater reuse, and warm water reduction technologies, were assessed. The assessment of the technologies was performed by using a multicriteria decision method that combined the Analytical Hierarchy Process (AHP) with Cost-Benefit analysis (CBA). The AHP contained four steps in which weights were assigned to criteria, and scores were given to each alternative based on the comparisons of each criterion. The criteria used for this research attempted to capture the most critical influencers of the decision-making process for the municipality in Leeuwarden. Based on the application of the Technology Assessment Model, it can be concluded that in the current scenario, the rainwater harvesting system receives the highest percentage amongst the alternative technologies, according to the assigned, specified weights. This outcome means that there is a significant change that this is the best fitting technology for saving water and achieve the goal of reducing 5% of the domestic water use before 2030, which answers the main question. This result can be clarified by its performance on the heavier weighted criteria, in this case, the social and economic, over the other alternatives, e.g., greywater reuse systems, these systems are very intrusive when it comes to installing them into existing buildings are therefore very costly. This is supported by the outcome of the CBA.

The sensitivity analysis gives an insight into the robustness of the outcome. It shows that if the economic and technical criteria are changed, the warm water-saving and grey water reuse technologies gain significantly priority. Meaning, if buildings in the planning phase are made ready for the implementation of grey water reuse systems, the costs will go down, as well as the intrusiveness of the installation. Making this common practice will show people the possibilities, which might change the current perspective on the value of water. Besides that, it then represents a ´sunk costs´ which will make the house owner use it to its total capacity.

There is a delicate line between adequate incentives, cost-recovery and affordability. Even though the low water tariffs in the Netherlands are affordable, they do not provide an incentive for changing water use behaviour. In the past, other EU countries have substantially increased water prices which have exhibited changes in consummation levels that show a positive effect. However, to only focus on water pricing and neglecting the effects of each individual context seems unwise. When adjusting water prices, the first question should be whether the Dutch consumption is reactive to price changes; whether water demand is elastic to the price, which is highly influenced by affordability and the amount of water used per household. Studies show that the Dutch price elasticity is about -0.7 (European average 0.5), which means that demand for household consumption will decrease when the price increases. This elasticity might provide an excellent signal to maximize water-use efficiency as the prices are essential to send the message of the scarcity of the good. Other European water systems include ´free water up to a certain level´, increasing block tariffs, or reduced VAT rates to convey this message. The equality in affordability could be reconciled with schemes that imply cross-subsidization between poor and wealthy households.

The technology assessment model poses limitations because of the broad scope that was selected. Although the model gives a good insight into Leeuwarden's situation, if specific neighbourhoods had been analyzed, more specified recommendations could have been given. Besides that, this research is performed from the perspective of decision-makers. Even though criteria have been included that give insight into the factors that influence the adoption of specific technologies in the household sphere, a deeper understanding and more profound research on the willingness to participate would benefit the robustness of the outcome. A third limitation is the selection of three technologies; many smaller technologies could have been added to the research. The fourth and last limitation to this research was that the research process was performed in a situation of Covid-19 restrictions, which had a negative influence on the reachability of participants, besides that these participants could not be met in real-life which might have harmed the quality of acquired data.

Even though current system is a top-down water system, the municipality shows that they want to invest in a more decentralized situation in which families or neighbourhoods hold more power over the water cycle. When this happens the centralized top-down approach is replaced with the multi-level governance model, involving more actors and new-relations between them. Therefore, for future research, it is recommended to perform research on a more specified level by doing more participatory assessments involving neighbourhoods and communities. Besides that, a more extensive selection of alternatives would be interesting to include to provide decision-makers with more complete advice for their consideration. The technology assessment model provides a helpful structure that is recommended to be used in solving similar problems, improving climate resilience and water security.

6. Recommendations

Based on the model's outcome, it is recommended for the Municipality of Leeuwarden to support the adaptation of rainwater harvesting systems. The community's perception of the value of water should be focused on providing insight into the water-saving potential in the city, e.g., capturing rainwater in public, grey infrastructural spaces, showing the amount of water saved over time, as well as the domestic reuse possibilities in private spaces. The value of water is also incorporated in the price of water, which affects the economic criterion; the price of water is low, representing the value that the community gives to the water. A change in price or pricing method should affect the perception of the value. It is therefore recommended to include this factor in the project to clarify its potential further.

In addressing the situation in Leeuwarden by the partnership, it is recommended to focus on the Vitens divided sub-areas based on water supply. These sub-areas mostly contain households with the same characteristics so that measures can be applied more effectively. Besides that, the project group contains stakeholders from various levels, but the regional water authority is not included. Adding a member of the water authority could be valuable in making the step towards a more circular water system, which will make residents more aware of the value of wastewater and the importance of using runoff water, reducing the cost and energy of the WWTP.

When the rainwater harvesting system is applied to specific neighbourhoods, the percentage of water saved is over 50% representing over 65 lpppd. Since the research objective (a 5% reduction) represents a reduction of 7lpppd, a significant water-saving potential is lost. Therefore, the objective should be revised and adjusted to the maximum amount of water that can be saved in Leeuwarden before 2030.

The main focus of the project is water-saving. However, to use the already matured energy transition, linking water-saving benefits to the water-energy nexus synergies is recommended as saving water shows synergies with energy-saving in water supply, use and disposal (treatment). Such savings are significant for households, are financially interesting and might provide an extra incentive.

The model presented an outcome for the current situation in Leeuwarden. When new building projects are considered, the technical and economic sub-criteria will have less impact on the greywater reuse systems and the warm water reduction systems, which means that these alternatives will fit better to the situation and should be seriously considered. Therefore, it is recommended to revise the water section/water test procedure in Leeuwarden and work closely together with project developers to make sure that the residential buildings of the future are ready for the efficient implementation of water-saving technologies.

By implementing these recommendations, the climate resilience of Leeuwarden will be improved, as the current linear water system can be slightly transformed into a circular one, increasing water efficiency, saving more than the supposed 5%, while simultaneously increasing energy efficiency.

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Appendix A. Interview Guides

Before the interview

- Selecting the participants
- Introducing myself and explaining my role/research/goals
- Inform that the interview will take 45-60 minutes
- Send invite for Microsoft Teams meeting
- Send a copy of the consent form
- Inform them in case the participants should prepare for the interview

During the interview

Introduction

- Introducing myself.
- Introducing the topic and objectives of the research.
- Informing that the time allocated for each interview is 45-60 minutes.
- Ethics declaration and terms of confidentiality
- Informed consent form should be signed right after the interview
- Explanation of the format of the interview
- Do you have any questions before we begin?
- Permission to record the interview.

General Questions

- What is your experience with domestic water-saving projects or technologies?
- Could you explain your role in the project? (What specific tasks did you carry out?)

Part: Urban Water Management Principles

This part focuses on the Urban Water Management Principles used to make the shift towards the (practical) management of water resources in Leeuwarden. These questions are about the integration of the elements of water management. Then the researcher will ask questions about specific indicators that will help understand the situation of water supply, use, and disposal (sub-question 1), including energy use (sub-question 2).

Questions to Experts Vitens and the Waterboard

Water supply

- What are the factors that influence the water supply?
- Which factors influence the water quality
- Which factors influence the quantity of water available for domestic consumption?
- What are potential or existing water quality problems?
    - How do you prevent or monitor them?
- To what extent do droughts influence water supply?
- Is energy use in water supply considered, and how?

Water use

- In domestic water use, which factors *(e.g. social, cultural, economic, technical)* do you take into account for the assigning of water-saving technologies?
- How would you describe the role of policy interferences in domestic water use? *(E.g., water tariffs, regulations, responsibilities or different organizations)*
- Do you measure water use efficiency and if yes, how do you measure it?
- What is the role of energy in water use? (*E.g., transportation, heating)*

Water treatment (Disposal)

- In the Netherlands wastewater is treated in centralized treatment plants. What are the advantages and disadvantages of this approach?
    - What is your opinion about decentralized wastewater treatment technologies?
    - How does the process work?
    - What is the influence of water-saving on the treating process?
    - Is energy efficiency considered in the treating process?
    - What are the tariffs?

Questions for experts in water-saving technologies

To be able to decide between alternative water-saving technologies, they should be understood, and the distinction between them should be clear. It is therefore essential to know the characteristics of each technology and the factors that affect their adoption by the users.

- What are key elements in your technology/saving measure?
    - To what extent does it contribute to water-saving?
    - What is its lifetime?
- What factors (social, economic, technical, etc.) are important to know before installing a water-saving technology?
    - How do you approach a client; do you give advice for certain installations?
    - Do you have an idea of the size of the house or family?
    - Are you aware of what kind of warm water heating system the customers have?
- What would be the reason for residents or policymakers to choose for this technology over other technologies?
- What are possible hindrances against choosing this water-saving technology? (*why would the water users not want to adopt these technologies*)
- Can it be installed in a rental house? Or should the user be the house owner?
- What are the price ranges? If it an easily affordable or an expensive technology?
- Do you focus on certain customer profiles? Do you do customer surveys or market research?
    - Are you aware of the motivation of clients to buy the product?
- What knowledge is needed to use or implement it? Is it simple or complex?
- *Only for wastewater reuse*: Which water does it reuse? And what are the requirements?
- *Only for wastewater reuse*: What is the water quality of the effluent water?
    - How is water quality monitored? What are the standards to ensure water quality?
    - Does the water quality fluctuate or has it been changing over time?
- What are the policy measures that effect this technology?
    - Are there subsidies, permits, policy restrictions to install this technology?
    - Are these helping to increase the adoption of the technology?

    - Should there be additional policy measures to increase the adoption of the technology?
- What are the energy requirements of the technology? Is it low or high?

Closing Questions for all participants

- Do you have any questions?
- Is there anything you would like to add?
- Do you have any contact recommendations?
    - *Thank for participation*
    - *Outcomes can be shared when interested*
    - *For questions or remarks later, the phone number of the interviewer is shared*

After the interview

- Make sure the signed consent form is sent back or submitted by the respondent a.s.a.p.
- Transcribe the interview
- If requested, send the transcription to the respondent for clarifications or just for their information.

Appendix B. Informed Consent Form

General info: With the municipality of Leeuwarden as initiator, a group of organizations and institutions, i.e., the Municipality of Leeuwarden, Vitens, the province of Friesland, Wetsus, and the Centre of Expertise Water Technology, which all have to do with providing high-quality clean drinking water in Leeuwarden, decided to join forces in a new partnership. The aim of this partnership is to reduce the household water consumption in Leeuwarden by 5% by the year 2030.

The aim of the study is to obtain the information that provides an understanding of the entire, holistic situation surrounding domestic water use is necessary because there are many different variables and actors that influence this consumption, including energy in water.

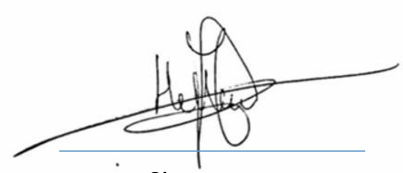
The study was previously approved by the ethics committee of the Department of Behavioral, Management and Social Sciences (BMS for the English abbreviation). The participant is free to withdraw from the research at any time, i.e. during the interview(s) and the writing of the thesis, namely that the information provided, if applicable, is not used or cannot be used or modified by the participant. That being said, it is important to state that any information collected will be used solely for the purpose of answering the research questions and will be protected for the duration of the research, which ends on August 31, 2021. After that, Once the thesis is published, the only existing information is contained in the document (information that is pre-approved by the participant). In any case, the participation can is anonymous; no names will be shared in the document.

Select the correct option (Yes/No):

	Yes	No
I have read and understood the information about the research, or it was read to me by someone else. The doubts I have had about the survey have been satisfactorily answered and clarified.	○	○
I give my voluntary consent to participate in this study and understand that I may refuse to answer questions and withdraw at any time without giving a reason.	○	○
I understand that being part of this research involves a video meeting or answering an online survey. In case of a meeting, it will be recorded, and the information will only be used for the research and no other.	○	○
I give permission for the research activity to be recorded.	○	○
I understand that the information provided will be used to develop the research results and help answer the research questions.	○	○
I understand that any information collected, including information about me, such as my name or address, will not be shared with anyone or used outside the purpose of this research.	○	○
I give permission for the data I provide to be archived for use during the research. The information is stored in the cloud's multiplatform file hosting service: Dropbox, where the researcher has only access via an access account.	○	○

Name participant	Date	Signature

The participant has had the opportunity to ask questions, and I confirm that they have freely given their consent.

Hille Jan Hellema	08/06/2021	
Name researcher	Date	Signature

Contact details:

Researcher: Hille Jan Hellema, +31683058171, hellemahillejan@gmail.com

If you have questions about your rights as a research participant, would like to obtain information, ask questions or discuss concerns about this research with anyone other than the researcher(s), please contact the secretariat of the Faculty Ethics Committee or Behaviour, Management and Social Sciences of the University of Twente via Ethics Committee-bms@utwente.nl and the telephones: 053-489-3520 / 053-489-3294.